Assessing the impact of Colombian public land acquisitions on forest cover in the Andes

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Abstract

Public land acquisitions (PLAs) are a promising conservation instrument, combining the permanence of protected areas with the voluntary, compensatory structure of payments for ecosystem services, yet causal evidence on their effectiveness remains limited. Colombia's Article 111 mandate, which requires departments to allocate 1% of revenue to land acquisition for watershed protection, has produced one of the world's largest and longest-running PLA programs, enabling rigorous evaluation. We estimate the impact of 2,512 PLAs in the Colombian Andes on parcel-level forest cover from 2001 to 2021 using covariate matching and staggered difference-in-differences. PLAs have a statistically significant, time-accumulating effect on forest cover, increasing from 0.16 percentage points after one year of protection to 2.53 percentage points after 15 years. Effects are driven primarily by forest regrowth rather than avoided deforestation, consistent with program targeting and active reforestation on acquired parcels. Benchmarking against the literature, estimated effect sizes fall within the range reported for protected areas and payments for ecosystem services. These results indicate that PLAs can generate measurable conservation gains even when implemented in relatively low-threat landscapes. Crucially, impacts emerge slowly and accumulate over time, implying that evaluations based on short post-treatment windows will systematically underestimate their effectiveness.

Introduction

As climate and development-driven ecosystem pressures increase, governments around the globe are committing to ambitious area-based conservation targets, such as the 30x30 initiative outlined in the Kunming-Montreal Global Biodiversity Framework, to protect biodiversity and critical ecosystem services (Convention on Biological Diversity, 2022). At the same time, there is growing consensus that traditional protected areas (PAs), which often rely on state control and the exclusion of human activity, are insufficient on their own to meet these targets (Maxwell et al., 2020). PAs face well-documented constraints on where they can feasibly be established, with acquisition and political costs pushing them toward low-threat, low-value landscapes (Börner et al., 2020; Joppa and Pfaff, 2009). The result is a global PA network that has expanded rapidly in coverage while remaining poorly aligned with global biodiversity targets (Dinerstein et al., 2024; Hoffmann, 2022). At the same time, a substantial body of literature documents equity concerns associated with PAs, including displacement and undermining land use rights of Indigenous communities (Dawson et al., 2021; Tauli-Corpuz et al., 2020). These critiques have shifted conservation instruments toward participatory frameworks in which equitable outcomes are understood as a precondition for legitimate conservation.

In response, the past two decades have seen growing investment in incentive-based alternatives. Payments for ecosystem services (PES), which compensate landowners on a voluntary, time-limited basis for maintaining or restoring ecosystems on private land, are particularly popular (Salzman et al., 2018; Wegner, 2016) but face well-documented limitations and do not consistently outperform other conservation instruments. A meta-analysis of 136 normalized effect sizes by Börner et al. finds that PES are moderately effective on average, with effect sizes broadly comparable to those reported for PAs and other instruments (Börner et al., 2020). Because participation is voluntary, enrollment tends to concentrate in areas of low opportunity cost where land-use pressure is also low and the potential for additional impact is therefore limited (Izquierdo-Tort et al., 2024; Wunder, 2007) - a trait PES share with PAs. Some studies suggest that effects, on average, are driven more by new forest growth than by avoided deforestation, though this depends on program targeting and contract design (Patrick and Potts, 2023; Ruggiero et al., 2019). The distinction of forest types is important, as desired biodiversity outcomes often depend on the protection of existing primary forests rather than the establishment of secondary growth. Finally, because contracts are time-limited, PES do not guarantee the kind of long-term protection that is often needed for ecosystem recovery and biodiversity conservation.

Public land acquisitions (PLAs) are an incentive-based conservation instrument that have the potential to deliver the permanence required to protect biodiversity and ecosystem services while simultaneously avoiding the equity concerns raised by PAs. PLAs compensate landowners directly for permanently ceding land-use rights and, because participation is voluntary, pose, at least in principle, fewer equity risks than PAs. In theory, the long-term nature of PLAs can support sustained management and enforcement needed to maintain ecosystem services, protect biodiversity, and allow degraded habitats to recover. However, despite their theoretical promise, PLAs, like PES and PAs, may be systematically directed toward cheaper, lower-threat landscapes rather than those where conservation is most needed. PLAs also include higher up-front costs relative to PES and require formal documentation of land ownership which can be a significant barrier to enrollment in contexts where tenure is informal, records are incomplete, or land rights remain disputed following conflict or displacement.

Given their potential to meet biodiversity targets in a more equitable way, and the theoretical ambiguity surrounding the contexts under which PLAs are effective, evidence from rigorous empirical evaluations could help gauge the potential value of PLA for tropical forest conservation. Yet, large-scale assessments of PLA effectiveness remain limited. PLA programs are rare in tropical countries, and where they exist, individual transactions are typically small and geographically scattered, making it difficult to assemble sample sizes required for credible causal inference within a relatively homogeneous setting. As a result, the conditions under which PLAs meet conservation goals remain poorly understood.

Colombia presents a rare opportunity to address this gap. The Colombian Tropical Andes is one of the most biodiverse regions in the world with uniquely high levels of endemic and threatened species and frequently cited as a global conservation priority. Colombia's population and economy are concentrated in the Andes resulting in high rates of forest degradation and deforestation (Armenteras et al., 2011). In response to this pressure on watersheds, since 1993, Article 111 of Law 99 mandates that all Colombian departments spend 1% of their annual income on land acquisitions for water conservation and to conserve and restore ecosystems on acquired land (Fondo Acción, Fundepúblico y WCS, 2017). As a result of this law, Colombia is home to one of the largest and longest-running PLA programs in the world, providing a rich empirical context to study their impact. Previous empirical research on PLA in Colombia found that acquisitions were directed primarily toward cheaper, less threatened ecosystems (Reboredo Segovia et al., 2023), a pattern consistent with the location biases documented for both PAs and PES (Börner et al., 2020). Critically, this work stops short of causal impact assessment, leaving the fundamental question of PLA effectiveness unexplored.

We address three related questions to advance our understanding of the conditions under which PLAs are an effective conservation instrument. First, we evaluate the impact of PLAs on forest cover in the Colombian Andes between 2001 and 2021, using a combination of matching and difference-in-differences (DiD) with multiple time periods where percent forest cover is our primary outcome variable. We then assess whether PLA impact on forest cover is driven primarily by new forest growth or by avoided deforestation. To the best of our knowledge, this represents one of the first efforts to quantify the effectiveness of any large-scale PLA program. Finally, we discuss whether PLAs, PES, and PAs differ in their causal impact on forest cover, benchmarking our effect size estimate against the broader literature on forest conservation interventions.

Results

To measure the impact of Colombian PLAs on forest cover in the Andes, we use matching followed by DiD with multiple time periods. We consider PLAs across the Colombian Andes which we define as the maximum extent of three ecoregions: Northern Andean Montane Forests, Northern Andean Parámo, and Tumbesian-Andean Valleys Dry Forests (Olson et al., 2001). Matching variables were selected to control for observable confounding variables that might impact forest cover change including access to cities, terrain, nearby protection, baseline forest cover, and municipality. Of 2,542 PLAs established between 2000 and 2019 with valid spatial and treatment date information, 2,512 were successfully matched (Figure 1). Matching successfully controlled for the selected covariates except for 30 PLAs which were dropped when a match could not be found within one standard deviation for one or more of the covariates (Figure 2).

For the DiD regression, we use DiD with multiple treatment periods which allows for staggered treatment (Callaway and Sant'Anna, 2021). This design is necessary because we consider PLAs

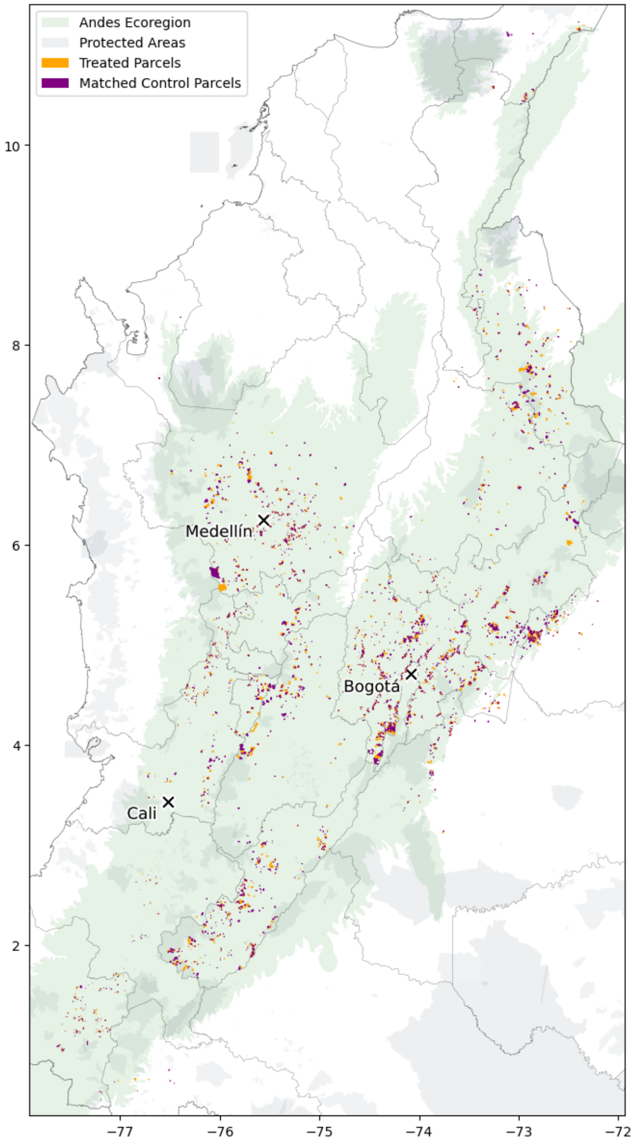

Figure 1. Distribution of PLAs and corresponding matched controls across the Colombian Andes.

that were established over 20 years. Our outcome variable was the forest percentage within each parcel. Forest percentage was calculated from an annual forest cover dataset that was made specifically for the Colombian Andes with satellite-based remote sensing imagery. We estimate the average treatment effect on the treated (ATT) for each treatment cohort in each year between 2001 and 2021, weighing all estimates by parcel area. For each cohort-year combination, the ATT is estimated by comparing the forest cover change between treated parcels' pre-treatment baseline and the post-treatment year against the equivalent change in their matched controls over the same window. We then aggregate these cohort-year ATTs by the number of years a parcel has been protected (exposure length), allowing us to assess how the impact of PLAs on forest cover accumulates over time.

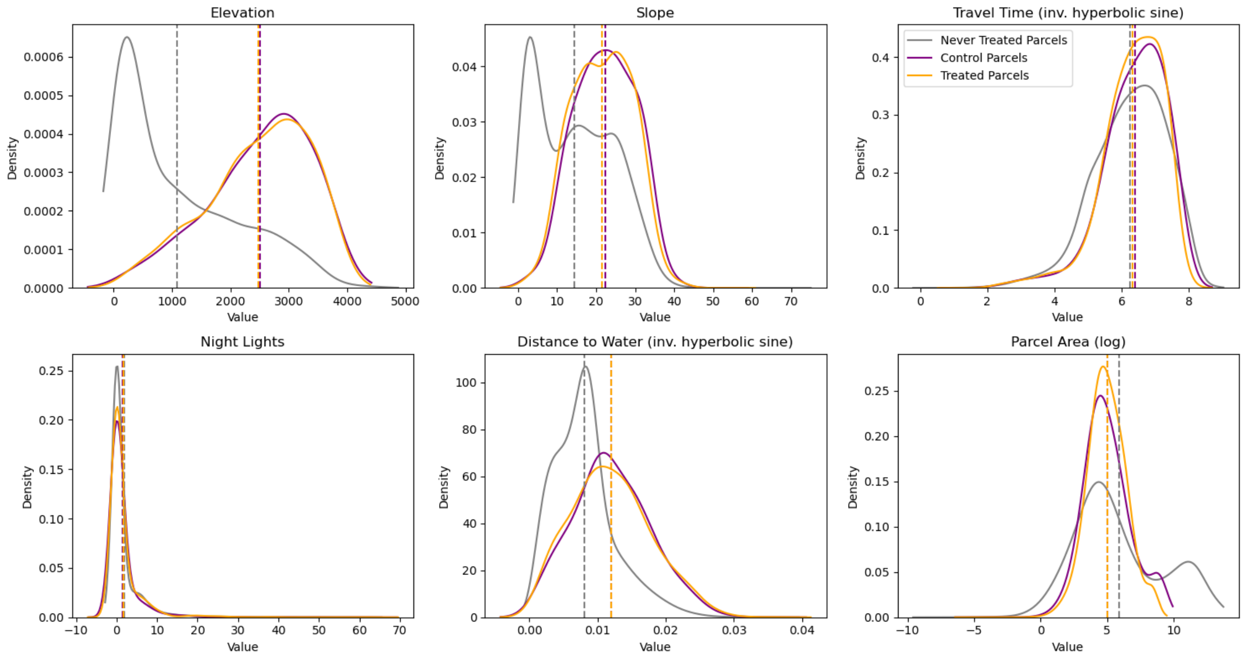

Figure 2. Distribution of matching covariates for treated parcels, matched controls, and the full pool of never-treated parcels. Distributions are weighted by parcel area. Overlap between treated parcels and matched controls indicates covariate balance.

Against a background forest change rate of approximately 0.03 percentage points per year, PLAs have had a statistically significant positive impact on forest cover, with effects that accumulate over time growing from an estimated 0.16 percentage points in the first year of protection to 2.53 percentage points after 15 years (Figure 3). After 15 years, estimates decline and by 19 years post-treatment they are no longer statistically significant due to small sample sizes. Pre-treatment estimates show a modest negative trend in the years prior to protection; while this does represent a potential violation of the parallel trends assumption, the magnitude of this trend is small relative to the post-treatment effects and is unlikely to negate the estimated impact of PLAs on forest cover.

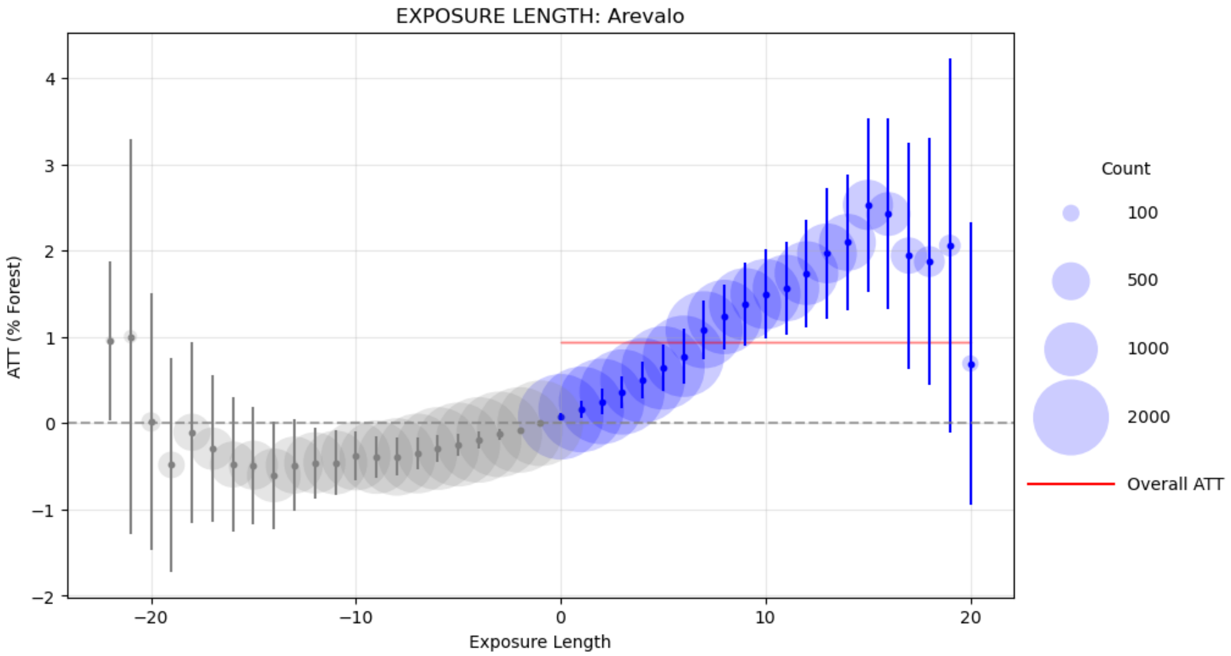

Figure 3. ATTs averaged by number of years pre- and post-treatment. Error bars show the 95% confidence interval for the estimate.

To assess whether PLA impact on forest cover is driven by new forest growth or avoided deforestation, we re-estimate the DiD with multiple treatment periods on a dataset where forest regrowth has been excluded. Post-treatment estimates with regrowth excluded are small and statistically significant only at intermediate exposure lengths of seven to thirteen years (Figure 4). Comparing these estimates to the full model reveals that avoided deforestation accounts for a small fraction of the total effect, indicating that PLA impact on forest cover is driven primarily by new forest growth rather than avoided deforestation.

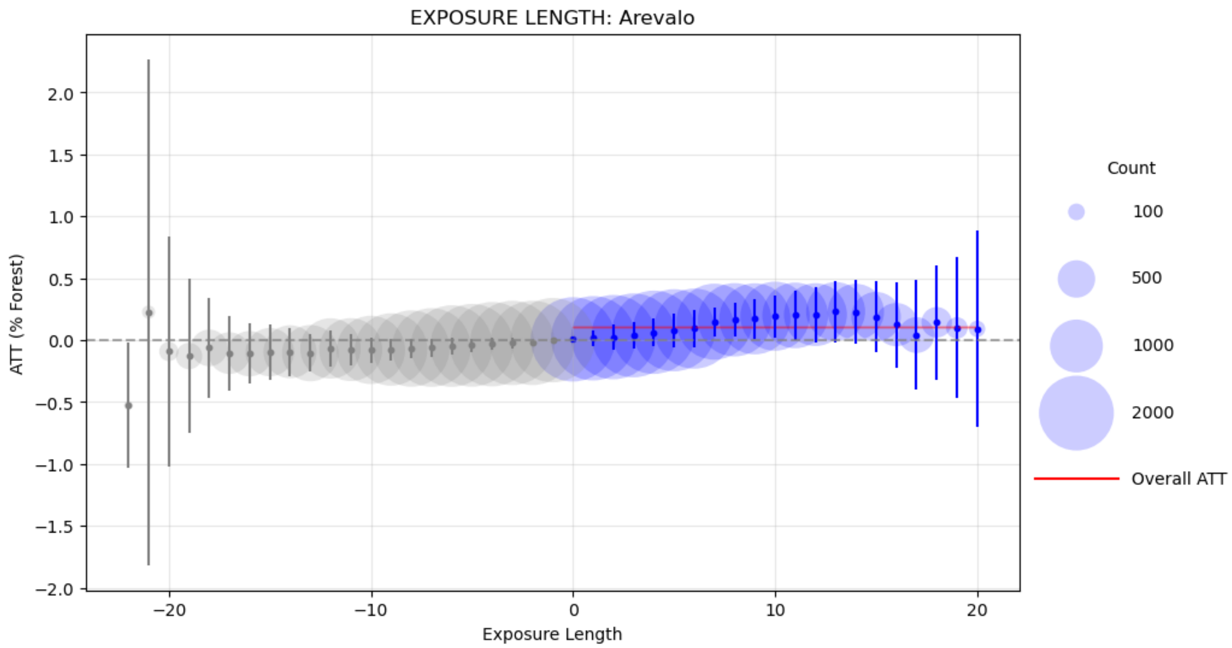

Figure 4. ATTs averaged by number of years pre- and post-treatment, estimated on a dataset from which forest regrowth has been excluded. Error bars show the 95% confidence interval for the estimate.

Discussion

The impact of Colombian PLAs on forest cover is comparable in magnitude to effect sizes reported across forest conservation interventions globally (Börner et al., 2020). Börner et al. synthesized 136 normalized effect sizes across 10 categories of forest conservation intervention, including PAs and PES, and find that forest conservation instruments are moderately effective on average, with most intervention types clustered between a Cohen's d of 0 and 0.2. Our exposure-length estimates fall squarely within this range when translated to Cohen’s d. At one year of protection the estimated Cohen’s d effect is negligible, 0.004, consistent with the expectation that land acquisition alone produces little immediate change in forest cover but grows to 0.04 at the average exposure length of nine years and to 0.07 after 15 years. Overall, these results suggest that PLAs produce forest cover effects that are broadly consistent with PES and PAs.

PLA impacts were undetectable in the first years of protection and continued accumulating through fifteen years, yet the average treatment length in this study was approximately 8.5 years. In this context, our estimates likely understate the long-run impact of the Colombian PLA network. Evaluations conducted over shorter time horizons, or on programs that have not yet matured, will systematically underestimate impact. Designing evaluations with sufficient post-treatment observation periods is therefore particularly important for accurately evaluating the impact of PLAs.

Prior work has shown that Colombian PLAs have been directed primarily toward cheaper, lower-threat landscapes, with acquisitions driven by watershed protection goals rather than forest cover outcomes explicitly (Reboredo Segovia et al., n.d.). That measurable effects are detectable even under these conditions suggests that well-targeted PLAs in higher-pressure landscapes could produce substantially larger impacts.

Impact was driven primarily by forest regrowth rather than avoided deforestation. This outcome is consistent with program targeting which prioritized watershed protection rather than deforestation threat to established forests. Evidence from eastern Antioquia indicates that this reflects deliberate management. PLA funds were frequently used to reforest acquired parcels and fence out cattle, actively facilitating the regrowth that drives our estimates

Pre-treatment estimates show a modest negative trend in the years prior to protection, which we interpret cautiously. Two mechanisms could produce this pattern. First, treated parcels may have been losing forest at a slightly faster rate than controls in the pre-treatment period. Alternatively, control parcels may have been gaining forest at a faster rate than treated parcels prior to acquisition. Given that background forest dynamics in the study region were largely stable to slightly positive over the study period, the latter interpretation is perhaps more plausible. Given the evidence from Eastern Antioquia that program funds were intentionally used to facilitate reforestation, we speculate that program officials may have preferentially acquired parcels in which natural regeneration was suppressed by ongoing human activity such as grazing or smallholder cultivation. This would explain the observed pre-treatment pattern if matched controls, while similar on observable covariates, were subject to less intensive ongoing land use and therefore more capable of passive regeneration in the years prior to acquisition. Regardless of mechanism, the magnitude of the pre-treatment trend is small relative to the post-treatment effects and is unlikely to fully account for the cumulative impacts we observe.

Our results are specific to the Colombian Andes and should be extrapolated cautiously. The Colombian mandate has produced one of the largest and longest-running PLA programs in the world, with sustained public funding and an active management culture that may not be replicable in other institutional contexts. Additionally, PLAs in this study were implemented in a landscape characterized by active land use and relative accessibility which shaped both the forest dynamics we observe and the feasibility of active management interventions. In contexts where PLAs are implemented in more remote or extensively forested landscapes, the mechanisms driving impact, and therefore the magnitude and character of effects, may differ substantially. Further evaluation across a broader range of institutional and landscape contexts is needed before generalizing these results to PLA programs elsewhere.

This study assessed just one dimension of PLA impact, forest cover change. Theory suggests that PLAs are more socially responsible than PAs; however, we do not consider whether compensation was adequate and whether transactions were voluntary in practice. Effects on species diversity, habitat connectedness water quality and quantity, and cost-effectiveness were not addressed. Each of these dimensions is relevant to the practical choice between PLAs and other instruments.

Conclusions

We find that PLAs in the Colombian Andes have had a modest but statistically significant impact on forest over with effects comparable in magnitude to those reported for PAs and PES globally. Impact increased steadily over the first 15 years of treatment and was driven primarily by forest regrowth rather than avoided deforestation, consistent with both program targeting and evidence of deliberate reforestation on acquired parcels. Pre-treatment estimates show a modest negative trend, though its magnitude is small relative to the post-treatment effects and is unlikely to negate the estimated impact.

We cautiously consider that our results might underestimate the total effect of the Colombian PLA network because we do not follow all treated parcels through the full fifteen years post-treatment where we expect to see increasing impact and because PLAs were targeted for watershed protection rather than forest outcomes explicitly. Whether PLAs deliver on their broader theoretical promise depends on outcomes beyond forest cover, including effects on biodiversity, water quality, and the equity of transactions, that remain to be assessed.

Materials & Methods

Our study area includes 416 Colombian municipalities with significant geographic, ecological, and socioeconomic heterogeneity. Importantly, the Colombian Andes are part of the tropical Andes biodiversity hotspot, one of the most species-rich regions on Earth. Forests in this region provide critical ecosystem services including carbon storage and water regulation; yet recent estimates suggest that Andean forests occupy less than 50% of their potential extent, with cattle grazing, smallholder agriculture, infrastructure development, and extractive industries among the primary drivers of historical forest loss (Llambí et al., 2020). Socioeconomically, the region is characterized by rapid population growth, urbanization, and a complex land tenure and governance context shaped in part by decades of violent conflict and ongoing post-conflict land restitution processes.

Public land acquisition data was compiled by contacting government officials via phone, letter, or in person. Contributing agencies include 24 regional environmental agencies, 14 departments, and 107 municipalities. For a complete description of the data collection process, see (Reboredo Segovia et al., 2023). Parcel data for all departments was obtained from the Colombian cadaster (IGAC) data portal except for Antioquia which has its own geodatabase.

Our primary unit of analysis is the land parcel, and our primary outcome is percent forest cover at the parcel level. Percent forest cover was derived from annual land cover maps for the years 1997 to 2021 (Arévalo et al., 2025). These maps were generated by applying the Continuous Change Detection and Classification (CCDC) algorithm (Zhu and Woodcock, 2014) to Landsat time-series data and training a random forest classifier on a custom-labeled dataset derived from a combination of existing land cover maps, opportunistic samples, and manually interpreted high-resolution imagery. The resulting classifications were refined through temporal consistency enforcement, rule-based post-processing, and stratified accuracy assessment using visually interpreted reference samples from high-resolution imagery and Landsat time series.

We compiled our treatment dataset by selecting cadaster parcels that share more than 80% of their area with a PLA boundary. Because cadaster parcel boundaries were used to compile the original PLA dataset, in most cases PLA and cadaster geometries were equivalent. Due to the temporal limitations of the land cover data, we limit our analysis to PLAs established between 2000 and 2019 to avoid errors associated with measuring treatment effect over a very narrow window, less than three years. Given our imposed temporal limitations as well as missing spatial and treatment date information we were only able to measure the impact for 2,542 of the PLAs from the original dataset.

To estimate the causal impact of PLAs on forest cover, we used matching followed by difference in differences (DiD) with multiple time periods. The goal of matching is to control for observable confounding variables so that the forest cover trends for matched parcels mirror the counterfactual outcome for treated parcels. In other words, the forest cover trends for control parcels should be the same as those that would have been observed on treated parcels had they not been treated. Selected matching variables include percent forest cover on the year prior to treatment, slope, elevation, measures of accessibility including travel time to cities and night lights, distance to water, parcel area, and whether the parcel is inside an existing protected area. See Table 1 for a complete description of matching variables. To increase the chances of finding a quality match for as many treatment parcels as possible, we allow treated parcels to match either never-treated or not-yet-treated parcels. To do this we follow a novel protocol where treated parcels are drawn randomly one at a time and matched to a dynamically created pool of control parcels. This protocol allows us to 1) dynamically select not-yet treated parcels based on the treatment year of the comparison treated parcel (Nolte et al., 2019), 2) select control parcel attributes for the years prior to the treatment year and 3) ensure that treatment cohorts at the beginning of the study period would not be matched better than others by virtue of being matched first (Reboredo Segovia et al., n.d.). Post-matching standardized mean differences (SMD) between treatment and control groups were small (<0.1 SMD for all variables).

Table 1. Matching variables and justification.

Variable	**Source**	**Resolution**	**Justification**
% forest cover on year prior to treatment	Bullock and Arévalo, in progress	30 m	Affects the potential for forest change and whether decisionmakers might select it for protection.
% forest loss within a 60-pixel buffer in the 3 years prior to treatment	Bullock and Arévalo, in progress	30 m	Deforestation pressure is an important predictor of forest change.
% protection within a 60-pixel buffer	RUNAP, 2023; Agencia Nacional de Tierras, 2024	30 m	Areas with significant adjacent protection may experience spillover deforestation.
Elevation	Japan Aerospace Exploration Agency, 2021	30 m	Can influence deforestation pressure.
Slope	Derived from elevation	30 m	Areas with high slope are less arable and may have lower deforestation pressure. Can affect treatment selection because steep slopes are a priority for water source protection.
Travel Time to Cities (inverse hyperbolic sine)	Nelson, 2008	925 m	Accessible areas have higher deforestation pressure. Remote parcels may be less expensive to

			acquire if other economic activity is limited by inaccessibility.
Night Lights (Accessibility)	Small et al., 2011	925 m	Commonly used proxy for accessibility.
Distance to Water (inverse hyperbolic sine)	Derived from elevation	30 m	Areas with limited access to water may have lower deforestation pressure. Parcels may be less expensive to acquire if other economic activity is limited by lack of irrigation.
Parcel Area (log)	GIS Calculation based on IGAC and Antioquia cadasters	Vector	Determines the yearly level of observable deforestation with 30m land cover data.
Protected Area Category	RUNAP, 2023; Agencia Nacional de Tierras, 2024	Vector	Protected areas have varying restrictions and enforcement that may influence deforestation and regrowth dynamics.
Municipality and Direct Abutters	Departamento Administrativo Nacional de Estadística, 2005	Vector	Accounts for unobserved regional socioeconomic differences that influence deforestation, enforcement, and enrollment.

Two-way fixed effects DiD design has been shown to produce biased estimates for interventions that were implemented over multiple years. We use DiD with multiple time periods to address the staggered implementation of PLAs. We rely on the R package, DiD which calculates the ATT for individual group-time cohorts and aggregates them by treatment cohort, calendar year, and exposure length (Callaway and Sant’Anna, 2021).

To benchmark our effect size estimates against the broader forest conservation literature, we calculate Cohen's *d* following Börner et al. (2020), by dividing the treatment effect by the standard deviation of the outcome variable in the control group. We adapt this approach to our study framework by dividing our ATT estimates by the standard deviation of control group percent forest cover in 1999. We use 1999 because all PLAs in this study were established in 2000 or later, making it an appropriate pre-treatment baseline year for the full sample.

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Supplementary Materials

Table S1. Standardized mean differences for all matching variables.

Variable	**SMD**
% forest cover on year prior to treatment	0.03
% forest loss within a 60 pixel buffer in the 3 years prior to treatment	0.00
% protection within a 60 pixel buffer	0.01
Elevation	0.04
Slope	0.01
Travel Time to Cities (inverse hyperbolic sine)	0.03
Night Lights	0.05
Distance to Water (inverse hyperbolic sine)	0.01
Parcel Area (log)	0.09