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Land tenure security and forest cover in the Colombian Amazon

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Land tenure security (LTS) is important for achieving many sustainable development goals but its influence on forest cover is mixed. The uncertain relationship between LTS and forests is driven, in part, by the moderating influence of other drivers of deforestation. In this paper we illustrate this complex relationship between LTS and forest cover for individual private landholders in the Colombian Amazon. We use household surveys and econometric analysis with matching techniques to examine whether formal land titles and perceptions of LTS influence forest cover. We explore how the effect of a land title on forest cover is moderated by perceptions of LTS, time to markets, and participation in a conservation program. We find that more secure land tenure, on average, has a statistically significant and negative influence on forest cover in our sample. The negative association between LTS and forest cover is stronger when landholders perceive they have secure tenure and are closer to markets. However, we find the negative relationship between land title and forest cover goes away when a landholder participates in a conservation program. While our cross-sectional data and quasi-experimental methods cannot lead to causal statements, our results are in line with many recent studies in the Amazon region, and our household-level data provides important insight regarding drivers of deforestation that moderate the relationship between land title and forest cover. Our results inform the design of future LTS interventions and conservation efforts.

KEYWORDS

Amazon basin, Colombia, conservation, deforestation, forest, land title, land tenure

1 Introduction

Forests are critical for climate regulation, biodiversity, and myriad other ecosystem services but continue to experience rapid loss due to agricultural conversion, wildfire, commodity extraction, and urbanization (Curtis et al., 2018). Colombia, one of the most biodiverse countries in the world, has witnessed accelerating rates of forest loss since its 2016 Peace Accord to end civil conflict, with conversion of forests driven by commodity expansion, cattle production, and illicit land uses (Reardon, 2018; Murillo-Sandoval et al., 2020; Murillo-Sandoval et al., 2021). Even areas within protected areas, including national parks as well as community and ethnic collective titles, have not been immune to post-conflict deforestation pressures (Armenteras et al., 2019b; Clerici et al., 2020), although they have fared better than forests on individual private lands (Bonilla-Mejía and Higuera-Mendieta, 2019; González-González et al., 2021).

Weak land tenure is thought to have contributed to these land use conversions, including informal land rights, land grabbing in the face of weak institutions, and a practice of clearing the forest to claim land (Armenteras et al., 2019a; Sánchez García and Wong, 2024). There is

a strong correlation between areas with low state presence and insecure land tenure in Colombia (Munoz-Mora et al., 2018). Following the 2016 Peace Accord, Colombia has been investing in the formalization of land tenure across the country. This approach aims to address land inequalities and conflicts and formalize land titles nationwide to complement the multi-purpose cadaster policy (Botero and Velásquez Ospina, 2022; Agencia Nacional de Tierras, 2022; Agencia Nacional de Tierras, 2024).

In parallel to land tenure formalization, Colombia is attempting to increase economic development, decrease illicit crop production, and stop unsustainable forest loss. One main approach has been a national program aimed at illicit crop substitution (Spanish: *Programa Nacional Integral de Sustitución de Cultivos de Uso Ilícito-PNIS*). According to recent evaluations, however, the program has not been successful, with coca cultivation actually increasing in some areas (Departamento Nacional de Planeación, 2022; Londoño et al., 2023). Another approach has been to make deforestation illegal in 2021 through Law 2111. The government has invested in enhancing law enforcement and judicial capacity to enforce this new law (Fundación Ideas para la Paz, 2020; Ministerio de Defensa Nacional, 2023). Colombia has also developed new incentive programs to try and encourage compliance with forest restrictions. A national Payments for Ecosystem Services (PES) policy (Law No. 870/2017 and Decree 1007/2018) was developed in 2018 to increase opportunities for programs that provide economic incentives for conservation (Moros et al., 2020). By 2020, almost 300,000 hectares and 4,000 families were involved in PES programs across the country (Ministerio de Ambiente y Desarrollo Sostenible, 2021). Additionally, the government of Colombia has entered into a number of zero-deforestation initiatives to try and curb deforestation (Furumo and Lambin, 2020).

Globally, there has been increasing interest in land rights (e.g., Salmerón-Manzano and Manzano-Agugliaro, 2023) and the interactions between land tenure and forests (e.g., Robinson et al., 2018; Masuda et al., 2020; Tseng et al., 2021). The empirical literature on land tenure and forest outcomes suggests the relationship is mixed and context specific (Robinson et al., 2014; Busch and Ferretti-Gallon, 2023). Many more studies focus on the form of land tenure, versus land tenure security (LTS), where tenure form refers to who has land rights and LTS refers to the assurance that a land manager feels their rights to the land will be upheld by society (Arnot et al., 2011; Robinson et al., 2014). In this study we focus on LTS, keeping tenure form constant, in order to better isolate the influence of LTS. A recent global synthesis of drivers of forest outcomes concluded that there was no consistent association between LTS and deforestation (Busch and Ferretti-Gallon, 2023). One reason for this mixed relationship is that strengthening tenure is rarely done to directly influence conservation behaviors (Robinson et al., 2018). However, LTS directly influences the land use decision making process and interacts with other underlying drivers and policies that can influence forest cover. For this reason, more rigorous studies are needed across multiple contexts and in understudied regions to build the evidence base on LTS and forests (Robinson et al., 2018; Hänggli et al., 2023).

One pathway through which LTS can influence forests is by increasing investments in economically productive land uses, because of increased assurances in reaping the benefits of those investments or increased access to credit. Known as the "investment effect" in the LTS literature, this pathway often results in clearing forest or other natural land covers to produce marketable commodities (Arnot et al., 2011; Liscow, 2013). Recent studies from Brazil, Panama, and Vietnam all point to investment in agriculture at the expense of forests following formalization of land titles (Probst et al., 2020; Abman and Carney, 2020; Walker, 2021). However, an alternative type of investment is possible if landholders with LTS are enabled to participate in conservation initiatives or programs that provide incentives to conserve. For example, Jones et al. (2017) find that private landholders in Ecuador signed up for external conservation incentives once they received land titles, reducing deforestation on their land compared to a counterfactual group. A second pathway in which LTS can influence forests is by eliminating the need to "clear land to claim it" and/or by allowing land managers to ward off outside claimants. This "protective effect" was found in Holland et al. (2017) where landholders that received land titles were able to prevent surges in deforestation that occurred on similar lands that did not have LTS.

In this study, we add to the empirical base on the complex interactions between LTS and forests by studying the influence of LTS on forest cover in the Colombian Amazon. Our data come from a 2022–2023 household survey of individual private landholders in three northwestern departments of the Colombian Amazon; a region experiencing some of the greatest levels of forest loss in the country (Murillo-Sandoval et al., 2021). Our guiding research questions are: (1) What is the influence of LTS on forest cover? and (2) Do other drivers of deforestation moderate the effect of LTS on forest cover? These research questions address several important gaps. Related to the first question, we include two different measures of LTS—formal titles and perceptions of LTS—in the same study. While most empirical studies on LTS use formal land titles or documentation to represent LTS, many scholars argue that LTS goes beyond formal documentation to include the assurances that land rights will be protected, which involves formal or informal institutions and a supportive political economy (Arnot et al., 2011; Robinson et al., 2018; Masuda et al., 2020). We test the individual influence of these two measures on forest cover and also test for a joint effect. Related to the second question, we directly account for the complex interactions that can occur between land tenure and forest outcomes (Sills and Jones, 2018) by explicitly testing how the influence of LTS on forests varies with two moderating factors: proximity to markets and participation in a conservation program. In addition to contributing to the global evidence base on LTS and forests, this study has practical implications for Colombia so that efforts to address LTS and land reform, which are critical for social justice and human well-being in the country, do not negatively influence global and local ecosystem service benefits.

2 Materials and methods

2.1 Study area

The Colombian Amazon is an important landscape for biodiversity and climate regulation, making up close to 42% of the country's terrestrial surface and almost 7% of the total Amazon biome in South America (Mendoza and Ortiz, 2008; Rangel-Ch, 2015). Almost 80% of the Colombian Amazon is dominated by forest (IDEAM, 2017), and three quarters of the region are under some form of legal conservation management, including Indigenous Reserves (56%), Protected Areas, which include national and regional parks (23%), and Forest Reserve (2nd Law) (71%), a conservation figure

established in 1952 that includes state lands with land use restrictions oriented to the forest economy and watershed protection. Forest Reserve can overlap with Protected Areas, Indigenous Reserves, or private landholdings. Despite its ecological relevance, the Colombian Amazon has been particularly affected by deforestation over the last several decades (Armenteras et al., 2019a; Armenteras et al., 2019b), with the area of forest lost per year increasing from 0.16% in 2014–2016 to 0.33% in 2018–2020 (Rodríguez et al., 2021). As of 2022, about 10% of the region was under some kind of agricultural use, primarily pastures for cattle ranching (Instituto Sinchi, 2022).

This study focuses on private individual landholders (non-Indigenous peoples) living in the Amazonian departments of Putumayo, Caquetá, and Guaviare (Figure 1). Each department experienced government-directed colonization processes in the 19th and 20th centuries by families from the Andes seeking land and fleeing political violence (Centro Nacional de Memoria Histórica, 2015; Centro Nacional de Memoria Histórica, 2017). However, the settlement process often lacked structure and access to public goods (Marín-Taborda, 2002), and the weak presence of the state led to various manifestations of armed violence for territorial control, leading in part to the rise of the coca economy that still persists today (Centro Nacional de Memoria Histórica, 2017). Even after the 2016 Peace Accord, disputes over resource exploitation and control of illicit rents continues (Samper and Krause, 2024). While land has emerged as a critical issue shaping social inequality and conflict in the Amazon region, informal land tenure persists, estimated at 61% in Putumayo, 59% in Caquetá, and 32% in Guaviare (Unidad de Planificación Rural Agropecuaria, 2019).

2.2 Household sample and variables

Data on landholders in these three Amazonian departments come from a USAID-funded cross-sectional survey. The survey was implemented as a baseline for a five-year biodiversity project being funded by USAID (2021). The households included in the survey were not randomly selected, but targeted based on deforestation pressures, security, and their willingness to participate in the USAID program. An independent survey firm conducted the survey over the years 2022 and 2023. The original USAID survey included 544 private individual landholders and spanned nine municipalities and over 100 *veredas* (the smallest administrative sub-division within rural municipalities in Colombia). The exact location of landholder parcels was not recorded in the survey, so we used GPS points of where the baseline survey was conducted—typically at a person's house—to develop a map that shows the approximate areas where the data were collected (Figure 1). For this study, we use a smaller subset of households based on variable creation and analysis procedures; these decisions are explained below.

2.2.1 Dependent variable

The dependent variable in this study is the percent of reported forest on the landholder's primary parcel at the time of the survey. There are no cadastral maps for the study area and the baseline survey did not collect parcel boundaries; therefore, remote sensing information on forest cover cannot be used. Landholders reported the total area and the area of different land cover types, including natural forest, on their primary parcel, in hectares. We tested for outliers in forested hectares and total hectares of land through graphs and by calculating the interquartile range of the variables. We detected outliers in the total parcel size and excluded extreme outliers, defined as three times the interquartile range, from the sample used in our analysis. This removed 17 households. We also dropped 38 households that reported zero forest on their primary parcel. We did this because we cannot know if the parcel was ever forested while they were the landholder. Self-reported hectares of forest were divided by the total size of the parcel and converted into a percent to create the dependent variable. During preliminary analysis, a Breusch-Pagan test indicated the presence of heteroskedasticity in the non-transformed dependent variable. A log-transformation of percent forest cover removed the skewness and kurtosis, and we use the log-transformed variable in data analysis.

2.2.2 Land tenure security

Presence of a formal land title was derived from a categorical response question in the survey. Having formal title was defined as "holding a deed or resolution that was registered with the state." No formal title was defined in the survey as "having a promise, purchase-sale paper or letter of sale, but no public deed with the state." There were four additional categories included in the survey that represent more ambiguity in terms of formality, and households that selected these options were removed from this analysis to make the comparison between formal and no formal title as clear as possible. These categories included having a lease, having a deed that had not been registered with the state, having land in probate, or not knowing the status of their tenure. This removed 125 households from the analysis.

The survey measured perceptions of LTS using five different Likert-scale questions, each using a 5-point scale ranging from totally disagree (1) to totally agree (5), with a neutral option and a "does not know" option. After preliminary testing between perceptions of LTS, presence of a formal title, and percent forest cover, we decided to include two of the five questions in this analysis based on their correlations. The two perceptions of LTS questions used in this analysis both focus on expropriation and land grabbing, with one question asking the respondent their assurance that the government cannot take their land (referred to as "government LTS" in rest of paper) and the other asking about their assurance an external group cannot take their land (referred to as "external group LTS" in rest of paper). The three perception questions not included in this analysis asked about the respondent's certainty that they would not lose their land rights in the future, certainty that they would have no land conflicts in the future, and whether their property boundaries were respected by their neighbors. There was no detectable relationship between these perception variables and forest cover in our sample.

2.2.3 Control variables

We control for several independent variables expected to be correlated with forest cover in this analysis. The variables we selected are based on the global land cover/land use change literature (e.g., Busch and Ferretti-Gallon, 2023) and Colombia-specific studies (e.g., Bautista-Cespedes et al., 2021; González-González et al., 2021; Ganzenmüller et al., 2022), as well as the variables available in the USAID survey. First, we included several variables that capture land use and economic productivity. These included binary variables on whether the respondent owned cattle or cultivated coffee, which were the two most common agricultural

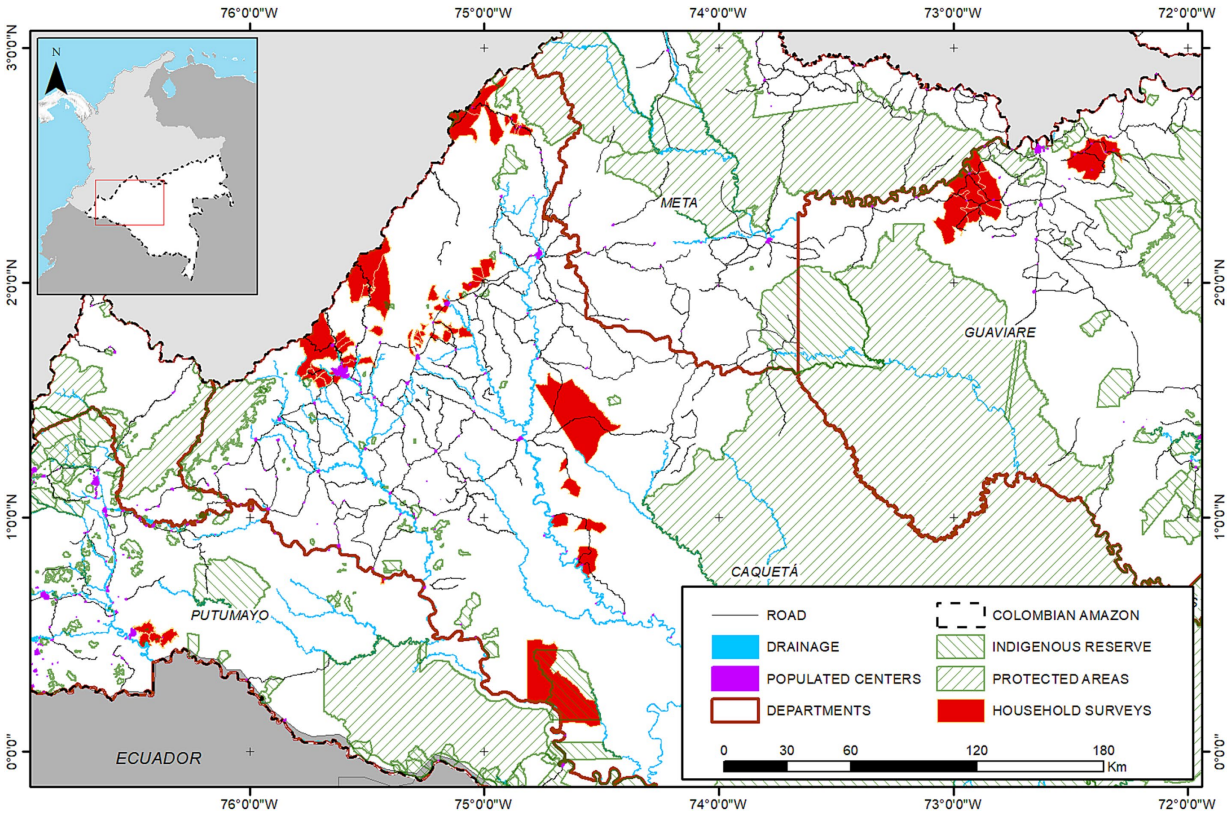

FIGURE 1
Study area map showing general location of household surveys used in this analysis in red, as well as major protected area designations and human development in the region.

practices in the study area; the respondent's monthly income in Colombian pesos; and a binary variable on whether the respondent reported commodity agriculture as their primary occupation. Second, we included variables that would influence access to markets including road quality and time to the nearest market. Road quality was recorded as a binary variable as either poor or fair/good quality roads, and time to market was their self-reported minutes to get to the nearest market using the means they typically take (e.g., foot, boat, motorcycle, etc.). We included two demographic or social variables from the survey. The first was the number of years the landholder had lived in the area, and the second was the size of their immediate family. We also included fuelwood use, given the high reliance on wood as the main source for cooking in the study area. The survey did not collect any self-reported information on land productivity, such as soil quality, and without access to geospatial coordinates we could not include parcel-level information on slope or aspect.

2.3 Matching estimator

Formal land titles are not randomly distributed across households, and this can lead to bias when trying to estimate the relationship between LTS and forest cover (Cochran and Rubin, 1973; Jones et al., 2022). For example, wealthier landholders and those closer to urban areas, might be more likely to get a land title, and these same characteristics could be correlated with forest cover outcomes. Using our cross-sectional survey data, we can use matching to minimize omitted variable bias by constructing a counterfactual group without formal title that is as similar as possible to the landholders that have formal land title. We use Propensity Score Matching (PSM) to trim our sample of 364 households to the most similar observations. PSM creates a weighted score for each observation based on the propensity of treatment, in this case land titles, and then finds the non-treated observation with the closest score (Harris and Horst, 2019). We selected covariates that would theoretically influence both the outcome, forest cover, and the probability of having a formal land title, while avoiding variables that could be influenced by having a formal land title (Caliendo and Kopeinig, 2008). These covariates included land size, monthly income, time to nearest market, and years living on the land. We estimated a propensity score for each observation using these four variables and logistic regression. We specified one-to-one nearest neighbor matching without replacement and used a caliper to limit the match distance and common support, both best practices to maximize covariate balance. The matched sample size was reduced to 308 observations. Post-matching tests show that covariate balance was improved considerably in the matched data (Supplementary Table S1).

2.4 Data analysis

2.4.1 Linear regression

To test the effect of formal land title on forest cover we first use ordinary least squares (OLS) regression with no interaction terms:

$$Y_i = \alpha + \beta_1 T_i + \beta_2 Z_i + \beta_3 D_i + \varepsilon_v \quad (1)$$

where Y_i is the log-transformed percent forest cover for each individual landholder, i; T_i is the binary measure of formal land title, and Z_i is the vector of other covariates. We tested for multicollinearity across all covariates and land title using correlation tests and variance inflation factors (VIF) following regression and did not find any high levels. To help control for unobservable variables that could bias Equation 1 we included department-level fixed effects as D_i. To account for spatial associations and dependencies across landholders in our sample we use cluster robust standard errors, ε_v. We cluster standard errors in all regression models using the *vereda* (smallest administrative unit) the respondent reported living in. The cluster size ranges from one to 25 with an average of four landholders per cluster.

After estimating Equation 1 with only formal land title as the LTS variable, we next add the perception of LTS variables as an additional covariate to Z_i. We tested pairwise correlation coefficients across formal title and perception of LTS variables and conducted two-sided Wilcoxon rank sum tests to determine whether we could include formal title and perception of LTS variables in the same regression. Both tests showed that formal title and LTS perception variables are not strongly correlated and can be included in the same regression model (Supplementary Table S2). However, there was strong collinearity (99% confidence level) between the two perception of LTS variables. Thus, we do not estimate Equation 1 with formal title and both perception of LTS variables at the same time but estimate two separate regressions.

2.4.2 Interaction terms

To test for a moderating influence of different variables on formal title, we introduce an interaction term to our OLS regression, where $\boldsymbol{M_i}$ is the moderating variable, and all other variables are as defined in Equation 1:

$$Y_i = \alpha + \beta_1 T_i * M_i + \beta_2 Z_i + \beta_3 D_i + \varepsilon_v \quad (2)$$

To test whether there is a joint effect of having a land title and perceived LTS, we interact T_i with each perception of LTS variable and estimate the marginal effect of formal title at each of the five levels of perceived tenure security. To understand whether time to closest market moderates the influence of formal land title on forest cover, we interact these two covariates and graph the marginal effects of formal title across different values of time to closest market. Lastly, to test whether participating in a conservation program moderates the influence of formal title on forest cover, we interact formal land title with a binary variable on whether a landholder reported they were participating in a PES program at the time of the survey.

In Equations 1 and 2, the marginal effects of the covariates on the log-transformed dependent variable must be interpreted by exponentiating the beta coefficients, subtracting it from one and multiplying by 100. We present these exponentiated marginal effects for our main variable of interest, LTS, as well as the original coefficient and standard errors in the results section.

2.4.3 Forest reserve land

The location of our study area has some overlap with the protected category of Forest Reserve land. Of the 364 households originally included in our matching estimation, 67 were located on Forest Reserve land based on a geospatial assessment of their survey location and a national shape file of Forest Reserve land. Being located on Forest Reserve land could affect our coefficient estimates in multiple ways. First, landholders on Forest Reserve land may be less likely to remove forest because of restrictions on using the land. Second, landholders on Forest Reserve land may have more difficulty in acquiring formal titles because of land use restrictions. As a check to our analyses above, we removed the 67 households that overlapped with Forest Reserve land and redid the PSM (Supplementary Table S1) with a sample of 297 households. We then estimated Equations 1 and 2, with the 244 matched households that are not located on Forest Reserve land; this reduced sample is referred to as "Reduced Sample" versus "Full Sample" in the results.

2.5 Limitations

Our observations come from a non-random baseline study that was conducted for purposes other than this research, leading to limitations in the data available. We rely on self-reported measures of forest cover in this study since we do not have spatial information on parcel locations. If we had parcel locations, we could use global forest cover datasets, like Global Forest Watch, to approximate forest cover for these landholders. However, from our interaction with the survey team, we know that many landholders live in town and their parcels are located elsewhere. Thus, using these forest cover datasets at the location where the survey was conducted would mis-represent forest cover. Using self-reported forest cover as our dependent variable could introduce measurement error if a landholder mis-calculates the amount of land they have in different land cover types. This could be the case if landholders purposively inflate or deflate reported forest cover levels, given that this survey was a baseline assessment for a USAID-funded project. However, as long as this mis-reporting is consistent across all households and does not vary systematically with our LTS measures, then it should not bias our coefficient estimates of LTS since the error is in the dependent variable. Additionally, since we only have a cross-sectional sample and the year title was received was not asked in the survey, we cannot use temporal variation to help control for unobservable bias in our estimations. We try to minimize this potential bias through matching on observable variables and including department-level fixed effects in our analysis. However, not having this temporal variation limits our ability to detect the specific pathway through which LTS is related to forests, since LTS could lead to clearing forest or clearing forest could lead to LTS. Overall, our analysis points to correlations between our variables and not a causal relationship.

3 Results

3.1 Summary statistics

In the full sample, average forest cover was about 33% on individual private parcels and households had a total of 56 hectares (Table 1). Due to matching, the proportion of households with and without formal title are the same. The average perception of LTS is high, at an average of 4.3 (out of 5) for certainty the government cannot take their land and

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TABLE 1 Mean and standard deviation of all variables for full and reduced samples.

Variable and (unit)	Full sample	Reduced sample
Percent forest cover (%)	32.94 (23.10)	33.75 (23.49)
Log-transformed percent forest cover	3.86 (0.42)	3.92 (0.41)
Formal title (binary)	0.50 (0.50)	0.50 (0.50)
Government LTS (5-point Likert-scale)	4.31 (0.85)	4.32 (0.81)
External group LTS (5-point Likert-scale)	3.97 (1.10)	3.95 (1.09)
Land size (hectares)	56.32 (51.08)	55.56 (50.87)
Cattle (binary)	0.57 (0.50)	0.58 (0.49)
Coffee (binary)	0.20 (0.40)	0.13 (0.34)
Monthly income (Colombian Pesos)	1,176,873.70 (1,064,967.70)	1,026,327.00 (844,486.64)
Commodity agriculture (binary)	0.32 (0.47)	0.32 (0.47)
Road quality (binary)	0.56 (0.50)	0.57 (0.50)
Time to nearest market (minutes)	92.42 (73.61)	87.11 (71.84)
Years living there (years)	33.55 (15.56)	34.06 (15.69)
Family size (number)	3.82 (1.74)	3.86 (1.78)
Fuelwood use (binary)	0.77 (0.42)	0.75 (0.44)
PES program (binary)	0.15 (0.35)	0.16 (0.37)
Observations	308	244

4.0 (out of 5) for assurance that an external group cannot take their land. More than half of households owned cattle (57%), 20% produced coffee on their land, and about 30% stated that commodity agriculture was their primary occupation. Average monthly income in 2023 Colombian pesos was about 1.2 million (USD 272). A little over half of households reported their roads to be fair/good (56%), with an average time to market of 92 min. The average years living in the area was 34 years and most people had a family size of four. Fuelwood use was high, at 77%. Participation in a PES conservation program was around 15%. The reduced sample that excludes households on Forest Reserve land appears very similar to the full sample except for a few key variables. First, there is less coffee produced by households outside of Forest Reserve lands. Second, there is lower reported monthly income when Forest Reserve lands are removed, at about 1.0 million 2023 Colombian pesos (USD 237). Finally, the average time to a market is shorter for individuals located outside Forest Reserve lands, at 87 min.

3.2 Title, perception of LTS, and forest cover

Formal land title is statistically significant and has a negative influence on percent forest cover in both the full and reduced samples (Table 2). The exponentiated coefficient (marginal effect) is around 13% and is statistically significant at a 95% confidence level in the full sample (Figure 2). Thus, when a landholder goes from no title to having a formal title, there is an average reduction of 13% forest cover. This marginal effect is slightly higher at 14% in the reduced sample that excludes Forest Reserve lands (Figure 2). Four other covariates are statistically significant in the regression model with the full sample, and three covariates are statistically significant when the reduced sample is used (Table 2). Land size has a positive influence on percent forest cover, and cattle production and monthly income have a negative influence on forest cover, using both sample sizes. Coffee production has a negative and statistically significant effect at the 90% confidence level in the full sample but is not statistically significant in the reduced sample. In terms of marginal effects, only cattle has a larger marginal influence than land title on forest cover, with around a 20% reduction in forest cover when a landholder goes from no cattle to having cattle. These regression models explain about 19% of the variation in percent forest cover.

When the two perception of LTS variables are included in a regression model with land title, formal title remains statistically significant at the 95% confidence level and has similar marginal effect sizes as above (Table 2 and Figure 2). The government LTS variable is statistically significant at the 95–99% confidence level in both sample sizes and has a negative effect on forest cover (Table 2). The marginal effect of an increase in the perception that land is safe from government taking by one level (on a 5-point scale) is a reduction in forest cover of 6%. The external group LTS variable is also statistically significant at the 95% confidence level in both sample sizes, with a negative influence on forest cover (Table 2). The marginal effect of an increase in the perception that land is safe from land grabbing by an external group by one level is a reduction in forest of about 4%. Similar covariates are statistically significant in the regression models that include formal title and a perception of LTS variable, with time to nearest market becoming statistically significant (90% confidence level) in the full sample but not statistically significant in the reduced sample. These regression models explain about 20% of the variation in percent forest cover.

3.3 Moderators of title and forest cover

3.3.1 Perceptions of LTS

When formal land title and a LTS perception variable are interacted in the same regression model we find that the two variables have a joint effect on forest cover at higher values of perceived LTS (Table 3). Specifically, for both LTS perception variables, formal title has a statistically significant influence on forest cover when perceived LTS is high (Likert-scale of 4) or very high (Likert-scale of 5). The size of the marginal effect is larger, in most cases, than what was seen in Table 2, with 17–18% less forest cover due to having both a formal land title and very high perceptions of LTS at the same time (Figure 3). These results are robust to both sample sizes, with slightly higher marginal effects when Forest Reserve land is excluded (Figure 3). Formal land title has no statistically significant influence on forest cover when tenure security is perceived as insecure (Table 3).

3.3.2 Time to market

Including an interaction term between formal land title and time to market suggests time to a market moderates the influence of land title on forest cover in the full sample (Figure 4). There is a statistically significant

TABLE 2 OLS regression to test influence of formal title and perception of LTS variables on log-transformed percent forest cover using matched dataset and two sample sizes.

Variable	Only formal title		Formal title & Government LTS		Formal title & External group LTS	
	Full sample	Reduced sample	Full sample	Reduced sample	Full sample	Reduced sample
Formal title	−0.123** (0.049)	−0.130** (0.057)	−0.115** (0.049)	−0.133** (0.056)	−0117** (0.051)	−0.139** (0.058)
Government LTS	NA	NA	−0.061*** (0.023)	−0.056** (0.028)	NA	NA
External Group LTS	NA	NA	NA	NA	−0.040** (0.020)	−0.044** (0.022)
Land size	0.002*** (0.001)	0.002** (0.001)	0.002*** (0.001)	0.001** (0.001)	0.002*** (0.001)	0.001** (0.001)
Cattle	−0.217*** (0.063)	−0.198*** (0.069)	−0.224*** (0.063)	−0.204*** (0.072)	−0.219*** (0.063)	−0.196*** (0.007)
Coffee	−0.120* (0.065)	−0.046 (0.073)	−0.116* (0.064)	−0.080 (0.071)	−0.122* (0.067)	−0.085 (0.072)
Monthly income	−0.000*** (0.000)	−0.000** (0.000)	−0.000*** (0.000)	−0.000*** (0.000)	−0.000*** (0.000)	−0.000*** (0.000)
Commodity agriculture	−0.025 (0.051)	−0.056 (0.056)	−0.034 (0.050)	−0.046 (0.056)	−0.032 (0.052)	−0.038 (0.057)
Road quality	−0.059 (0.055)	−0.034 (0.060)	−0.057 (0.056)	−0.030 (0.062)	−0.058 (0.057)	−0.034 (0.062)
Time to nearest market	0.001 (0.000)	0.000 (0.000)	0.001* (0.000)	0.001 (0.000)	0.001* (0.000)	0.000 (0.000)
Years living there	0.0010 (0.002)	0.001 (0.002)	0.001 (0.002)	0.001 (0.002)	0.001 (0.002)	0.001 (0.002)
Family size	−0.006 (0.013)	0.002 (0.014)	−0.007 (0.013)	−0.002 (0.014)	−0.008 (0.013)	−0.004 (0.014)
Fuelwood use	−0.058 (0.050)	0.035 (0.054)	−0.052 (0.051)	0.057 (0.057)	−0.062 (0.051)	0.047 (0.057)
Department fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Observations	306	243	302	238	298	238
R^2	0.19	0.19	0.20	0.20	0.20	0.21

Coefficient and standard errors in parenthesis. Significance levels: * p-value < 0.1; ** p-value < 0.5; *** p-value < 0.01.

TABLE 3 OLS regression interacting formal title and a perception of LTS variable on log-transformed percent forest cover using matched dataset and two sample sizes.

	Formal title x Government LTS		Formal title x External Group LTS	
Level of perceived LTS	Full sample	Reduced sample	Full sample	Reduced sample
Lowest perceived LTS	0.113 (0.164)	0.039 (0.187)	−0.125 (0.138)	−0.103 (0.158)
Low perceived LTS	0.043 (0.121)	−0.013 (0.136)	−0.122 (0.100)	−0.115 (0.115)
Neutral perceived LTS	−0.026 (0.080)	−0.066 (0.089)	−0.119* (0.067)	−0.127 (0.077)
High perceived LTS	−0.095* (0.051)	−0.119** (0.058)	−0.117** (0.051)	−0.139** (0.058)
Highest perceived LTS	−0.164*** (0.056)	−0.172** (0.068)	−0.114* (0.066)	−0.152** (0.074)
Observations	302	238	298	238
R^2	0.21	0.21	0.20	0.21

All covariates were included in regression model but are not reported here. Coefficient and standard errors in parenthesis. Significance levels: * p-value < 0.1; ** p-value < 0.5; *** p-value < 0.01.

and negative influence of land titles on forest cover for landholders located closer to a market. At very short distances to a market this influence on forest cover is at its highest, with about 19% less forest cover associated with having a formal title and being close to a market. The effect of a land title on forest is no longer statistically significant after about 150 min from a market. In the reduced sample, the slope of the marginal effect line is much flatter, with little difference in the size of the marginal effect as time to market changes. However, in this reduced sample, title also has a statistically significant influence on forest cover only at shorter distances—between 50 and 150 min—similar to that found in the full sample. At the median distance to market in both samples, the reduction in forest cover is about 13% (Figure 3).

3.3.3 Participation in a conservation program

When formal land title is interacted with participation in a PES program, we find no statistically significant influence of having a title on forest cover when the individual is enrolled in the PES program for both samples (Table 4). However, for individuals with title, but not participating in a PES program, title has a negative and statistically significant influence on forest cover similar in magnitude to that

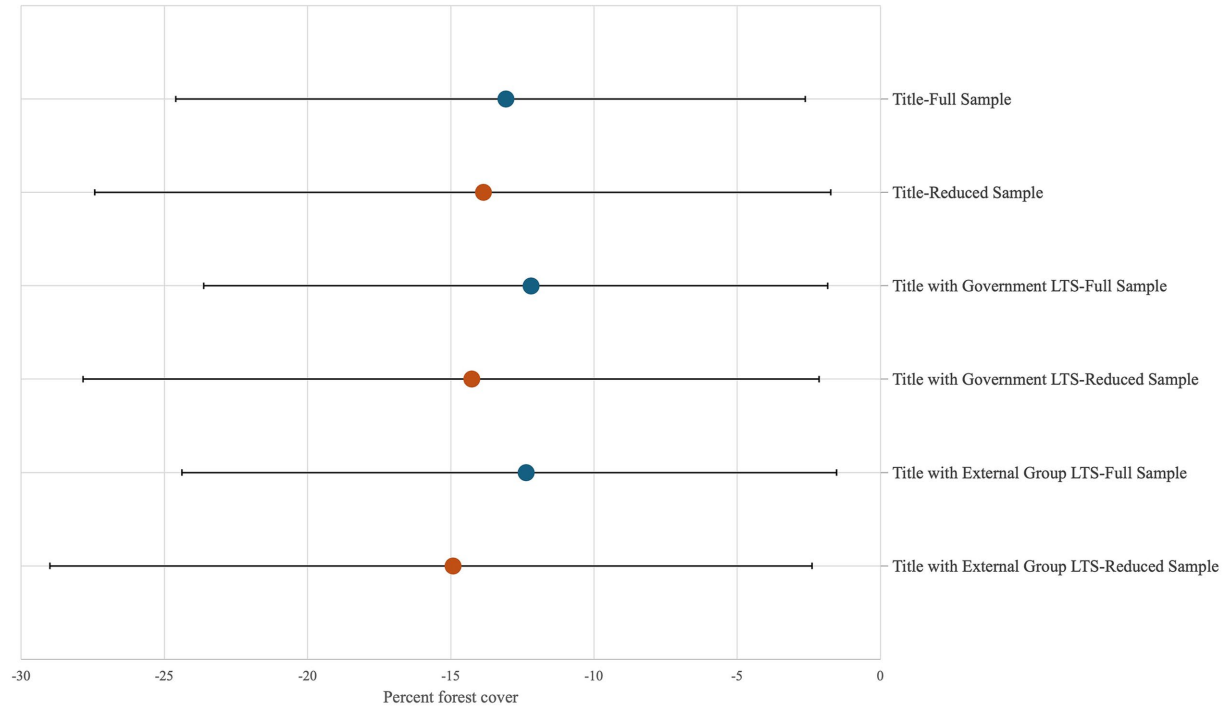

FIGURE 2
Marginal effect (i.e., exponentiated coefficient) of formal title on forest cover from OLS regression models using matched dataset and the full and reduced sample sizes. The marginal effect is represented by a dot and represents the difference in percent forest cover due to having a land title; the 95% confidence interval is shown by the solid line.

found when title is not interacted with enrollment in the conservation program (Figure 3).

4 Discussion

4.1 Land tenure security and forest cover

There are important differences between tenure form and tenure security and their potential influence on land management decisions (Arnot et al., 2011; Robinson et al., 2014; Robinson et al., 2018; Masuda et al., 2022). While studying the influence of tenure form, such as private, community, indigenous, or public, is important, a clearer understanding of the role of LTS can occur if we keep those forms constant and vary LTS as done in this analysis. Using primary data, we are able to include a measure of both formal land title and perceptions of LTS—that land is secure from expropriation or land grabbing—in our analysis. Most studies of LTS measure the influence of titling or formalization interventions (Tseng et al., 2021), and do not explicitly capture the influence that formal or informal institutions have on assuring rights are upheld.

Our main finding is that LTS for private individual landholders—measured both as formal title and perceptions of LTS—are associated with a decrease in forest cover. This result is consistent with many recent empirical studies, especially those focused on the impacts of formal land titles for individual landholders (e.g., Probst et al., 2020; Lipscomb and Prabakaran, 2020; Abman and Carney, 2020; Walker, 2021; Faingerch et al., 2021; Álvarez-Berrío et al., 2021; Boillat et al., 2022). This outcome might be attributed to the "investment effect" of securing land tenure: landholders with certain levels of capital accumulated and increased access to credit and agricultural markets clear more forest (Arnot et al., 2011; Liscow, 2013). One pathway through which LTS can lead to clearing forest is by increasing access to efforts to increase agricultural productivity and spur economic growth. For example, in Ecuador, Holland et al. (2017) find that newly titled private landholders were able to access government-sponsored agricultural programs that contributed to clearing forest. In Colombia, there are programs such as the Colombian Fund for the Financing of the Agricultural and Livestock Sector (Spanish: *Fondo para el Financiamiento del Sector Agropecuario-FINAGRO*), that finances rural development in the Colombian Amazon through credits and incentives (Ministerio de Ambiente y Desarrollo Sostenible, 2022; Visión Amazonía, 2020). Amazonian municipal governments have also offered loans for livestock development with favorable conditions for producers, such as grace periods and no co-debtor requirements (Contexto Ganadero, 2018).

However, our cross-sectional data limit testing specifically for this "investment effect" pathway. It could also be the case that landholders cleared forests to claim their land prior to the survey used in this study, and this clearing of the forest resulted in higher perceived LTS and obtaining a land title. This practice of clearing land to claim it has been documented in the Amazon (Russo Lopes and Bastos Lima, 2022; Hänggli et al., 2023), and additional data would be needed to verify the specific pathway in our study. We do not, however, find any "protective effect" of LTS in terms of increasing forest cover (Holland et al., 2017). In Colombia, there is evidence that weak governance has provided an opportunity for multiple types of actors to convert forests to illicit crops or pasture for both subsistence and commodity

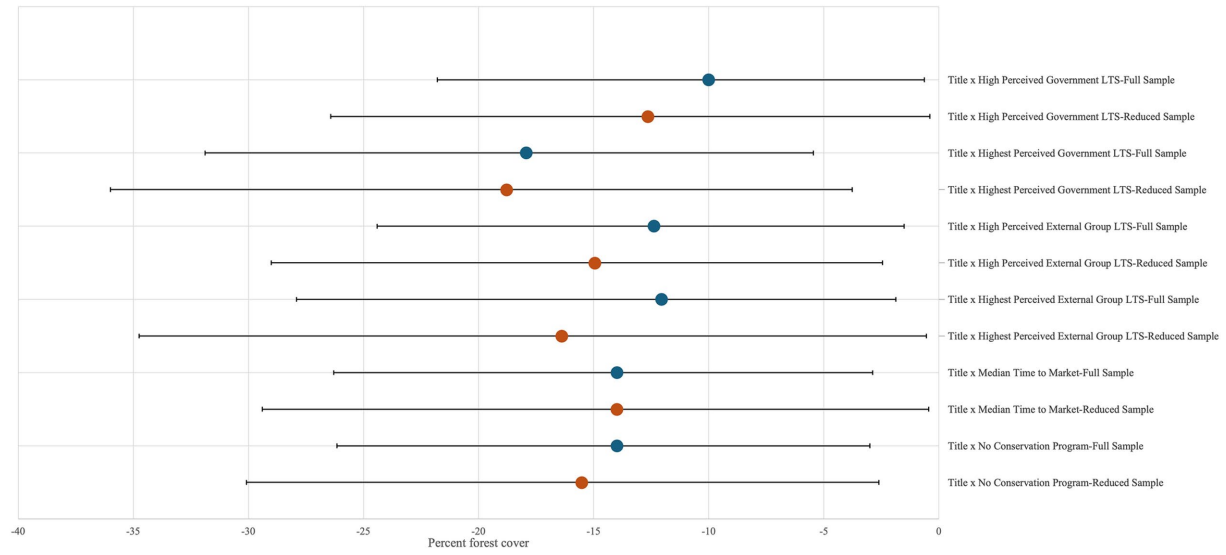

FIGURE 3
Marginal effect (i.e., exponentiated coefficient) of formal title on forest cover when moderated by another covariate through an interaction term in OLS regression models using matched dataset and the full and reduced sample sizes. The marginal effect is represented by a dot and represents the difference in percent forest cover due to having a land title at the specified interaction (e.g., high perceived LTS, median time to market, or no conservation program); the 95% confidence interval is shown by the solid line.

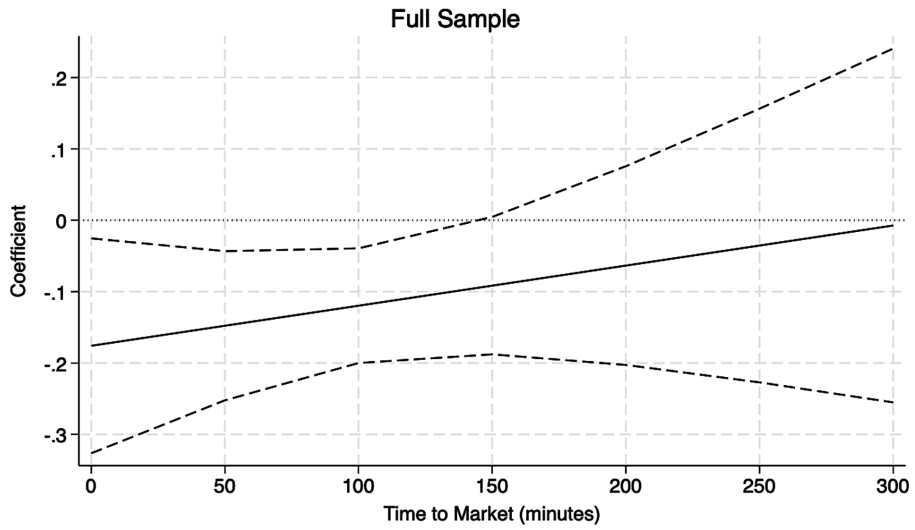

FIGURE 4
Non-exponentiated coefficient of formal title on log-transformed percent forest cover when interacted with time to nearest market in OLS regression models using matched dataset. Results using full sample shown in figure. The non-exponentiated coefficient is shown by the solid line and the 95% confidence interval by dashed lines.

production following the 2016 Peace Accord (Munoz-Mora et al., 2018; Sánchez García and Wong, 2024). A similar process of land grabbing and speculation has been documented in the Brazilian Amazon, where those with power coerce smallholders from their lands with little to no compensation (Kröger, 2024). In our sample, having a formal title or having more certainty that one's land could not be expropriated or taken by other actors does not show any association with a protective effect on forests by either being able to ward off these types of outsiders or invest in longer-term sustainability measures on their land. However, the average perception of LTS in our sample was high (average of 4) and different results might be found in areas with more variation in perceived LTS.

It is important to reflect on the generalizability of our results. The negative relationship we find between LTS and forests in the Colombian Amazon may not hold for other actors in Colombia or in other contexts where different mechanisms play out. Within Colombia, our results represent individual smallholders that have been living in the area for many years and may not be representative of decision-making processes by landholders that have more recently migrated to the area, larger land speculators, or Indigenous communities. Within other

TABLE 4 OLS regression interacting formal title and enrollment in a PES conservation program on log-transformed percent forest cover using matched dataset and two sample sizes.

Conservation program status	Full sample	Reduced sample
Not enrolled in PES	−0.131** (0.051)	−0.144** (0.059)
Enrolled in PES	0.003 (0.155)	−0.003 (0.141)
Observations	306	243
R^2	0.20	0.20

All covariates were included in regression model but are not reported here. Coefficient and standard errors in parenthesis. Significance levels: * p-value < 0.1; ** p-value < 0.5; *** p-value < 0.01.

contexts, different pathways may play out. For example, in Benin, a recent randomized control trial found that land rights reduced tree cover loss because farmers were able to intensify agricultural production (Wren-Lewis et al., 2020). There may also be differences in short-term versus long-term land use decisions with LTS. A study in Panama concluded that private titling led to deforestation in the short term, but that there were signs of reforestation after more time had passed (Walker, 2021). Finally, the influence of LTS on forests can be dynamic: changes in the political economy and the institutions that enforce land rights can mean changes in LTS and thus its influence on forests over time (Kuschnig et al., 2023).

4.2 Moderators of title and forest cover

In addition to formal land title and the perceptions of LTS having individual effects on forest cover, we also find a joint effect of having formal documentation and the assurance that property rights will be upheld. When both forms of LTS are present, the result is less forest cover. However, just as interesting is the finding that when landholders do not perceive their tenure as secure, the presence of a formal title does not lead to differences in forest cover. Thus, the assurance aspect of LTS appears to play an important role in moderating how land titles influence forest cover in this study area. This supports the literature that argues that the ability to enforce one's land rights is just as important as the formal documentation of those rights (Arnot et al., 2011; Robinson et al., 2018; Masuda et al., 2020).

When we control for the moderating influence of time to market on land titles we find that it is titled landholders located closer to markets that have less forest cover, providing support for the investment effect mechanism. In the full sample, the magnitude of the influence of a formal title on forest cover is larger as the proximity to a market increases. While the magnitude does not change as much in the reduced sample, possibly because of less variation in time to markets in this smaller sample, we still find that location plays an important role in whether a formal title is correlated with less forest cover or not. Deforestation in the Colombian Amazon is associated with cutting forests for cattle pastures and illicit crops, and one of the deforestation hotspots in the country is the transition zone between the Andes and Amazon regions that are closer to markets and populated centers (Correa Ayram et al., 2020; Murillo-Sandoval et al., 2021). Other studies have also found that the influence of land titles on forests is moderated by other differences in economic opportunity. For example, Lipscomb and Prabakaran (2020) find that a formalization program in Brazil increased deforestation more rapidly in counties with higher capital accumulation and Probst et al. (2020) find that agricultural prices moderated deforestation on titled lands.

While the investment effect in the LTS literature focuses primarily on agriculture, there are increasingly opportunities for landholders to invest in conservation practices. In our study, titled landholders that participated in a conservation program did not have a statistically significant change in forest cover. The negative influence of formal title on forest cover in our study is driven by landholders not enrolled in a PES conservation program. A study by Jones et al. (2017) found that access to conservation incentive programs like PES, after gaining formal title, was seen as an investment option for landholders in Ecuador. In their study, they found that enrolling in PES went on to buffer forest loss, something we did not rigorously test for in this paper. We must be cautious and not causally attribute the finding in our study of no forest loss when enrolled in the PES program to the conservation program itself, as there could be self-selection into the program by landowners that would have conserved anyway. In theory, however, enrolling in a conservation program could offset the need to invest in agricultural production, leading to a "protective effect" for forests. For example, there could be cases where landholders want to conserve their forests, but do not have the economic means to do so, and access to incentives from a conservation program allows them to tap into existing motivations that lead to a "conservation investment effect" if their opportunity costs are covered (Rueda et al., 2019). While we were only able to account for interactions of LTS with PES programs in our study area, there is a need to more rigorously consider the various policy mixes being used to curb deforestation and their influence on forest outcomes in Colombia (Furumo and Lambin, 2020).

4.3 Land tenure security measurement and policy implications

Our finding that formal land titles and perceptions of LTS have individual and joint influence on forest cover suggest there is value in collecting information on multiple aspects of LTS. While academics have increasingly pointed to the importance of measuring the assurances of LTS, practitioners conceptualize LTS more readily as formal titles and documentation (Masuda et al., 2020). Our results show that to completely understand the complexity and multifaceted relationship between LTS and land management decisions, both are important. This would be especially important where the strength of formal institutions is weak, to capture the moderating influence of these assurances on land management decisions. Of course, collecting data on multiple aspects of LTS would be more costly than relying on secondary datasets of formal title alone, and requires on-the-ground knowledge of the different factors that can influence LTS (e.g., Robinson et al., 2018).

Additionally, our findings suggest that it is important for future studies on LTS and forests to clearly specify how LTS is measured and recognize that different measurements can capture different aspects of LTS (Robinson et al., 2018). Some recent synthesis studies do not differentiate across measurements of LTS, comparing studies that use formal titles to those that measure years living on farm or customary rights as indicators of LTS (e.g., Busch and Ferretti-Gallon, 2023), confounding what can be concluded in terms of the influence of specific aspects of LTS on land management decisions.

The results of this study also highlight the important role of moderating factors on the relationship between land titles and forest. The heterogenous effect of formal title on forest due to other drivers

of deforestation suggests that future studies of LTS should pay more attention to these potential moderating effects (Sills and Jones, 2018; Hänggli et al., 2023). In particular, studies that find a null effect of LTS on forests may be overlooking how formal and informal institutions, access to markets, or land productivity, moderate the influence of land titles on land management decisions. Future studies that cannot test for the role of moderators quantitatively should at least qualitatively consider the role these moderating factors might have on the relationship between LTS and forests.

In Colombia, and similar contexts where LTS appears to increase pressure on forests, the potential of investing in conservation friendly land uses will be important for achieving sustainable development goals and meeting climate mitigation targets. At a minimum, titling and other LTS interventions need to monitor the potential unintended effects they could have on forests so they can adaptively manage their programs. Ideally, future titling and LTS interventions located in strategic environmental areas would be coupled with efforts to increase access to conservation incentives or sustainable livelihood programs to avoid losses to forest and biodiversity. Of course, these types of conservation programs are not a panacea either, with notable challenges faced in implementation and achieving additionality (Holmes and Cavanagh, 2016).

5 Conclusion

In this study we use a novel household dataset of individual private landholders in the Colombian Amazon to test the influence of LTS on forest outcomes. First, we find that formal land titles and perceptions of LTS—that land is secure from expropriation or land grabbing—both individually decrease forest cover. These two measures of LTS also have a joint effect on forest cover, with forest cover reduced more if a landholder has a formal title and high levels of perceived LTS. Second, we find that having a land title decreases forest cover only if the landholder is located closer to markets and not enrolled in a PES conservation program. While our cross-sectional data do not allow us to use before-after variation, our results are robust when using a counterfactual group, department-level fixed effects, and two sample sizes. Our findings directly contribute to our understanding of the nuanced and complex relationship between LTS and forests. Our results support the increasing evidence base showing that LTS can negatively influence forest and conservation outcomes when traditional economic markets that value agricultural uses are prominent. We also show that the influence of LTS on forests varies with other drivers of deforestation. Finally, our results highlight the critical importance of future LTS interventions to understand, monitor, and adaptively manage the unintended consequence they may have on forest and biodiversity. In Colombia, national efforts to address land conflicts and formalize land titles are an important part of the peace building process but should not come at the expense of biodiversity and ecosystem services.

Data availability statement

The data analyzed in this study is subject to the following licenses/restrictions: The full survey data can be requested from USAID/Colombia. The smaller dataset used for this analysis can be requested from the lead author. Requests to access these datasets should be directed to kwjones@nmsu.edu.

Ethics statement

Ethical approval was not required for the studies involving humans because the study was conducted for evaluative purposes. The participants in the study were direct beneficiaries of a USAID-funded project and data was collected for monitoring and evaluation. The studies were conducted in accordance with the local legislation and institutional requirements. Written informed consent for participation was not required from the participants or the participants' legal guardians/next of kin in accordance with the national legislation and institutional requirements because beneficiaries of this USAID-funded project agreed to participate in monitoring and evaluation across the 5-year project. This baseline survey collected information prior to project implementation.

Author contributions

KJ: Conceptualization, Formal analysis, Writing – original draft, Writing – review & editing. NC-R: Formal analysis, Writing – review & editing. NC: Writing – original draft, Writing – review & editing. EM: Visualization, Writing – original draft. MV: Conceptualization, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/ffgc.2024.1487898/full#supplementary-material

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