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When Do Property Rights Reduce Illicit Crops?*

Market Connectivity as the Binding Constraint

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July 16, 2026

Abstract

This paper estimates the effect of land property rights on illicit crop cultivation under weak institutions. We study *Formalizar para Sustituir* (FxS), a Colombian program that allocated land titles to farmers in coca-producing areas as part of the 2016 peace agreement with the FARC. Matching administrative titling records to annual high-resolution satellite imagery of coca fields at the 1 km $\times$ 1 km grid level, we compare titled grids to neighboring non-titled grids over 2011–2021 using a difference-in-differences design. Land titling reduces coca cultivation by 42–64% immediately, but the effect fades within two years. In the short term, titled households increase credit demand and investment in productive activities, and report incomes above what coca farming generates. These changes are consistent with property rights operating through the channels theory predicts, yet they are insufficient to sustain substitution on their own. The FxS×Placa-Huella interaction coefficient ($\hat{\psi}$) implies an additional sustained reduction of 33–38% relative to the pre-treatment coca mean in grids that combine land titling with tertiary road construction, suggesting that connectivity to local markets is the binding constraint for long-run transition away from illicit crops. Roads alone, by contrast, are associated with more coca — a result consistent with prior evidence that infrastructure without institutional preconditions benefits illegal as much as legal activity.

Keywords: Illicit Crops, Alternative Development, Land Titling, Rural Roads.
JEL: Q15, Q18, O17, R5, K11.

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¿Cuándo los derechos de propiedad reducen los cultivos ilícitos?*

La conectividad con los mercados como restricción determinante

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16 de julio de 2026

Resumen

Este artículo estima el efecto de los derechos de propiedad sobre la tierra en la siembra de cultivos ilícitos en contextos de instituciones débiles. Estudiamos *Formalizar para Sustituir* (FxS), un programa colombiano que entregó títulos de propiedad a agricultores en zonas productoras de coca como parte del acuerdo de paz de 2016 con las FARC. Cruzando los registros administrativos de titulación con imágenes satelitales anuales de alta resolución de los cultivos de coca a nivel de grillas de 1 km $\times$ 1 km, comparamos grillas tituladas con grillas vecinas no tituladas durante 2011–2021 mediante un diseño de diferencias en diferencias. La titulación de la tierra reduce el cultivo de coca en 42–64% de manera inmediata, pero el efecto se desvanece en un plazo de dos años. En el corto plazo, los hogares titulados aumentan la demanda de crédito y la inversión en actividades productivas, y reportan ingresos superiores a los que genera el cultivo de coca. Estos cambios son consistentes con derechos de propiedad que operan a través de los canales que predice la teoría, pero por sí solos son insuficientes para sostener la sustitución. El coeficiente de la interacción FxS$\times$Placa-Huella ($\hat{\psi}$) implica una reducción adicional y sostenida de 33–38% frente a la media de coca previa al tratamiento en las grillas que combinan la titulación de tierras con la construcción de vías terciarias, lo que sugiere que la conectividad con los mercados locales es la restricción determinante para abandonar los cultivos ilícitos en el largo plazo. Las vías por sí solas, en cambio, están asociadas con más coca — un resultado consistente con la evidencia previa de que la infraestructura sin precondiciones institucionales beneficia tanto a la actividad ilegal como a la legal.

Palabras clave: cultivos ilícitos, desarrollo alternativo, titulación de tierras, vías rurales.
JEL: Q15, Q18, O17, R5, K11.

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1 Introduction

Colombia registered 260,000 hectares of coca cultivation in 2024, the highest level on record and nearly double the 2016 figure despite two decades of active drug policy (UNODC, 2025). This persistence has shifted attention toward alternative development: programs that address the structural conditions driving farmers toward illicit crops rather than destroying the crops themselves. These programs are more cost-effective than military interdiction (Mejía et al., 2015; Mejia and Restrepo, 2016), but their track record is uneven. Coca endures in areas where underlying conditions are hardest to change: poverty, absent credit markets, poor infrastructure, and insecure land rights. Then, addressing these conditions may solve the persistence of coca cultivation. Does formalizing property rights in coca-producing areas reduce illicit cultivation, and if so, under what conditions does the reduction persist?

Land titling is the most common instrument in programs of this kind. Besley (1995) establishes that secure property rights raise the return to investment by reducing expropriation risk; Goldstein and Udry (2008) show, using plot-level variation within households in Ghana, that insecure tenure causes systematic underinvestment in land fertility—the same farmer invests less in plots where her claim is weaker. For formal land titles specifically, Galiani and Schargrodsky (2010) exploit a natural experiment in Buenos Aires and find that titling substantially increases housing investment but does not expand credit access, pointing to security against seizure as the operative channel rather than financial deepening. On the conflict side, Dube and Vargas (2013) find that falling wages in labor-intensive crops raise violence in Colombia through an opportunity cost mechanism: when legal agricultural income drops, the cost of joining an armed group falls with it. Yet higher legal returns matter only if farmers can act on them.

A further complication is that armed groups in coca-growing areas provide informal tenure security to coca producers (Mejía et al., 2015), insulating coca revenues from expropriation risk even without formal title; formal land rights must therefore displace not only insecurity but an entire parallel institutional arrangement before they can improve the relative returns to legal cultivation (Dube and Vargas, 2013). In coca-growing areas of

Colombia, fewer than 5% of coca grids have access to any tertiary road. Whether property rights can produce durable reductions in illicit cultivation in such settings, and whether market connectivity is the binding constraint, remains an open question (Thomson et al., 2022).

This paper estimates the effect of land property rights on coca cultivation and asks whether market connectivity determines whether that effect persists. We study *Formalizar para Sustituir* (FxS), a Colombian program that allocated land titles to farmers in coca-producing areas as part of the 2016 peace agreement with the FARC. The program targeted at least 7,300 farming families in 32 municipalities in 14 departments, giving it substantial geographic breadth and a defined implementation timeline. Our dataset combines geolocated title records with annual SIMCI satellite imagery of coca fields at the 1 km $\times$ 1 km grid level over 2011–2021. We supplement this with household surveys of 441 FxS beneficiaries, nighttime lights and Sentinel-2 satellite imagery for grid-level economic activity, and SECOP[1] and PDET[2] records of road construction. We apply a difference-in-differences design with staggered treatment timing, comparing titled grids to neighboring non-titled grids. To address the biases standard two-way fixed effects estimators produce in this setting, we use heterogeneity-robust estimators from Callaway and Sant'Anna (2021), Goodman-Bacon (2021), and Borusyak et al. (2024), and bound pre-trend violations using the sensitivity analysis of Rambachan and Roth (2023). Grids with titled land experienced a reduction of 0.25–0.38 hectares of coca relative to neighboring non-participating grids, equivalent to 42–64% of the pre-treatment mean. The effect is immediate but fades within two years.

What sustains the reduction is market connectivity. We test this by interacting titling with *Placa-Huella* (PH) tertiary road construction, a program implemented alongside FxS in the same municipalities. The FxS $\times$ PH interaction coefficient ($\hat{\psi}$) implies an additional sustained reduction of 33–38% of the pre-treatment coca mean in grids that combine land titling with road access. Roads built without titling, by contrast, are associated with more coca cultivation—consistent with prior evidence that infrastructure in areas with weak institutions benefits illegal as much as legal activity (Wigton-Jones, 2021; Moreno et al.,

[1]The *Sistema Electrónico de Contratación Pública* (Electronic Public Procurement System).
[2]The *Programas de Desarrollo con Enfoque Territorial* (Programs for Development with a Territorial Focus)

2020; Müller-Crepon et al., 2021). This is what practitioners in Colombia call the *mochila* hypothesis: ten kilograms of coca paste fit in a backpack; twenty sacks of plantains do not. Formal land rights do not change the relative profitability of coca when transport costs make legal crops unviable.

The paper contributes to three strands of the literature. First, it advances the evidence on property rights and illicit economies. Prior work establishes a negative association between land titling and coca cultivation in Colombia (Muñoz-Mora et al., 2018; Thomson et al., 2022); we go further by documenting that the effect is short-lived, and by identifying the condition under which it is not. The fade-out does not mean property rights are ineffective—it means their effectiveness depends on complementary market access. Second, the paper contributes to the literature on public goods provision in fragile states. Road construction in low-capacity settings typically raises both coca cultivation and armed conflict (Wigton-Jones, 2021; Moreno et al., 2020; Müller-Crepon et al., 2021); we show this result is conditional on institutional context, with roads reducing coca when implemented alongside a functioning titling program and raising it otherwise. Third, the results speak to how integrated rural development programs should be designed. Angrist and Kugler (2008) show that coca income in Colombia accrues largely to armed groups rather than to farmers, which implies that the farmer's substitution decision depends on whether legal agriculture can compete on cost.[3] Our estimates suggest that land formalization and road provision are complements, and that programs deploying them jointly are more likely to produce lasting results. The rest of the paper proceeds as follows: Section 2 describes the FxS program and its institutional context. Section 3 develops the theoretical framework. Section 4 presents the data. Section 5 lays out the empirical strategy. Section 6 reports the main results on coca cultivation. Section 7 examines mechanisms—credit access, economic activity, private investment, and the role of rural roads. Section 8 concludes.

[3]Angrist and Kugler (2008) study the effect of coca windfalls on civil conflict and income in Colombia. The specific claim about the distribution of coca rents between armed groups and farmers is also supported by Mejia and Restrepo (2013); the two citations are consistent on this point.

2 Institutional Framework: Comprehensive Development and Formalization for Transitioning Coca Producers

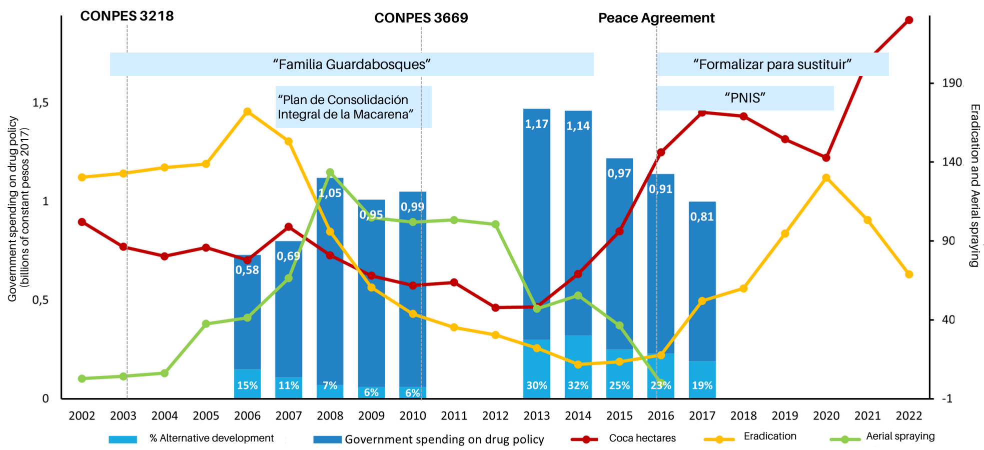
Coca-producing regions in Colombia have remained a central focus of drug policy since the 2000s. For the past two decades, these areas have consistently accounted for roughly 60% of coca cultivation (Mejia and Restrepo, 2013). This ongoing trend raises critical questions about the effectiveness of all policies to reduce drugs. Initially, policymakers prioritized a military approach, primarily targeting aerial operations. However, as coca cultivation failed to respond to this traditional strategy, new methods began to emerge. Alternative development programs aim to provide structural transformation among coca-producing communities by offering productive projects and income-generating activities. Consequently, drug policy has shifted to focus on preventing the expansion of illicit crops while also providing stable income alternatives, employment opportunities, and asset valuation for participating rural families and communities (see CONPES[4] 3669 and *Ruta Futuro*[5]).

[4]National Policy for Manual Eradication of Illegal Crops and Alternative Development for Territorial Consolidation.

[5]It is a comprehensive policy from the National Narcotics Council that seeks to address the entire drug chain, including illicit crops, territorial transformation, money laundering, organized crime, consumption, and international cooperation.

Figure 1

Drug Policy Spending and Coca Cultivation in Colombia, 2002–2021



Notes: This timeline shows the main programs from the drug policy of the Government of Colombia between 2002 and 2021. The blue bars represent the government spending on drug policy in billions of constant COP of 2017. The light blue shade represents the percentage of spending that is allocated to alternative development programs. The red line measures the evolution of coca crops in the country in thousands of hectares. Author's elaboration based on the available information from Departamento Nacional de Planeación and OACP (Oficina del Alto Comisionado para la Paz).

The peace agreement with the Revolutionary Armed Forces of Colombia (FARC) signed in 2016, marks an important turning point in the context of drug-related conflicts in Colombia. As part of the agreement, the drug policies transformed into a comprehensive agenda that addressed critical local development issues as a key element in ensuring long-term peace. In this context, the national government created the *PNIS*[6] and *Formalizar para Sustituir* (FxS) [7]. These two alternative development programs aimed to transform the socioeconomic conditions in regions affected by illicit crop cultivation as they transition to legal economies.

The FxS initiative aimed to mitigate territorial vulnerability and curb the spread of illicit crops by formalizing rural properties (UNODC, 2016). This initiative was part of the *Transformación del campo* component within the National Development Plan 2014–2018,

[6]The PNIS was an alternative development program aimed at achieving the voluntary substitution of illicit crops through the creation of programs and projects designed to lift these communities out of poverty.

[7]In 2016, the National Land Agency (ANT by its Spanish acronym), an agency of the Colombian Ministry of Agriculture, in agreement with the *United Nations Office on Drugs and Crime* (UNODC) Colombia, created the program *Formalizar para Sustituir FxS.*It was subscribed through International Cooperation Agreement No. 112, signed on August 16, 2016, between the ANT and UNODC.

aiming to improve land access for agricultural producers by ensuring legal security over property rights (DNP, 2014). The program targeted assistance for at least 7,300 farming families. To identify those most likely to benefit, a sweep methodology was deployed in 32 prioritized municipalities within 14 departments nationwide. The program's initial phase encompassed nine municipalities and four departments, while the second phase expanded to 23 municipalities, including the Territorial Spaces for Training and Reincorporation (ETCR). For a visual representation, refer to the Map 1 showing the prioritized municipalities.

Map 1

Municipalities prioritised by *FxS* and ETCR programs

Notes: This map shows the municipalities prioritized in the *Formalizar para Sustituir* program (9 municipalities) and in the Territorial Spaces for Training and Reincorporation (23 municipalities). The map shows the departments to which each municipality belongs. Source: author's elaboration based on information from UNODC.

Selection of regions relied on their historical coca crop presence and the existence of prior alternative development programs. *FxS* was structured in eight fundamental stages. In the first stage, land was selected, followed by the cross-checking of various layers of information and the sampling of families subject to titling. Subsequently, a detailed characterization of the properties and families was carried out. To qualify as a beneficiary of the program, it was necessary to meet key requirements: not being an improper occupant of vacant land, lacking a judicial record of convictions, demonstrating a link to the property in question, having participated in Alternative Development initiatives and being recognized by the National Land Agency (ANT), by Decree 902 of 2017, as a subject of social ordering. In addition, a commitment was made not to plant illicit crops again. [8].

After ensuring that the families met the key requirements and completed the initial characterization of the properties and families, the next stage of the formalization process involved a thorough legal and cadastral analysis. Subsequently, the beneficiary families completed the FISO[9], followed by the necessary topographic survey. Once these preliminary stages were completed, the appropriate legal route was detailed and applied to each property, based on the guidelines established in the *Rutas de Formalización* (Formalization Pathways) for each requested property. Finally, the ANT performed the official registration of the property in the Public Registry and Instruments Office (ORIP).

One of the main challenges in land formalization in rural areas lies in the legal complexities associated with formalizing property rights. In some cases, formalizing property rights is a straightforward administrative act. However, in other cases, it can become a lengthy judicial process that can last for years. Administrative and notarial routes typically prove to be more efficient, particularly when handling cases with clear registry records or those lacking apparent documentation. These cases can generally be addressed centrally without disputes over land claims. Conversely, judicial routes become necessary when land claimants fail to meet the requirements for adjudicating vacant land. The judicial process tends to take longer and is less efficient compared to the administrative alternative (MADR and UPRA, 2016).

Since its creation in 2018, FxS had completed 10,691 legal studies, which facilitated

[8]At the same time, the applicant must be of age, not be a public servant, and be located in one of the ANT prioritized municipalities.

[9]The Formato de Inscripción de Sujetos de Ordenamiento (Registration Form for Ordering Subjects).

the delivery of 1,490 titles covering more than 6,000 hectares. In 2019 alone, 7,300 files were for characterization and legal analysis. However, 4,954 cases were closed due to insufficient minimum requirements or the presence of insurmountable obstacles. Despite these challenges, 2,346 land titles were granted to families, resulting in a total of 10,373 hectares formalized that year. In 2020, the program advanced by initiating characterization and legal study processes for 1,600 properties. Of these, 960 unviable cases were closed, and 22 land titles were issued, covering a total of 180 hectares. Additionally, that year the program began 1,000 land formalization processes in areas targeted for intervention by the Directorate for the Substitution of Illicit Crops, as part of the PNIS initiative.

3 Theoretical Framework

We develop a model of crop choice to organize the empirical evidence and clarify the conditions under which land titling produces a durable reduction in coca cultivation. The framework adds two features that standard models of investment under insecure tenure (Besley, 1995) do not capture jointly: a market access friction specific to legal crops, and an informal arrangement that already protects coca production against expropriation. Together, these generate three predictions—a short-run effect of titling that fades, an adverse effect of roads without titling, and a complementarity between the two—which map directly to the estimating equations in Section 5.

3.1 Setup

Agents and environment. A representative farmer chooses whether to cultivate coca or a legal crop. The choice depends on the institutional environment (τ, θ), where $\tau \in [0, 1]$ is the probability that returns to legal investment are expropriated by a third party—armed groups, informal neighbors, or the state—and $\theta \geq 0$ indexes road quality, which determines the farmer's connectivity to the nearest output market for legal produce.

Returns from the legal sector. The farmer invests $k \geq 0$ in a legal crop. The farm-gate price is $P_L - c(\theta)$, where P_L is the market price and $c(\theta) > 0$ is a transport cost strictly decreasing in θ. Legal output is $f(k)$, with $f' > 0$ and $f'' < 0$, and returns are lost with probability τ. Expected returns from legal cultivation are:

$$\Pi_L(\tau,\, \theta,\, k) = \big(P_L - c(\theta)\big) \cdot f(k) \cdot (1-\tau) \;-\; r\, k \tag{1}$$

where $r > 0$ is the cost of capital. Maximizing over k gives the optimal investment level:

$$f'(k^*) = \frac{r}{\big(P_L - c(\theta)\big)\,(1-\tau)} \tag{2}$$

Both insecurity (τ high) and poor road access ($c(\theta)$ high) reduce k^* and therefore Π_L. This is the channel through which FxS and Placa-Huella jointly affect the production decision.

Returns from coca. Coca yields a fixed return $\Pi_C = P_C \cdot f_0$, where P_C is the farm-gate coca price and $f_0 > 0$ is baseline productivity. Two features distinguish coca from legal crops in this setting. First, transport costs for coca are near zero: ten kilograms of coca paste fit in a backpack, so $c_{\text{coca}} \approx 0$ regardless of θ. Second, armed groups provide informal protection of coca revenues, so the effective expropriation risk for coca is $\tau_C \approx 0$. Expected returns from coca are therefore:

$$\Pi_C = P_C \cdot f_0 \tag{3}$$

independent of (τ, θ). The farmer cultivates legally when $\Pi_L(\tau,\, \theta,\, k^*) > \Pi_C$. We adopt a partial-equilibrium framework throughout: output prices P_L and P_C are taken as exogenous to the farmer's decision, which is appropriate given that each 1 km^2 grid contributes negligibly to national coca or commodity supply.

3.2 Predictions

Substituting (2) into (1) defines a threshold curve in $(\tau,\, c(\theta))$ space below which the legal sector dominates. Three results follow directly.

Prediction 1. (Short-run effect of titling, with fade-out.) *A reduction in τ raises Π_L and can generate a switch to legal cultivation. If $c(\theta)$ remains above the long-run threshold, the switch is not sustained.*

Intuition. Titling reduces τ to $\tau' < \tau$, which lowers the right-hand side of (2), raising k^* and Π_L. If the updated pair $(\tau', c(\theta))$ crosses the threshold, the farmer switches to legal cultivation in the short run. However, if $c(\theta)$ remains high, the farm-gate price $(P_L - c(\theta))$ is still low relative to P_C, and legal income falls short of Π_C once the initial security gain is absorbed. The farmer returns to coca within one or two periods. This mechanism is consistent with Figure 4: an immediate reduction in coca cultivation that dissipates within two years of treatment.

Prediction 2. (Muted legal-sector gain from roads under insecure tenure.) *When $\tau > 0$, a reduction in $c(\theta)$ alone raises Π_L by less than it would under secure tenure: $\partial\Pi_L/\partial\theta\big|_{\tau>0} < \partial\Pi_L/\partial\theta\big|_{\tau=0}$. The relative advantage of coca therefore narrows less than it would if titles accompanied the road.*

Intuition. Roads lower transport costs for the legal sector, but the gain is scaled by the insecurity factor $(1-\tau)$: the marginal benefit of better connectivity is $(-c'(\theta)) \cdot f(k^*) \cdot (1-\tau)$, which is strictly decreasing in τ. Coca's return is unaffected by θ—transport costs for coca paste are near zero regardless of road quality, and coca is already protected from expropriation through informal arrangements with armed groups ($\tau_C \approx 0$). As a result, when tenure is insecure, roads generate a smaller legal-sector gain than they would under secure property rights, and the incentive to substitute toward legal cultivation remains weak. In the limit as $\tau \to 1$, the legal-sector gain from roads vanishes entirely. The raw data (Figure 6b) show that coca cultivation rose in grids exposed to Placa-Huella without land titling—a pattern consistent with this mechanism, and one that may also reflect additional channels, such as road-induced reductions in coca-sector input transport costs, that the model abstracts from.[10]

Prediction 3. (Complementarity.) *The marginal benefit of titling is increasing in road access, and the marginal benefit of roads is increasing in tenure security: $\partial^2\Pi_L/\partial(1-\tau)\,\partial\theta > 0$. Sustained substitution requires both τ and $c(\theta)$ to fall simultaneously below their respective*

[10]In the main specification (Equation 6), the standalone Placa-Huella coefficient $\hat{\beta}$ is absorbed by grid fixed effects, since road access indicators do not change within individual grids once a project is assigned. The cross-sectional evidence for the adverse effect of roads without secure tenure therefore comes from the raw data comparison in Figure 6b and the prior literature (Wigton-Jones, 2021; Moreno et al., 2020), not from $\hat{\beta}$ in the panel regression.

thresholds.

Intuition. From (1), $\partial \Pi_L / \partial(1-\tau) = (P_L - c(\theta)) \cdot f(k^*)$, which is increasing in θ: the return to reducing expropriation risk is larger when transport costs are already low. Conversely, $\partial \Pi_L / \partial \theta \propto (1-\tau)$: the return to better roads is larger when tenure is secure. The two policies are strategic complements. Joint implementation produces strictly more than the sum of separate effects, and the interaction coefficient $\hat{\psi}$ in Equation (6) is the reduced-form estimate of this supermodularity.

3.3 Testable Implications

The model delivers five predictions that Sections 6–7 test directly:

P1. FxS reduces coca at $t = 0$; the effect fades by $t + 2$. *(Prediction 1; Figure 4, Table 2)*

P2. PH alone yields a smaller coca reduction than it would under secure tenure; in the data, grids with PH only show rising coca. *(Prediction 2; Figure 6b)*

P3. FxS $\times$ PH generates a sustained coca reduction. *(Prediction 3; Table 5, $\hat{\psi} < 0$)*

P4. FxS raises credit access and private investment. *(Equation (2); Table 3)*

P5. FxS raises local economic activity. *(Equation (1); Table 4)*

The model also yields a falsification prediction. If sustained coca reduction were driven by a general increase in state presence rather than by market connectivity specifically, any public goods intervention should interact positively with titling. Prediction 3 predicts the opposite: the complementarity is specific to transport infrastructure, which is the only intervention that lowers $c(\theta)$ for legal crops. Consistent with this, we find no significant interaction between FxS and other public goods interventions in Columns 5–6 of Table 5.

4 Data

This section describes the data sources used in the analysis. Our main dataset is an annual panel covering the period 2011–2021 at the 1 km $\times$ 1 km grid level for all municipalities intervened by the *FxS* program. Table 1 presents summary statistics for the main variables, separately for *FxS* grids and neighboring control grids, over the pre-treatment period (2011–2017). A joint omnibus F-test of equality across the pre-treatment covariates yields $F(4, 767) = 2.10$ ($p = 0.080$); individual differences in coca prevalence ($p = 0.064$) and rural road access ($p = 0.085$) are not statistically significant at the 5% level. The pre-treatment difference in built-up area ($p = 0.034$, Panel B) reflects an existing settlement advantage in *FxS* grids; we show in the robustness analysis (Section 6) that conditioning on this baseline difference does not affect the main estimates.

Tabla 1
Summary Statistics: Pre-Treatment Period (2011–2017)

	FxS Grids		Control Grids		Diff. (*FxS*−Control)	*p*-value
Variable	Mean	SD	Mean	SD		
Panel A: Illicit Crops						
Share of grid with coca (%pt)	0.303	0.764	0.430	1.107	−0.127	0.064
Panel B: Economic Activity						
Night lights (log)	0.809	0.663	0.891	0.694	−0.082	0.116
Built-up area (pixels, 10m^2)	60.364	217.319	29.033	113.793	+31.331	0.034
Deforestation share (%)	0.755	0.976	0.723	1.014	+0.031	0.681
Panel C: Infrastructure						
Access to rural road (0/1)	0.061	0.240	0.057	0.232	+0.004	0.830
Access to *Placa-Huella* (0/1)	0.000	0.000	0.013	0.115	−0.013	0.008
Panel D: Sample						
Number of grids	246		526		772 total	
Grid-year obs. (2011–2017)	—		—		5,404	
Grid-year obs. (2011–2021)	—		—		8,492	

Notes: The table presents means and standard deviations for *FxS* grids (those receiving at least one land title from the FxS program) and neighboring control grids, computed at the grid level over the pre-treatment period 2011–2017. Grid-level means are computed by averaging all grid–year observations within the pre-treatment window. The "Difference" column reports the difference in grid-level means (*FxS* minus control); *p*-values are from two-sample *t*-tests with unequal variances (Welch). *Panel A: Crops* is the share of the grid covered by coca, expressed in percentage points. *Panel B: Night lights* is the log of harmonic-mean nighttime light intensity (Suomi-NPP VIIRS). *Built-up area* is the count of 10m×10m Sentinel-2 pixels classified as human construction (available from 2016). *Deforestation* is the cumulative proportion of primary forest lost relative to 2000 forest cover (Global Forest Change). *Panel C: Rural road* is a binary indicator equal to 1 if the grid contains any rural road within 1 km (OpenStreetMap). *Placa-Huella* is equal to 1 if a PDET tertiary road project was located within 1 km of the grid. The pre-treatment difference in built-up area ($p = 0.034$) indicates that *FxS* grids contain more existing settlement; the parallel pre-treatment trends in coca (Panel A) and infrastructure (Panel C) are consistent with the identifying assumption despite differences in levels. Source: SIMCI, ANT, Suomi-NPP, Sentinel-2, Global Forest Change, OpenStreetMap, SECOP, PDET datasets.

4.1 Land Property Rights and FxS Beneficiaries

Our main variable of interest is land property rights. We focus on the property titling and beneficiary assessment activities conducted between 2016 and 2020, including the delivery of property rights, topographic surveys, and assessments to evaluate changes in beneficiary well-being. In the first stage, the UNODC monitoring team conducted a baseline survey in 2016 to identify potential program beneficiaries. During this stage, 6,797 households across the 32 municipalities prioritized by FxS were surveyed. Following, between 2018 and 2020, 3,858 property titles were delivered.

For our analysis, we focus on property titles formalized through administrative pathways for three reasons: First, the administrative process typically avoids lengthy legal procedures, allowing landholders, particularly those in rural areas, to obtain formal titles in a shorter time period. Second, for lands classified as *baldíos* (public lands), the administrative approach allows for a more streamlined process of allocation, ensuring that these lands can be quickly titled and incorporated into the formal economy. This pathway is also more cost-effective, reducing legal fees and administrative costs for both the state and landholders. Finally, for all properties requested under administrative routes, detailed topographic surveys and administrative information were collected by the UNODC team.

After the first stage of property rights allocation in 2018, the UNODC team conducted an end-line survey. During this phase, the team used stratified sampling to collect 508 surveys from household beneficiaries. The surveys covered household socioeconomic characteristics, land use, illicit crops, infrastructure and services, family economy, good governance, and social capital. To measure potential changes in well-being, we identified 441 households that had received a property title from the program and also had available baseline information.

4.2 Illicit Crops

Our main outcome variable is the number of hectares with coca crops. This data is obtained from the Integrated Monitoring System of Illicit Crops (SIMCI, from its name in Spanish). SIMCI uses high-resolution satellite images to detect and monitor coca fields and complement them with aerial surveys and ground verification. Satellite images identify fields through spectral signatures, while aerial surveys with cameras and sensors provide additional details. Ground teams then verify and validate the data, assessing crop presence and conditions.

As a result, SIMCI provides the number of coca-planted hectares at a 1-km by 1-km grid level. The grids cover all Colombia and are available for the years 2001-2022. Since each 1-km by 1-km grid is 100 hectares, the number of hectares of coca in each grid can also be interpreted as the percentage of that grid covered by coca. To determine if the grids were exposed to the *FxS* program, we performed a spatial join of the layer of 833 titled properties with the UNODC grids. Figure A1 shows the distribution of the size of titled land plots and the share of titled land in UNODC grids.

4.3 Local Economic Activity and Infrastructure Investment

We use remote sensing data to measure outcomes that are otherwise unavailable at the grid level. We measure economic activity using satellite imagery of night-time lights (*NTL*). We use the Suomi National Polar-orbiting Partnership (Suomi-NPP) project, which provides monthly radiance measures since April 2012 at pixel level with a resolution of 15 arc seconds (around 450-meter by 450-meter at the Equator). The *NTL* data is aggregated at the grid level by averaging annual NTL within the grid, and the resulting variable is log-transformed for a more straightforward interpretation.

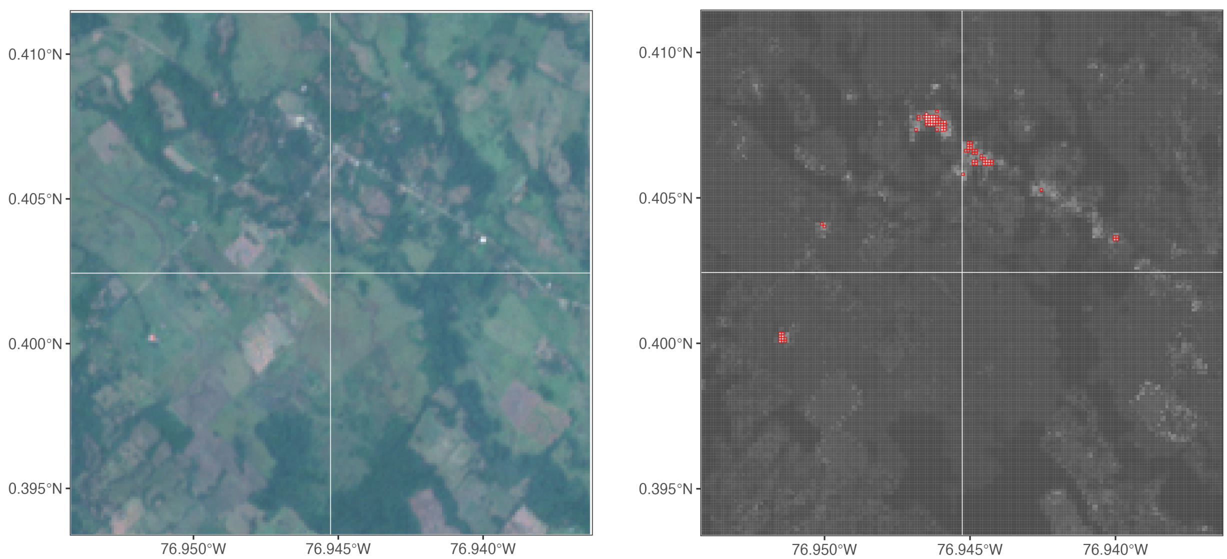
We use high-resolution satellite imagery from the Sentinel-2[11] dataset, along with machine learning models, to identify infrastructure developments such as buildings and roads within each 1-km by 1-km grid. First, we select a random sample of approximately 20% of the illicit crops grids. Next, we use the 10-meter by 10-meter RGB bands of Sentinel-2 imagery to manually identify pixels within each illicit crops grid that was covered by cement, roads, or rivers. Finally, we complement our training dataset with land cover predictions from the Brown et al. (2022) database.

Using the training dataset, we develop a neural network model to predict built-up areas

[11]Sentinel-2 provides high-resolution imagery with 13 spectral bands, offering resolutions of 10 meters, 20 meters, and 60 meters, depending on the band.

within Sentinel-2 pixels across the full sample of illicit crops grids for the period 2015 to 2021. In Figure 2, we display the RGB bands from the Sentinel-2 dataset and the corresponding building probability values estimated for a randomly selected sample of grids. All pixel-level predictions are aggregated at the grid level by summing up the urbanized land cover or infrastructure area within each grid. Finally, we also measure long-term investments at the grid level using deforested areas[12] from the Global Forest Change dataset Hansen et al. (2013).

Figure 2
Prediction of Private Infrastructure Investment:



(a) RGB bands of Sentinel-2 **(b)** Built-up Area Predicted

Notes: In Panel **(a)**, we show the 10-meter by 10-meter RGB bands from the Sentinel-2 dataset for four 1-kilometer by 1-kilometer grids from UNODC. In Panel **(b)**, we present building probability values estimated for each pixel in the UNODC grids. We highlight in red the pixels predicted as built-up areas by the neural network model, representing urbanized land cover or infrastructure.

4.4 Public Goods and Rural Roads

We construct a measure of rural roads provision from two main sources. First, we use the dataset from SECOP[13], a platform that centralizes information on public procurement

[12]Formalization encourages agricultural development through more efficient practices (Toulmin, 2009) and long-term agricultural investments, such as tree planting and fallow practices (Fenske, 2011).
[13]The *Sistema Electrónico de Contratación Pública* (Electronic Public Procurement System).

processes in Colombia. Then, we filter approximately 62,000 public contracting processes related to the construction or improvement of land, buildings, structures, or roads between 2010 and 2021. Each administrative record contains the launching date, the amount invested, the process status, and details of the project to be contracted. Next, we use text mining to extract the name of the village and geolocated each infrastructure construction.

Second, we employ the dataset from PDET[14], a rural development program in Colombia. We collected information on 701 road infrastructure projects and social or public service projects completed between 2018 and 2020 in Colombia. Each record contains data on the project's exact geolocation, delivery date, investment amount, and the number of potential beneficiaries. Finally, we perform a spatial merge of the PDET and SECOP infrastructure construction datasets with the 1 km x 1 km illicit crops grids.

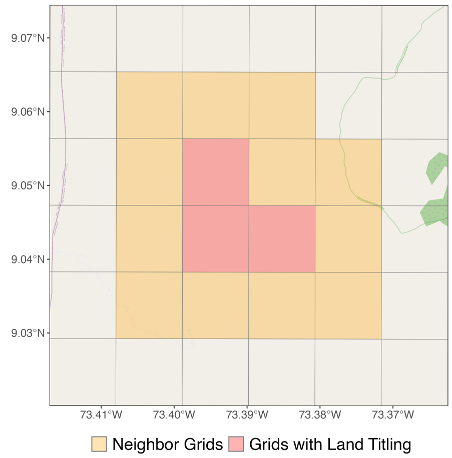
5 Empirical Strategy

5.1 Baseline Specifications

We exploit spatial and time variation of the implementation of *FxS* to estimate the causal effect of property rights on the area with illicit crops. First, we define a grid as treated if it has at least one hectare with a land title allocated by *FxS*. Then, we select as control those grids located in a neighboring area but do not receive a title from *FxS* program (See Figure 3).

[14]The *Programas de Desarrollo con Enfoque Territorial* (Programs for Development with a Territorial Focus) is a management and planning tool created by the Colombian government aimed at promoting economic, social, and environmental development in the areas of the country most affected by the internal armed conflict

Figure 3
Neighbor definition



Notes: The red squares have at least one hectare of landholding with a land title delivered by FxS. We define a grid as neighbors (orange squares) if it shares at least one boundary point with one *FxS* grid.

This control group choice balances two concerns. Immediate neighbors share geographic conditions—soil quality, altitude, distance to markets—with treated grids, making them credible counterfactuals for parallel trends. At the same time, proximity creates a potential SUTVA concern: if coca cultivation is displaced from titled grids to adjacent non-titled grids, the DiD estimator would conflate the true property rights effect with a displacement effect, overstating the benefit of titling. Three features of the design reduce this risk. First, the mechanism through which property rights reduce coca (formal tenure enabling credit access and legal investment) does not have a natural displacement channel to neighboring grids that lack titles; farmers cannot relocate their legal entitlements across grid boundaries. Second, we find no detectable effect of FxS on coca in grids exposed only to other public goods interventions (columns 5–6, Table 5), which is inconsistent with a general displacement hypothesis under which any state presence near titled areas should raise coca in control grids. Third, we implement a "donut" test using 1,103 second-ring neighbor grids—grids adjacent to Ring 1 control grids but not adjacent to treated grids—as an alternative control group. If coca were displaced from titled grids to Ring 1 control grids, the baseline estimate would be biased toward zero relative to the donut estimate (which uses a control group further from any displacement spillover). The donut estimate is -0.527 (SE $= 0.100$, $p < 0.001$), larger in magnitude than the Ring 1 baseline of -0.383—which is the opposite of what a displacement story would predict and suggests the baseline estimate is conservative rather than overstated. Appendix Table A8 reports the full comparison across specifications.

We use a difference-in-differences methodology to estimate the causal effect of land titling on coca hectares as follows:

$$y_{g,p,t} = \alpha_g + \lambda_t + \gamma_{p,t} + \phi \cdot \text{FxS}_{g,p,t} + \epsilon_{g,p,t} \tag{4}$$

where $y_{g,p,t}$ is the coca-area percentage[15] in grid g in province p in year t. $FxS_{g,p,t}$ is measured in two ways. For the extensive margin, it is a dichotomous variable that takes the value of 1 if grid g in province p in year t has at least one hectare with a land title allocated by *FxS*, and 0 if it is a grid with no beneficiaries of the program. For the intensive margin, it is measured as the percentage of the titled area in the grid.

Likewise, α_g and λ_t represent grid and year-fixed effects respectively and $\gamma_{p,t}$ are annual/province shocks. α_g captures time-invariant characteristics in each grid, such as altitude, and λ_t captures temporal shocks that affect all grids equally. $\epsilon_{g,p,t}$ is the regression error term and clustered at the grid level (772 clusters: 246 treated, 526 control).[16] The coefficient ϕ captures the change in the coca area between the grids with formalized landholdings for the following years in which the land title was granted. In the language of Section 3, ϕ is the reduced-form estimate of the effect of lowering τ on the farmer's crop choice—the short-run gain from reducing expropriation risk predicted by Prediction 1.

However, the identification of ϕ is conditioned on the assumption of parallel trends. This

[15]As an illicit crop grid has an area of 100 hectares, the number of hectares planted with coca can be interpreted as the percentage of the grid area covered by illicit crops.

[16]Coca cultivation exhibits spatial autocorrelation across neighboring grids. Standard errors clustered at the grid level account for temporal autocorrelation within grids but not spatial correlation across adjacent grids. Conley (1999) standard errors with a spatial cutoff provide an alternative that accounts for both dimensions; we use grid-level clustering as our baseline given the 772 clusters in the sample. Appendix Table A7 reports the main coefficient under Conley standard errors at 1 km, 5 km, and 10 km spatial cutoffs. The result remains significant at the 5% level through a 5 km cutoff—the appropriate benchmark for local coca spillovers given the 1 km grid structure, covering five rings of spatial influence—and at the 10% level under the 10 km bandwidth, which spans ten grid-rings in each direction and likely overcorrects for spatial dependence in coca cultivation decisions.

assumption holds that, in the absence of land titling, the evolution of coca cultivation would have been similar both in the grids with titled land and in those grids without formalized land. To test whether there are differential trends between treated and control grids, an event study model is estimated as follows:

$$y_{g,p,t} = \alpha_g + \lambda_t + \gamma_{p,t} + \sum_{t\neq -1}^{-7\leq t\leq 3} (\phi_t \cdot \mathrm{FxS}_{g,p,t}) + \epsilon_{g,p,t} \tag{5}$$

The coefficients ϕ_t capture the difference in the coca area between the period t and the period before the allocation of the title deeds in the properties of the grids g with respect to the grids. The coefficient ϕ_t can be interpreted as the difference in coca crops in grids with land titles allocated by *FxS* in year t, relative to the beginning year of the program.

5.2 The Role of Rural Roads

We estimate an additional specification to provide evidence of the role of road infrastructure provision in the persistence of coca crops on those grids that received a land title from FxS. The equation to estimate is:

$$y_{g,p,t} = \alpha_g + \lambda_t + \gamma_{p,t} + \beta \mathrm{PH}_{g,p,t} + \phi \cdot \mathrm{FxS}_{g,p,t} + \psi(\mathrm{PH}_{g,p,t} \cdot \mathrm{FxS}_{g,p,t}) + \epsilon_{g,p,t} \tag{6}$$

The standalone term $\beta \cdot \mathrm{PH}_{g,p,t}$ is included in the estimating equation but is collinear with grid fixed effects in the estimation sample, as the combined PDET road variable rarely switches values within individual grids once grid-level heterogeneity is absorbed; it is therefore omitted by the estimator and not reported in Table 5. The identification of the complementarity ψ is unaffected by this collinearity, since $\mathrm{PH}_{g,p,t} \times \mathrm{FxS}_{g,p,t}$ varies within treated grids over time. In the language of Section 3, ψ identifies the supermodularity from Prediction 3: the marginal return to lowering $c(\theta)$ is larger when τ has already been reduced by the title.

Where $\mathrm{PH}_{g,p,t}$ takes the value of 1 from the period t in which a *PH* was built in the grid

g onwards and 0 otherwise. The PH[17] is known as public projects for the improvement of tertiary roads in Colombia. Within the framework of PDET works, more than 294 road-plate construction projects were implemented in the country between January 2018 and December 2020. Using the geolocation of PDET projects, we identified if the grid was exposed to a road with a PH project.

A potential concern with the estimation of Equation 6 is that PH projects may not be randomly assigned across grids. If the government systematically directed road investments toward areas with greater prospects of legal economic transformation—including grids where the *FxS* program was already generating observable progress—the interaction coefficient ψ could capture positive selection rather than a causal complementarity. We provide three pieces of evidence that help address this concern. First, the estimated effect of PH in isolation is associated with an *increase* in coca cultivation (Column 3, Table 5), inconsistent with the hypothesis that road projects were targeted toward areas already transitioning away from illicit crops. Second, we find no significant interaction between *FxS* and other public goods interventions by the Colombian government (Columns 5–6, Table 5), suggesting the result is specific to road connectivity rather than a general pattern of state targeting of productive areas. Third, PH projects in our sample were allocated through PDET, whose prioritization criteria were based on historical conflict exposure and poverty indices established prior to the implementation of *FxS* (Presidencia de la República de Colombia, 2017), making systematic targeting of post-*FxS* progress unlikely. Nonetheless, we acknowledge that residual endogeneity in road assignment cannot be fully ruled out, and we interpret ψ as an upper bound on the true complementarity effect if any positive selection remains.

6 Results

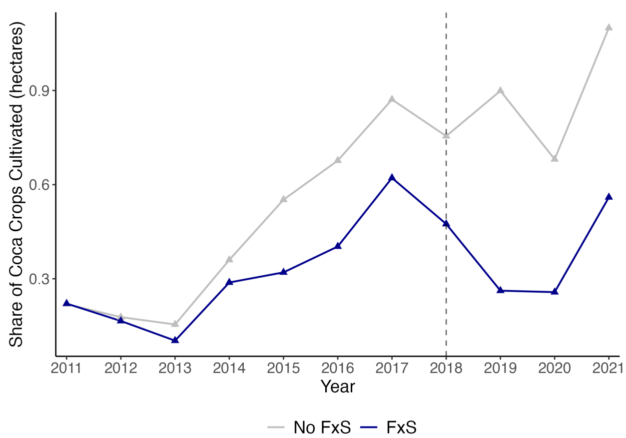
We begin by studying the relationship between land property rights and illicit crops. Panel **a** in Figure 4 presents the raw data of coca area of *FxS* and *non-FxS* grids. We observe that before 2018, the two groups had different levels, but the trends in cultivation were parallel. Between 2018 and 2020, coca area decreased in *FxS* areas, while it remained stable in *non-*

[17]Figure A7 shows the image of a PH built as part of the PDET works in Colombia.

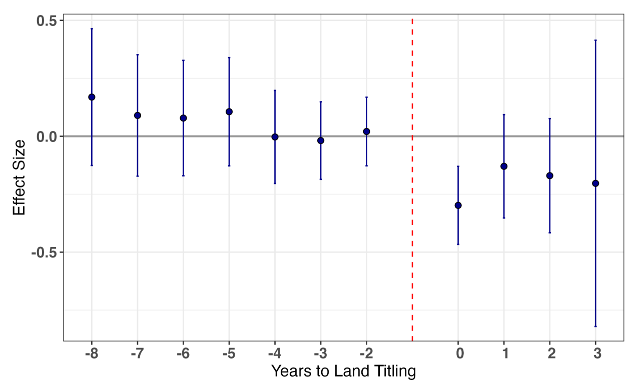
FxS. Panel **b** in Figure 4 presents the event study results with the coefficients from Equation 5. The results suggest that there are no differential trends between the treated grids and the non-treated grids before FxS began in 2018. Likewise, results suggest that titling leads to an immediate reduction in the coca area, but loses statistical significance in the second year after the title was allocated. This fade-out is the central prediction of Prediction 1 in Section 3: titling lowers τ, which raises Π_L in the short run, but $c(\theta)$ remains above the long-run viability threshold, and coca re-emerges within one or two periods. This pattern stands in contrast to Galiani and Schargrodsky (2010), who document sustained increases in housing investment following urban land titling in Buenos Aires. The key difference is that urban titleholders face near-zero transport costs and competitive output markets, whereas coca-growing areas in Colombia combine insecure tenure with near-prohibitive market access costs—a second constraint that land titles alone cannot relax.

Figure 4

Effect of Land Titling on Coca Cultivation: Raw Data and Event Study Estimates



(a) Raw data: *FxS/no FxS*



(b) Event study: *FxS/no FxS*

Notes: In Panel **(a)**, the x-axis represents time in years, and the vertical axis is the share of the hectares of coca crops cultivated in the grid. The solid blue line is for grids that received at least one title in 2018, while the gray solid line is for neighbor grids that did not receive titles in that year. In Panel **(b)**, the dashed line represents the year the first *FxS* title was delivered. Point estimates with 95% confidence intervals. The dependent variable is the share of the grid covered by coca cultivation (hectares per 100-ha grid, equivalently the percentage of grid area under coca). Regressions incorporate year and grid fixed effects. Standard errors are clustered at the grid level. The coefficient at $t = -2$ (calendar year 2016, coinciding with the peace agreement announcement and the FxS baseline survey) is -0.005 (95% CI: $[-0.160,\ 0.151]$, $p = 0.953$), providing direct evidence against anticipatory coca reduction prior to title delivery.

Table 2 presents the results for the difference-in-differences estimation on the percentage of the grids covered by coca crops in years after *FxS* was implemented (Equation 4). We present results for two dimensions of land formalization: Columns 1 and 2 show the estimation results for the extensive margin (grids with at least one hectare of land titled) and columns 3 and 4 present the intensive margin (effect of titling an additional one hectare on the percentage of the area planted with coca crops). We find that after receiving property titles, the grids with at least one hectare formalized experienced, on average, a decrease of 0.38-0.25 hectares of coca compared to neighboring grids that did not participate in the program. This is equivalent to a reduction of 64% - 42% relative to the 0.586 hectares average coca coverage in the neighboring control grids over the full 2011–2021 analysis period (the pre-treatment control mean for 2011–2017 is 0.430 hectares).

Results in Table 2 indicate that titling 1% of the area reduces coca crops by 0.009 hectares (Column 3) to 0.005 hectares (Column 4). These findings suggest that the marginal effect of land titling on illicit crop cultivation ranges from -0.9 to -0.5 hectares of coca per additional percentage point of the grid area titled (a linear "dose–response" relationship, not a structural elasticity). To put these results in perspective, Muñoz-Mora et al. (2018) find that, on average, an additional hectare of titled land is associated with a decrease of approximately 1.4 hectares destined for coca production.[18] These results suggest that allocating property rights may be more cost-effective than other drug policy interdiction measure. For example, according to ANT, under the *FxS* program, the average cost of formalizing a hectare of land was approximately USD $4,500. Meanwhile, the cost of aerial spraying to reduce one hectare of coca costs approximately $79,200 according to Mejía et al. (2015).

[18] One of the co-authors of the present paper (Muñoz-Mora) is also a co-author of that study. The prior estimate uses an OLS cross-sectional specification that does not control for time-invariant grid-level unobservables; the present DiD design differences these out, which likely accounts for the attenuation in the current estimates relative to the 2018 benchmark.

Tabla 2
Effect of Land Formalization on Coca Crop Areas:

	Share of the grid covered with coca crops:			
	Extensive Margin		Intensive Margin	
	(1)	(2)	(3)	(4)
FxS	-0.383^{***}	-0.254^{***}	-0.009^{***}	-0.005^{**}
	(0.103)	(0.095)	(0.002)	(0.002)
Mean Dep. Var.	0.5859	0.5859	0.5859	0.5859
N. Treated	246	246	246	246
N. Control	526	526	526	526
T.E. (Prov-Year)		✓		✓
Period	2011-2021	2011-2021	2011-2021	2011-2021
Observations	8,492	8,492	8,492	8,492

Notes: *** p<0.01; ** p<0.05 ; * p<0.1. The dependent variable is expressed as the share of the grid covered with coca crops. Columns 1 and 2 present the estimation of equation 4, where FxS is a dichotomous variable equal to 1 if the grid contains at least one hectare of landholdings with a delivered land title. Columns 3 and 4 present the estimation of equation 4, where FxS represents the share of titled area within the grid. All regressions include year and grid fixed effects. Standard errors are clustered at the grid level.

As a first robustness check, we replace the immediate-neighbor control group with ORIP grids — grids with parcels in the public land registry that had not yet received a title. The Callaway–Sant'Anna aggregate ATT using this comparison group (Table A2) yields estimates of −0.850 to −0.605 in the extensive margin, larger in magnitude than the TWFE estimates of −0.383 to −0.254; the two estimators use different comparison groups and therefore characterize different local average treatment effects. The TWFE event study using ORIP grids as controls (Figure A2, Online Appendix) confirms the direction and timing of the effect. As a formal sensitivity analysis for the parallel trends assumption, we apply the Rambachan and Roth (2023) approach to characterize the set of pre-trend violations that would overturn the main finding; these bounds are reported in Figure A8 in the Online Appendix. The immediate effect ($t = 0$, $\hat{\phi}_0 = -0.364$, SE $= 0.090$) remains entirely below zero—the 95% CI does not include zero—for all violations up to $\bar{M} = 0.190$ percentage points per year. This threshold is 40 times the observed pre-trend at $t = -2$ (-0.005, $p = 0.953$), making it highly unlikely that undetected anticipation or confounding trends account for the finding. The three pre-periods closest to treatment ($t = -4$, -3, -2: coefficients 0.020, -0.023, -0.005) are all near zero and precisely estimated; coefficients at $t = -6$ and $t = -7$ are larger in magnitude but reflect early-period differences that had already converged before treatment, consistent with the identifying assumption holding in the years immediately preceding FxS delivery.

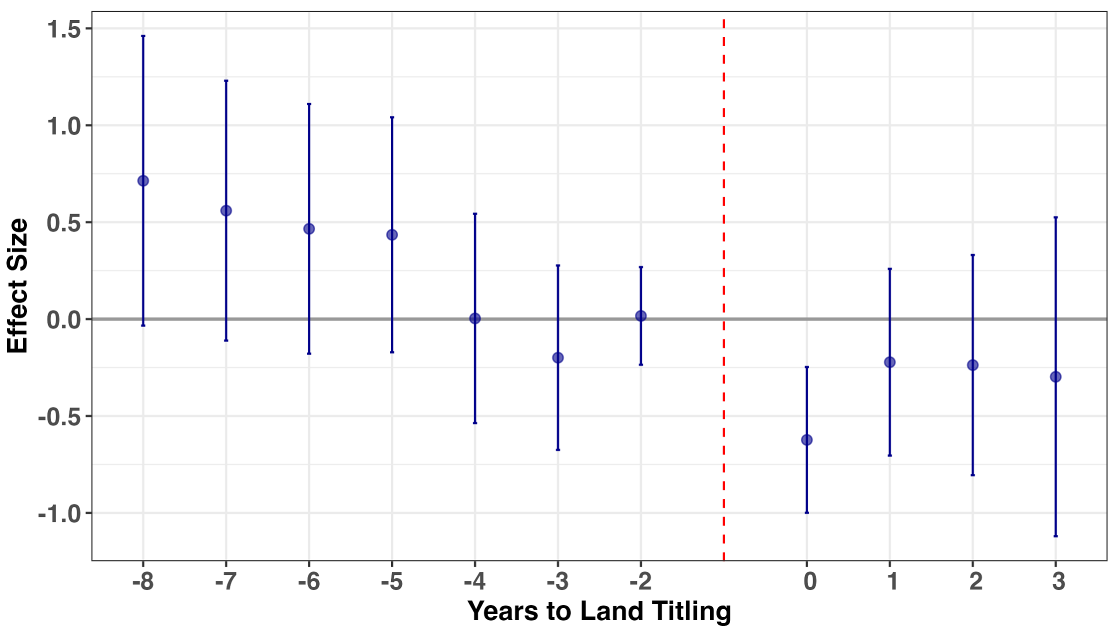
As a further robustness check, the Borusyak–Jaravel–Spiess (BJS)(2024) imputation estimator yields a static ATT of -0.419 (SE = 0.129, 95% CI: $[-0.671, -0.166]$), consistent with the TWFE estimate of -0.383. The BJS event study shows flat pre-periods at $t = -4$ through $t = -2$ and significant negative effects at $t = 0$ (-0.523), $t + 1$ (-0.314), and $t + 2$ (-0.453); the $t + 3$ estimate is uninformative owing to only 15 observations in the final post-treatment period. To address the pre-treatment difference in built-up area (+31.3 pixels; $p = 0.034$; Table 1), we add grid-specific linear time trends in pre-treatment built-up area to the baseline specification. The FxS coefficient changes from -0.383 (SE = 0.103) to -0.375 (SE = 0.103)—a 2% change—confirming that the settlement-level difference between FxS and control grids does not confound the main estimate.

Following Goodman-Bacon (2021) and de Chaisemartin and D'Haultfoeuille (2023), we re-estimate Equation 4 applying heterogeneity-robust weights for each treatment cohort. The Goodman-Bacon (2021) decomposition assigns 98.9% of total TWFE weight to clean "treated vs. never-treated" comparisons; the remaining 1.1% falls on "later-treated vs. earlier-treated" comparisons that could carry contaminated weights. This negligible share confirms that staggered treatment timing does not meaningfully bias the TWFE estimate, and that the two treatment cohorts (15 grids in 2018, 231 in 2019) are dominated by the clean comparison against 526 never-treated neighbors. Table A3 and Figure A3 (Online Appendix) present the full decomposition and the 2×2 weight scatter.

Figure 5 presents the Callaway–Sant'Anna (2021) group-time average treatment effects (ATT) for each cohort–period combination. The group-time ATTs confirm the pattern identified by TWFE: a negative and significant effect of land titling on coca in the periods immediately following title delivery, with a decay toward statistical insignificance in the medium run. The aggregate ATT (-0.850 to -0.605, Table A2) is larger in magnitude than the TWFE estimate (-0.383 to -0.254). Two differences between these estimators account for the gap: the Callaway–Sant'Anna estimator uses "not-yet-treated" ORIP grids as the comparison group (pre-treatment coca mean of 1.115 hectares), while the TWFE uses immediate neighbors (mean of 0.586 hectares); and C-S allows treatment effect heterogeneity across cohorts that TWFE averages over. The two estimates therefore characterize different local average treatment effects rather than estimating the same parameter under alternative assumptions.

Figure 5

Group-Time Average Treatment Effects on Coca Cultivation: Callaway–Sant'Anna Estimator



Notes: Group-time average treatment effects (ATT(g,t)) estimated following Callaway and Sant'Anna (2021). Each point represents the average treatment effect for a given treatment cohort in a given calendar year, relative to the period immediately before that cohort first received an *FxS* land title. Bands represent 95% confidence intervals. The comparison group consists of grids with parcels in the land registry that had not yet been titled at time t ("not-yet-treated" control group). Standard errors are clustered at the grid level.

7 How do Land Property Rights affect Illicit Crops?

Section 3 formalizes three channels through which the FxS–PH bundle operates: a tenure security channel ($\tau \downarrow$) that raises the return to legal investment, a market access channel ($c(\theta) \downarrow$) that makes that return realizable, and a complementarity between the two. We test each channel in turn. For the security channel, we examine credit access and private investment decisions using the household survey (Equation (2) predicts k^* rises when τ falls). For the market access channel, we examine nighttime lights and Sentinel-2 built-up area as proxies for local economic activity (Equation (1) predicts Π_L rises when $c(\theta)$ falls). We then turn to the complementarity, using the PH interaction to distinguish grids where both conditions are met from those where only one is.

7.1 Credit Access, Local Economic Growth, and Private Investment

First, we used baseline and end-line surveys from *FxS* beneficiary households to measure changes in access to the credit market and other development indicators, such as household income, household expenditure, and access to public services. Second, we employed satellite images of nighttime lights to assess the changes in local economic activity in treated grids. Finally, we identified changes in long-term investments to grid level using two sources: built-up areas predicted by remote sensing and changes in deforested areas.

Table 3 presents before-after comparisons for the 441 FxS households with both baseline (2016) and endline surveys. These are descriptive comparisons within the treated sample and carry no causal interpretation. We interpret them as evidence consistent with the mechanisms that theory predicts. Panel A shows that the share of households requesting loans was 8 percentage points higher at endline than at baseline (15% to 23%), and the credit approval rate rose from 14% to 21%. One third of approved endline loans used the property title as collateral — direct evidence that formal tenure relaxed the credit constraint.

Panel B reports changes in household expenditure. Spending on productive activity investments and on land and housing rose to USD 915.57 and USD 379.42 at endline, respectively. As an illustrative benchmark only, Dávalos et al. (2024) report that coca farmers in the state of Cauca spend around USD 1,118.7 on productive activity investments and USD 215.6 on land and housing. This comparison should not be read as causal: the FxS beneficiaries and the Dávalos et al. (2024) coca farmers differ in geography, program exposure, and selection into cultivation decisions, so the comparison does not control for any of these dimensions. With that caveat, the direction of the differences is consistent with titled households gradually shifting toward legal productive investments.

Panel C of Table 3 presents changes in the average household income by source. The results indicate that the aggregate yearly income of beneficiary households derived from wages and commercial activities increased by 1.1 times, rising to 2,357.42 USD at endline. According to Dávalos et al. (2024), coca farmers report annual revenues of 2,015.5 USD derived from activities related to the collection and processing of coca leaves. These findings suggest that beneficiary households could achieve incomes 1.16 times higher than those generated from illicit economies. We next examine the robustness of these results using alternative, grid-level measures of economic activity and private investment derived from remote sensing data.

Tabla 3
Changes in Household Access to Credit Markets, Expenditure, and Income:

	Endline	**Baseline**	**Difference of means**	**p-value on difference**
Panel A: Household with Requested or Approved Credits (Share):				
Requested Credits	0.23	0.15	0.08	0.00
Approved Credits	0.21	0.14	0.07	0.00
Panel B: Household Expenditure (USD):				
Productive Investments	915.57	201.94	713.63	0.00
Savings	24.21	17.28	6.93	0.29
Self-consumption	38.32	16.1	22.22	0.00
Payment of Loans	505.79	137.76	368.03	0.00
Land Investments	379.42	16.38	363.03	0.01
Other	66.41	49.71	16.7	0.22
Panel C: Household Income (USD):				
Wage	692.35	378.45	313.91	0.03
Rent	48.3	5.16	43.14	0.02
Subsidies	127.95	55.93	72.01	0.00
Daily Wages	556.4	334.09	222.31	0.00
Commercial	1108.67	406.57	702.1	0.00
Other	118.77	159.67	-40.9	0.84
Observations	441	441		

Notes: These are unconditional before-after comparisons within the 441 FxS beneficiary households with both baseline (2016) and endline surveys. No comparison group is used; these estimates carry no causal interpretation. Variables in Panel A are measured as the share of households, while those in Panels B and C are expressed as the average household income and expenditure, measured in USD as of December 2016. Column 1 shows unconditional means at endline; Column 2 at baseline. Column 3 shows the difference in means (endline minus baseline), and Column 4 shows the p-value for the test of equal means (two-sided t-test with unequal variances).

Table 4 presents the estimated effects of equation 4 on local economic activity and two measures of private investment. Log night light intensity at the grid level (Columns 1 to 2) provides an alternative proxy for GDP[19] in the grid; we find a point estimates ranging between 0.078 and 0.147. Llanes et al. (2024) estimates a robust elasticity of 0.175 by regressing log

[19] Literature has shown that night light intensity can capture changes in economic activity (Henderson et al., 2011).

GDP on log night lights in rural areas of Colombia. Taken together, our results suggest a substantial expansion of GDP ranging from 1.36% to 2.57%.

Columns 3 to 6 of Table 4 show the impact of land titling on the proportion of deforested area within a given grid/year relative to the total forest area in that grid in the year 2000, as well as on built-up areas in the grid, measured by the number of pixels classified as urbanized land cover or infrastructure. We find a small and insignificant negative effect on deforestation in treated grids, but positive and significant effects on built-up areas. Land titling causes the number of pixels predicted as urbanized land cover to increase by 4.8 and 2.8. Converting each 100-square-meter pixel to hectares, this corresponds to 0.048 and 0.028 hectares, representing a 10.5% to 17.9% increase relative to the control group mean. These findings align with changes in access to public services shown in Table A4. Additionally, we provide further evidence supporting the parallel trends assumption (see Figure A4).

Tabla 4

Effects of Land Formalization on Local Economic Activity and Long-Term Investment:

	Dependent variable:					
	Night Lights		**Deforestation**		**Building**	
	(1)	(2)	(3)	(4)	(5)	(6)
FxS	0.147***	0.078**	−0.101	−0.007	4.803**	2.820*
	(0.046)	(0.035)	(0.102)	(0.106)	(1.899)	(1.510)
Mean Dep. Var.	1.133	1.133	0.778	0.778	26.821	26.821
N. Treated	246	246	246	246	246	246
N. Control	526	526	526	526	526	526
T.E. (Prov-Year)		✓		✓		✓
Period	2011-2021	2011-2021	2011-2021	2011-2021	2016-2021	2016-2021
Observations	8,492	8,492	8,492	8,492	4,632	4,632

Notes: *** $p<0.01$; ** $p<0.05$; * $p<0.1$. This table presents the estimation of equation 4, where FxS is a dichotomous variable equal to 1 if the grid contains at least one hectare of landholdings with a delivered land title. Night Lights is measured as the logarithm of the nighttime light intensity in the grid/year. Deforestation is defined as the proportion of deforested area in a given grid/year relative to the total forest area in the grid in the year 2000. Building is defined as the number of 10-meter by 10-meter pixels from Sentinel-2 covered by houses or other human constructions. All regressions incorporate year and grid fixed effects. Standard errors are clustered at grid level.

Finally, we tested if the government deliberately targeted other drug policies in those areas that experienced an improvement in land formalization. We estimated equation 4 for two measures of law enforcement: The number of incidents involving police or military personnel with landmines and unexploded ordnance in the grid/year and the number of hectares of coca crops eradicated in the grid/year. Table A5 presents the results. We find a small and insignificant reduction for three of four estimations of law enforcement. Additionally, in Figure A5 we show that there are also no differential trends between treated and control grid in the periods following land titling.

These findings confirm Prediction 1 of Section 3: land titling lowers τ and generates an immediate switch toward legal cultivation, but the switch is not sustained when $c(\theta)$ remains above the long-run threshold. In the short term, land titling increases household loans and investment in productive activities and land, and titled households achieve higher incomes than those derived from illicit economies. However, these changes do not immediately translate into long-term reductions in illicit crops, because transport costs keep legal returns below the threshold that would make coca permanently uncompetitive.

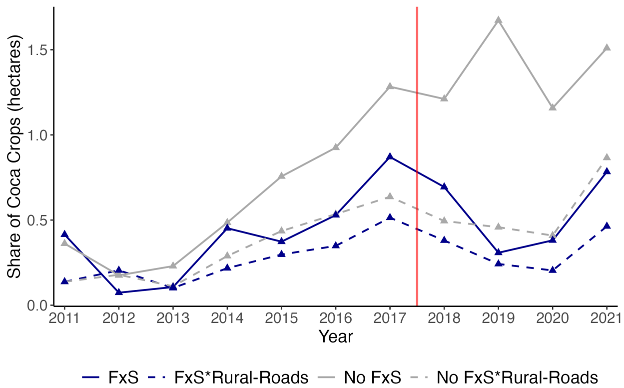
7.2 The role of rural roads in sustainable illicit crop reduction

We take advantage of the detailed granularity of our data to examine the heterogeneous effect of land titling on coca crops, using changes in access to road infrastructure as a proxy for structural transformation. Figure 6 shows the interaction between the *FxS* program and two alternative measures of road infrastructure access. Panel A presents the evolution of illicit crops in grids with access to *Rural Roads* within a 1-kilometer distance, as well as in grids with at least one property titled by *FxS*. Similarly, Panel B shows the evolution of illicit crops in grids exposed to *Placa-Huella*[20] interventions and those treated by the *FxS* program. *Placa-Huella (PH)* interventions are a common initiative for improving tertiary roads in Colombia. Between 2016 and 2020, they were part of a broader set of interventions by the Colombian government aimed at enhancing development conditions in municipalities affected by violence.

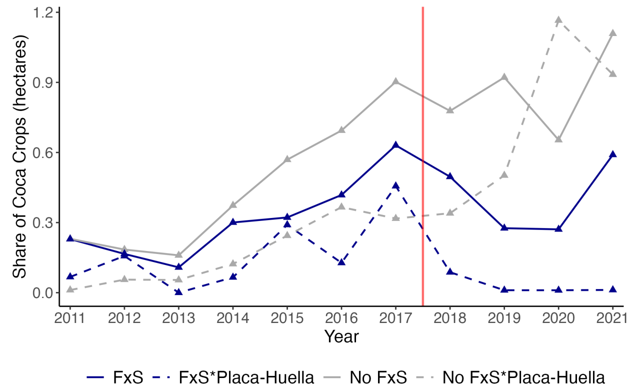
[20]Figure A7 shows an image of a *Placa-Huella (PH)*.

Figure 6

Evolution of coca crops by land formalization and access to rural infrastructure:



(a) Raw data: *FxS* and *Rural-Roads*



(b) Raw data: *FxS* and *Placa-Huella*

Notes: The x-axis represents time in years, and the y-axis represents the hectares of coca cultivation in the grid (equivalently, the share of the 100-ha grid area covered by coca). The red line indicates the year the first *FxS* title was delivered. The blue lines represent grids that received at least one title in 2018, while the gray lines represent neighboring grids that never receive titles. The dashed line represents grids with access to *Rural-Roads* or exposure to a *Placa-Huella* project within a distance of 1 kilometer.

Both panels in Figure 6 show that land titling generates an immediate reduction in the area planted with illicit crops. However, this reduction is only permanent in grids that received at least one hectare of land formalized and were also exposed to *Placa-Huella (PH)*. Consistent with previous literature on rural roads and illicit crops[21], we observe that coca crops increased in grids that received only *Placa-Huella (PH)*—consistent with Prediction 2 in Section 3: when $\tau > 0$, the legal-sector gain from lower $c(\theta)$ is scaled down by the insecurity factor $(1-\tau)$, leaving the relative advantage of coca—which has near-zero transport costs and informal armed-group protection—largely intact. In contrast, we do not observe a differential effect between grids that received land titling and have access to *Rural Roads* and those that only have access to *Rural Roads*. In the rest of this section, we present further evidence on how the effectiveness of property rights depends on the implementation of coherent policies that connect rural areas to market opportunities.

[21] Wigton-Jones (2021) shows that in areas with low institutional capacity, the construction of roads decreased transportation costs and increased the profitability of illicit economies. Moreno et al. (2020) demonstrates that in Colombia, *Placa-Huella* projects led to increased conflict, as armed groups now compete for higher criminal rents derived from illicit activities.

Tabla 5

Effects of Land Formalization and Road Infrastructure on Coca Crop Areas: Triple Difference Estimates

	Share of the grid covered with coca crops:					
	(1)	(2)	(3)	(4)	(5)	(6)
FxS	-0.369^{*}	-0.436^{**}	-0.372^{***}	-0.243^{**}	-0.394^{***}	-0.241^{**}
	(0.198)	(0.200)	(0.106)	(0.098)	(0.105)	(0.097)
FxS∗Rural-Roads	-0.020	0.271				
	(0.191)	(0.193)				
FxS∗Placa-Huella			-0.193^{**}	-0.221^{*}		
			(0.092)	(0.122)		
FxS∗Public-Goods					0.118	-0.143
					(0.261)	(0.268)
Mean Dep. Var.	0.586	0.586	0.586	0.586	0.586	0.586
N. Treated	246	246	246	246	246	246
N. Control	526	526	526	526	526	526
T.E. (Prov-Year)		✓		✓		✓
Period	2011-2021	2011-2021	2011-2021	2011-2021	2011-2021	2011-2021
Observations	8,492	8,492	8,492	8,492	8,492	8,492

Notes: *** p<0.01; ** p<0.05 ; * p<0.1. This table presents the estimation of equation 6, where the dependent variable is the share of the grid covered by coca crops. *Rural-Roads* is a dichotomous variable equal to 1 if the grid has access to any rural road within a distance of 1 kilometer. *Placa-Huella* is a dichotomous variable equal to 1 if the grid has been exposed to a project aimed at improving rural roads within a distance of 1 kilometer. *Public-Goods* is a dichotomous variable equal to 1 if the grid has been exposed to any public goods project within a distance of 1 kilometer. All regressions include year and grid fixed effects. Standard errors are clustered at the grid level. *Doubly-treated sample:* A total of 42 grid-year observations across 13 unique treated grids (5.3% of all 246 FxS grids) have both FxS active and PDET road access simultaneously; this underlies the wide confidence intervals on $\hat{\psi}$ and $\hat{\phi}+\hat{\psi}$. *Linear combination (Columns 3–4):* The total effect of *FxS* in *Placa-Huella* grids is $\hat{\phi}+\hat{\psi}$. Column 3: $\hat{\phi}+\hat{\psi} = -0.565$; exact delta-method 95% CI [-0.750, -0.380] (65%–128% reduction relative to the pre-treatment mean of 0.586). The estimated covariance $\widehat{\mathrm{Cov}}(\hat{\phi},\hat{\psi}) = -0.0054$ is negative, so the exact CI is narrower than the Cov = 0 bound of [-0.840, -0.290]. Column 4: $\hat{\phi}+\hat{\psi} = -0.464$; applying the analogous delta-method correction (the covariance is also negative in this specification) yields 95% CI [-0.700, -0.228] (39%–119% reduction), narrower than the Cov = 0 bound of [-0.771, -0.157]. *Road variable construction: Placa-Huella* is a combined binary indicator equal to 1 if the grid has access to any PDET tertiary road project (including Placa-Huella paving works) within 1 km; the combined variable is used because Placa-Huella projects are nested within the broader PDET road program in the administrative data.

In Table 5, we present the estimates of equation 6 for share of the grid covered with coca crops. Columns 1 and 2 show the results for access to *Rural-Roads*, Columns 3 and 4 for *Placa-Huella* interventions, and Columns 5 and 6 for another set of *Public-Goods* interventions by the Colombian government, different from those aimed at improving tertiary roads. We do find a very small and insignificant effect for *Rural-Roads*, but a significant reduction in coca crops for *Placa-Huella*. The linear combinations $\hat{\phi} + \hat{\psi}$ in Columns 3 and 4 — representing the total effect for grids with both FxS titling and *Placa-Huella* — show a point-estimate reduction of 96% to 79% relative to the pre-treatment mean (exact delta-method 95% CI: [−128%, −65%] and [−119%, −39%] respectively; see Table 5 notes for the full calculation including the covariance term).

The effect is statistically distinguishable from zero in both specifications, but the wide confidence interval reflects the small number of doubly-treated cells: only 42 grid-year observations across 13 unique grids (5.3% of treated grids) have both FxS active and PDET road access simultaneously. The interaction coefficient $\hat{\psi}$ alone captures the road complementarity most precisely: −0.193 to −0.221 percentage points, equivalent to 33–38% of the pre-treatment coca mean (columns 3–4), and statistically significant at the 5% level in both specifications—the empirical counterpart to Prediction 3 of Section 3: the return to lowering $c(\theta)$ is largest when τ has already been eliminated by the title, and the two policies together cross the threshold that neither crosses alone. In contrast, we find an insignificant and inconsistent effect for other public goods interventions. These results suggest that the mechanism is the effective connectivity to local markets, not a general strengthening of state presence through public goods provision.

Next, we examine the heterogeneous effects of land titling on access to credit markets and household expenditures as a function of road infrastructure provision (Table A6). There are differential results by access to road infrastructure: the change estimate for household without access to roads in endline (a 13 percentage point increase in the share of approved credits) is almost identical to the change for household with access to rural roads in endline (a 10 percentage point increase). However, for households with access to highways at endline, there is no significant change in the share of approved credits. In addition, we find that the increase in productive activity investment, as well as land and housing investment, was higher in households with access to rural roads or highways, relative to households without access to roads at the endline.

Table A10 estimates the differential impact of land titling on local economic activity and private investment based on pre-treatment differences in rural road access within the grid. Grids with both land titling and rural road access show significant increases in local economic activity (3.16% expansion of GDP), reduced deforestation (37.78% relative to neighboring grids), and greater built-up land cover (28.09% relative to neighboring grids). However, these effects lose statistical significance when province-by-year trends are added as controls, indicating sensitivity to the specification.

We also find that *Placa-Huella (PH)* produces no detectable differential effect on local economic activity or private investment (Table A11). This null result is worth noting directly: if FxS + Placa-Huella (PH) reduces coca by a large margin, as Table 5 suggests, the labor and land released from coca cultivation should eventually show up in legal economic activity. The absence of a detectable effect in night lights or built-up area for doubly-treated grids is most plausibly explained by the short panel: the sample ends in 2021, and the *Placa-Huella (PH)* interventions began in 2018–2020, leaving few post-treatment periods for economic effects to materialize. It may also reflect the scale of the *Placa-Huella (PH)*: a tertiary road improvement connects the farm to the municipal center, but does not by itself attract commercial investment large enough to be visible in nighttime lights at the 1 km grid level. We interpret this null as a limitation of our measurement horizon rather than as evidence that the economic transition has not begun. Additionally, we find no evidence that law enforcement was systematically redirected toward titled grids (Tables A12 and A13).

In sum, road infrastructure determines whether the effect of property rights on coca is durable. Sustained reduction requires the combination: *Placa-Huella* alone raises coca cultivation, while titling alone generates only a short-run reduction. Grids with both titling and rural roads show higher economic activity, less deforestation, and greater urban expansion—though these effects lose precision across specifications, which we interpret as evidence of heterogeneity in how quickly the complementarity takes effect.

8 Conclusions

Land titling reduces coca immediately. Grids with at least one titled plot under the FxS program saw a 42–64% reduction in coca area relative to neighboring non-participating grids. The effect is accompanied by measurable changes in household behavior: higher credit demand, greater investment in productive activities, and incomes that, at endline, exceed what coca farming generates. The evidence is consistent with Prediction 1 of Section 3: property rights lower τ and generate an immediate switch toward legal cultivation through the investment and income channels the model predicts.

But the effect does not last. Within two years, the gap between titled and control grids narrows to statistical insignificance. This is not an anomaly specific to FxS. It reflects a constraint that land titling alone cannot relax: without roads connecting farmers to output markets, the formal sector offers no practical alternative to coca. The *mochila* problem persists. An additional sustained reduction of 33–38% in coca cultivation (relative to the pre-treatment mean, from the FxS×*Placa-Huella (PH)* coefficient $\hat{\psi}$ in Table 5) is observed where titling is paired with tertiary road construction under the *Placa-Huella (PH)* program. Roads built without titling, by contrast, are associated with more coca in the raw data—consistent with Prediction 2, which shows that insecure tenure blunts the legal-sector gain from better connectivity, and with prior evidence that connectivity without institutional preconditions benefits illegal as much as legal economic activity (Wigton-Jones, 2021; Moreno et al., 2020; Müller-Crepon et al., 2021).

The policy implication is direct. Land formalization and market access are complements, not substitutes. Coverage overlap matters: road investments deployed without the institutional precondition of secure tenure are associated with more coca cultivation, while road investments implemented alongside titling are associated with less. The data cannot speak directly to sequencing—FxS and *Placa-Huella (PH)* were implemented contemporaneously in the municipalities studied here—but the complementarity result implies that coordinated coverage is the key design requirement. Programs that treat these two interventions as independent levers, or that roll out roads in untitled areas without a parallel formalization component, are likely to capture neither effect and may accelerate illicit crop expansion. Prediction 3 of Section 3 formalizes why: the two policies are strategic complements, and the marginal benefit of each is increasing in the level of the other. The evidence here suggests the binding constraint shifts over time: in the short run, insecure property rights suppress legal investment; in the medium run, high transport costs prevent the market from rewarding it.

These conclusions carry scope conditions. The FxS sample is drawn from municipalities in which FARC had recently demobilized and where the Colombian state could administer a titling program at scale. In active conflict zones—where armed groups retain territorial control and extract rents from coca production—neither land titles nor roads can be credibly delivered or maintained through administrative action. The transition documented here was enabled by a particular institutional window opened by the 2016 peace agreement. Whether similar windows exist elsewhere, and how to open them, is a question this paper cannot answer. What it does establish is that, given such a window, the combination of property rights and market connectivity can generate a durable reduction in illicit crop cultivation that neither policy achieves on its own.

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Data availability

The data and replication code for all results reported in this paper are deposited at https://doi.org/10.5281/zenodo.20559381. The SIMCI illicit crops data are produced by UNODC-Colombia and available upon request through the UNODC monitoring system. The ANT land titling records are administrative data from the Colombian National Land Agency available upon request. All other data sources (Suomi-NPP night lights, Sentinel-2, SECOP, PDET, Global Forest Change) are publicly available; sources are cited in Section 4.

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Online Appendix

A.1 Appendix Figures and Tables

Tabla A1

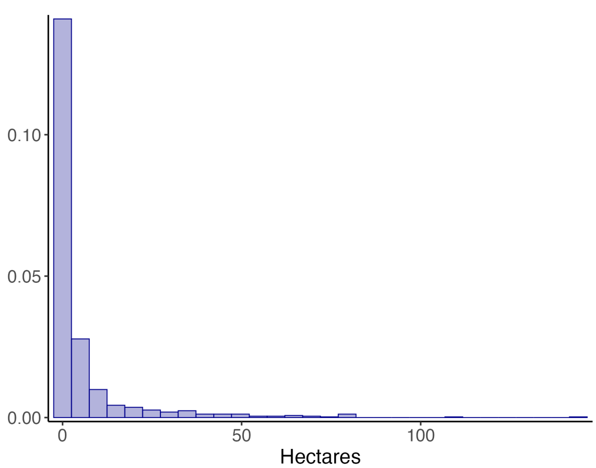
Share of Illicit Crops with Road Access in Colombia:

Year	Coca Crops (Ha.)	Urban Roads	Trunk Roads	Rural Roads	Bridleways	Unclassified
2016	146,479.2	10.76%	2.23%	35.42%	14.98%	10.37%
2017	171,750.0	10.36%	2.27%	35.87%	16.14%	9.36%
2018	169,258.1	10.28%	1.88%	36%	17.46%	9.3%
2019	154,769.6	11.68%	1.48%	36.99%	18.79%	9.19%
2020	143,067.6	11.37%	1.39%	37.31%	19.71%	8.58%
2021	204,628.8	10.95%	1.98%	34.03%	17.35%	8.91%

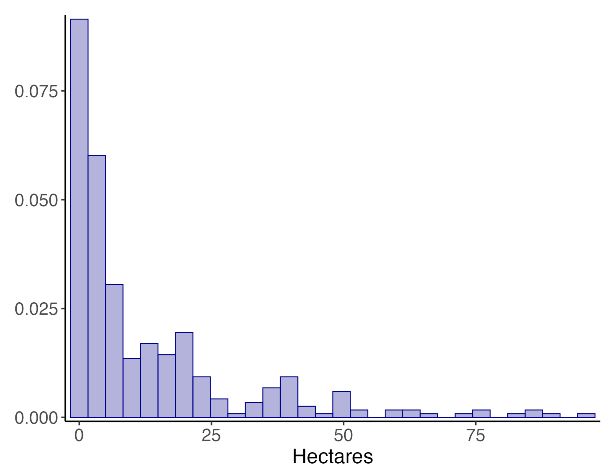
Notes: The column *Coca Crops (ha.)* represents the number of hectares of coca crops cultivated in Colombia, as measured using the geolocation of coca plots provided by the SIMCI dataset. The columns *Urban Roads*, *Trunk Roads*, *Rural Roads*, and *Bridleways* indicate the share of coca plots with access to any road within a distance of 1 kilometer. Roads are classified based on the definitions provided by *OpenStreetMap*. The geolocation of roads is sourced from geographic datasets provided by *OpenStreetMap* and the *National Geostatistical Framework* (MGN, by its acronym in Spanish) from the National Administrative Department of Statistics (DANE) of Colombia.

Figure A1

Distribution of the size of titled land plot



(a) Size of titled land plot



(b) Share of titled land in UNODC grid

Notes: In Panel **(a)**, we shows the sizes of individual land plots that have been formally titled as part of the *FxS* titling program. In Panel **(b)**, we show the distribution of the share of titled land within 1 km x 1 km grids used in the analysis.

Tabla A2

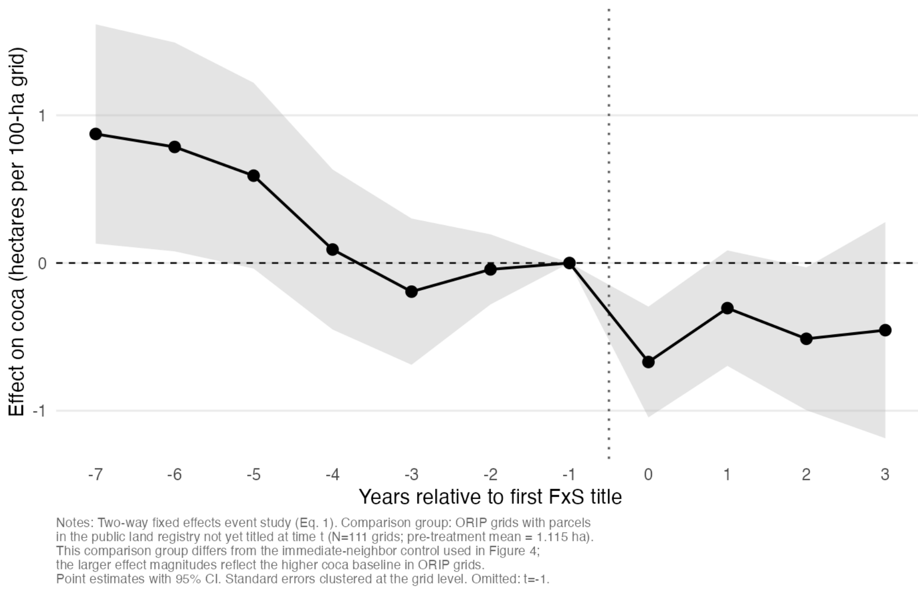
Effect of Land Formalization on Coca Crop Areas: Callaway–Sant'Anna (2021) Estimator

	Share of the grid covered with coca crops:			
	Extensive Margin		Intensive Margin	
	(1)	(2)	(3)	(4)
FxS	-0.850^{***}	-0.605^{**}	-0.011^{***}	-0.006^{**}
	(0.296)	(0.281)	(0.004)	(0.003)
Mean Dep. Var.	1.115	1.115	1.115	1.115
N. Treated	246	246	246	246
N. Control	111	111	111	111
T.E. (Prov-Year)		✓		✓
Period	2011-2021	2011-2021	2011-2021	2011-2021
Observations	3,927	3,927	3,927	3,927

Notes: *** p<0.01; ** p<0.05 ; * p<0.1. The dependent variable is expressed as the share of the grid covered with coca crops. Estimates use the Callaway and Sant'Anna (2021) heterogeneity-robust group-time average treatment effects, aggregated to an overall ATT. The comparison group consists of ORIP grids — grids with land parcels in the public registry that had not yet been titled at time t ("not-yet-treated" control group). This comparison group differs from the immediate-neighbor control used in Table 2: the ORIP not-yet-treated grids have a pre-treatment coca mean of 1.115 ha (versus 0.586 ha for the neighbor control), which accounts for the larger magnitude of these estimates relative to the TWFE. Columns 1 and 2 show the extensive margin (FxS binary); Columns 3 and 4 show the intensive margin (share of titled area in grid). All regressions include year and grid fixed effects. Standard errors are clustered at the grid level.

Figure A2

Event Study: TWFE with ORIP Not-Yet-Treated Control Group



Notes: Two-way fixed effects event study (Equation **??**). The comparison group consists of ORIP grids — grids with parcels in the public land registry that had not yet received a title at time t (111 grids; pre-treatment mean coca = 1.115 ha). This group differs from the immediate-neighbor control used in Figure **??**: ORIP grids have a higher baseline coca level, which accounts for the larger effect magnitudes. Coefficients at $t = -7$ and $t = -6$ reflect a pre-existing level difference between FxS and ORIP grids that had largely converged by $t = -4$; the three periods immediately preceding treatment ($t = -4$, -3, -2) are near zero. Point estimates with 95% confidence intervals. Standard errors clustered at the grid level. Omitted period: $t = -1$.

Tabla A3

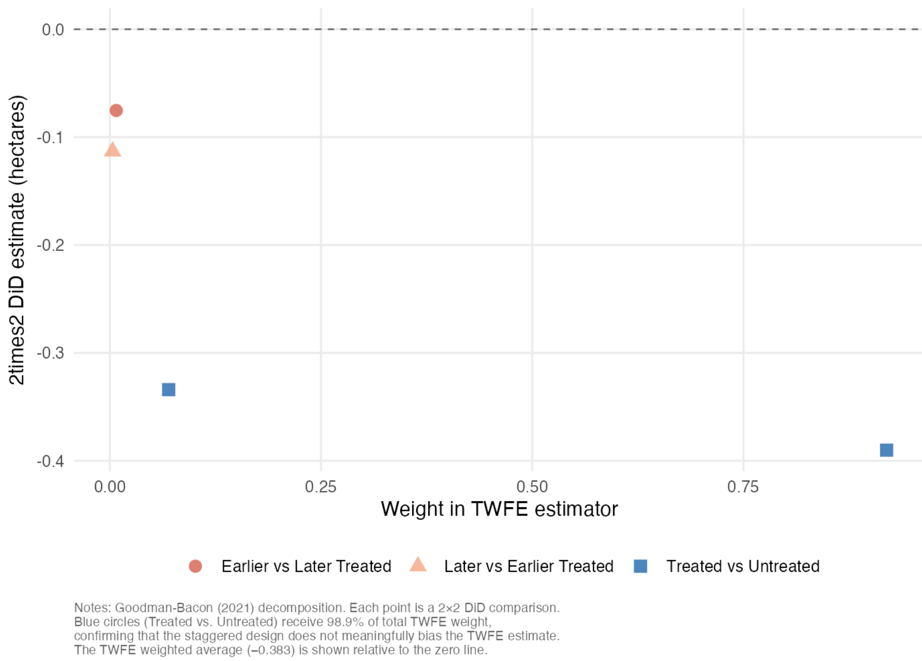
Goodman-Bacon (2021) Decomposition of TWFE Estimate

Comparison type	N pairs	Weight	Weighted estimate
Treated vs. Never-treated	2	0.989	−0.386
Earlier-treated vs. Later-treated	1	0.008	−0.075
Later-treated vs. Earlier-treated	1	0.003	−0.113
TWFE weighted average			−0.383

Notes: Goodman-Bacon (2021) decomposition of the TWFE estimate from Equation 4. The TWFE estimator is a weighted average of all 2×2 DiD comparisons in the data. "Treated vs. Never-treated" comparisons (weight = 98.9%) use the 526 never-treated neighboring control grids as the counterfactual. "Earlier-treated vs. Later-treated" (weight = 0.8%) and "Later-treated vs. Earlier-treated" (weight = 0.3%) comparisons use within-cohort variation, where earlier-treated grids (2018 cohort, $n = 15$) serve as controls for later-treated grids (2019 cohort, $n = 231$) and vice versa. The negligible weight on contaminated comparisons (1.1% total) confirms that staggered treatment timing does not meaningfully bias the TWFE estimate. The weighted average (−0.383) matches the TWFE coefficient in Column 1 of Table 2.

Figure A3

Goodman–Bacon Decomposition: 2×2 DiD Weights



Notes: Visual representation of the Goodman-Bacon (2021) decomposition. Each point is a 2×2 DiD comparison. Blue circles ("Treated vs. Untreated", 2 pairs) receive 98.9% of total TWFE weight. Red triangles ("Earlier vs. Later Treated") and orange squares ("Later vs. Earlier Treated") together account for the remaining 1.1%. The dominance of clean comparisons confirms that staggered timing does not materially bias the TWFE estimate.

Tabla A4

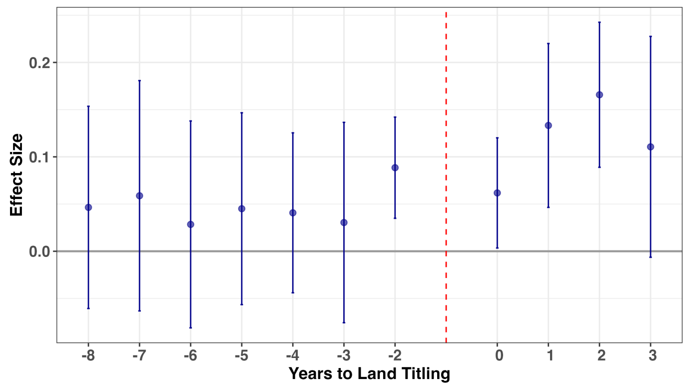
Changes in Household Access to Public Services:

	Endline	**Baseline**	**Difference of shares**	**p-value on difference**
Electricity	0.92	0.85	0.07	0.00
Internet	0.24	0.15	0.09	0.00
Water storage	0.74	0.46	0.28	0.00
Sanitation services	0.26	0.19	0.07	0.01
Sewage access	0.27	0.15	0.12	0.00
Natural gas access	0.53	0.38	0.15	0.00
Observations	441	441		

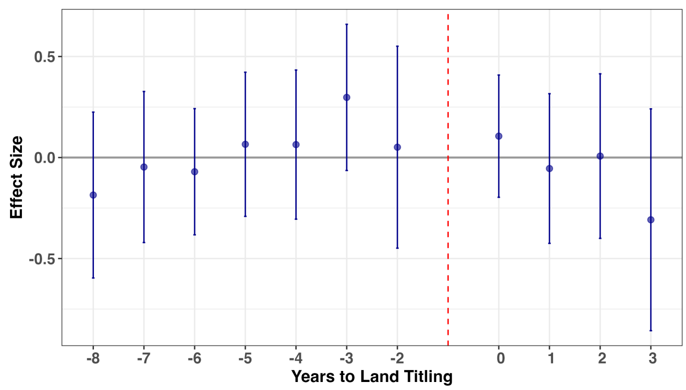
The table presents the share values for household access to public services, measured in the baseline and endline periods. Columns 1–2 show the unconditional share for all households at baseline and endline, respectively. Column 4 shows the difference in share across columns 2 and 3, and column 5 shows the p-value for the difference in shares.

Figure A4

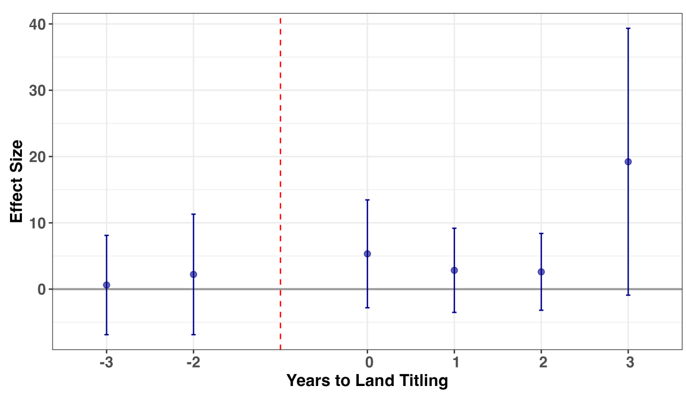
Dynamic Effect on Local Economic Activity and Private Investment:



A. Night Light Intensity



B. Deforestation



C. Building

Notes: Point estimates with 95% confidence intervals. The dependent variable is the logarithm of hectares under coca cultivation. Regressions include year and grid fixed effects. Standard errors are clustered at the grid level.

Tabla A5

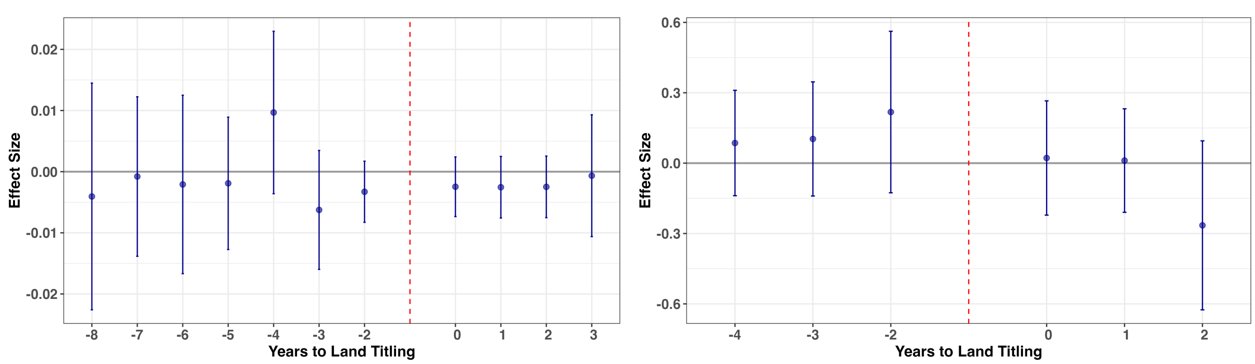
Effect of Land Formalization on Law Enforcement:

	Dependent variable:			
	Victims of Landmines		**Erradication**	
	(1)	(2)	(3)	(4)
FxS	−0.003	−0.001	−0.140**	−0.087
	(0.002)	(0.002)	(0.063)	(0.062)
Mean Dep. Var.	0.003	0.003	0.145	0.145
N. Treated	246	246	246	246
N. Control	526	526	526	526
T.E. (Prov-Year)		✓		✓
Period	2011-2021	2011-2021	2015-2020	2015-2020
Observations	8,492	8,492	4,632	4,632

Notes: *** p<0.01; ** p<0.05 ; * p<0.1. This table presents the estimation of equation 4, where FxS is a dichotomous variable equal to 1 if the grid contains at least one hectare of landholdings with a delivered land title. Victims of Landmines is the logarithm of the number of incidents involving law enforcement personnel with landmines and unexploded ordnance in the grid/year. Eradication is the number of hectares of coca crops eradicated in the grid/year. All regressions incorporate year and grid fixed effects. Standard errors are clustered at grid level.

Figure A5

Dynamic Effect on Law Enforcement:



A. Victims of Landmines　　**B.** Erradication

Notes: Point estimates with 95% confidence intervals. Regressions incorporate year and grid-fixed effects. Standard errors are clustered at the grid level.

Tabla A6

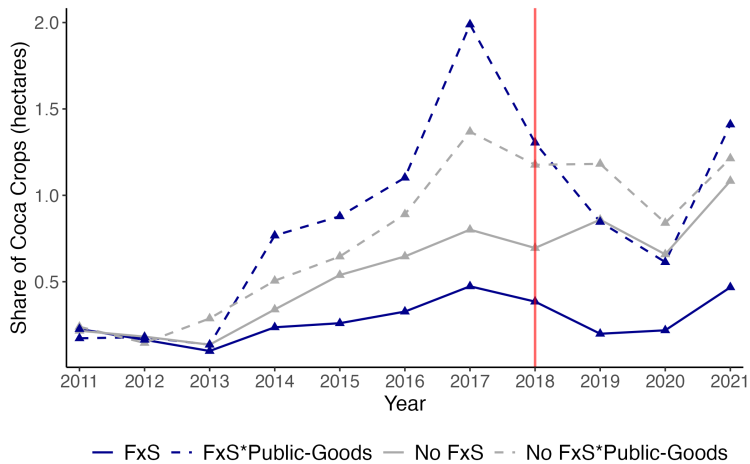
Changes in Household Access to Credit Markets, Expenditure, and Income by Road Infrastructure Access:

	No Roads				**Rural Roads**				**Highways**			
	Baseline	Endline	Difference of means	p-value on difference	Baseline	Endline	Difference of means	p-value on difference	Baseline	Endline	Difference of means	p-value on difference
Panel A: Household with Requested or Approved Credits (Share):												
Requested Credits	0.08	0.25	0.17	0.01	0.13	0.24	0.11	0.00	0.2	0.22	0.03	0.26
Approved Credits	0.08	0.22	0.13	0.02	0.12	0.22	0.1	0.00	0.19	0.2	0.02	0.35
Panel B: Household Expenditure (USD):												
Productive Investments	173.93	543.4	369.47	0.02	293.95	1099.49	805.54	0.00	117.99	834.93	716.93	0.01
Savings	52.64	0	-52.64	0.93	15.88	39.1	23.22	0.16	7.3	16.88	9.59	0.20
Self-consumption	11.12	36.57	25.45	0.02	22.62	49.18	26.56	0.03	11.13	27.76	16.63	0.03
Payment of Loans	93.87	176.8	82.93	0.04	84.93	470.96	386.02	0.00	205.31	639.99	434.68	0.00
Land Investments	0	21.73	21.73	0.08	27.29	289.64	262.35	0.04	10.64	577.76	567.12	0.05
Other	25.17	12.59	-12.58	0.86	42.72	60.32	17.59	0.20	64.68	89.27	24.59	0.30
Panel C: Household Income (USD):												
Wage	290.87	105.95	-184.92	0.90	218.58	560.58	341.99	0.05	568.27	999.98	431.7	0.07
Rent	0	13.58	13.58	0.12	11.92	17.61	5.68	0.31	0	89.45	89.45	0.03
Subsidies	131.36	110.87	-20.5	0.71	51.95	123.23	71.28	0.01	35.62	137.79	102.18	0.00
Daily Wages	632.22	675.03	42.8	0.39	225.52	518.5	292.97	0.00	347.58	558.6	211.02	0.01
Commercial	272.01	814.9	542.89	0.02	457.56	1208.45	750.89	0.00	398.48	1092.7	694.22	0.00
Other	151.21	53.53	-97.68	0.93	169.8	140.2	-29.6	0.68	152.17	117.24	-34.93	0.70
Observations	61	61			191	191			189	189		

Notes:The table presents the mean values for household characteristics, measured in the baseline and endline periods for three groups of households. The *No Roads* group includes households that reported having no access to any road infrastructure at the endline. The *Rural Roads* group includes households that reported having access to rural road infrastructure at the endline. The *Highways* group includes households that reported having access to trunk roads and highways at the endline. Variables in Panel A are measured as the share of households, while those in Panels B and C are expressed as the average household income and expenditure, measured in USD as of December 2016. The *baseline* and *endline* columns show the unconditional means for all households in 2016 and 2018, respectively. The *Difference of means* column shows the difference in means between the baseline and endline, while the *p-value on difference* column reports the p-value for this difference.

Figure A6

Evolution of coca crops by land formalization and access to public goods:



Notes: The x-axis represents time in years, and the y-axis represents the share of hectares of coca crops cultivated in the grid. The red line indicates the year the first *FxS* title was delivered. The blue lines represent grids that received at least one title in 2018, while the gray lines represent neighboring grids that did not receive titles that year. The dashed line represents grids exposure to a *Public-Goods* project within a distance of 1 kilometer.

Tabla A7

Main result under Conley (1999) spatial standard errors

Dependent Variable:	crops						
	Cluster	1 km	5 km	10 km	Cluster+PY	1km+PY	5km+PY
Model:	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Variables							
treated	-0.3829***	-0.3829***	-0.3829**	-0.3829*	-0.2541***	-0.2541***	-0.2541**
	(0.1031)	(0.0977)	(0.1822)	(0.2158)	(0.0955)	(0.0945)	(0.1183)
Fixed-effects							
id_grid	Yes	Yes	Yes	Yes	Yes	Yes	Yes
year	Yes	Yes	Yes	Yes	Yes	Yes	Yes
provincia_year					Yes	Yes	Yes
Fit statistics							
Observations	8,492	8,492	8,492	8,492	8,492	8,492	8,492
R^2	0.55191	0.55191	0.55191	0.55191	0.58427	0.58427	0.58427
Within R^2	0.00409	0.00409	0.00409	0.00409	0.00184	0.00184	0.00184

Signif. Codes: ***: 0.01, **: 0.05, *: 0.1

Notes: Each column reports the FxS coefficient from Equation 4 under a different variance estimator. Columns (1) and (5) replicate the baseline clustered SE from Table 2. Columns (2)–(4) and (6)–(8) use Conley (1999) spatial heteroskedasticity-and-autocorrelation-consistent standard errors at 1 km, 5 km, and 10 km cutoffs, respectively; centroids are extracted from the regression shapefile. Columns (5)–(8) add province×year fixed effects. The 5 km cutoff (covering five rings of the 1 km grid) is the benchmark spatial robustness check; the 10 km cutoff is reported as a conservative bound and likely overcorrects. Significance: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

Tabla A8

Donut test: second-ring neighbor control group

Dependent Variable:	crops			
	Ring1 (baseline)	Ring1 + Prov×Year	Ring2 (donut)	Ring2 + Prov×Year
Model:	(1)	(2)	(3)	(4)
Variables				
treated	-0.3829***	-0.2541***	-0.5269***	-0.3356***
	(0.1031)	(0.0955)	(0.1002)	(0.0944)
Fixed-effects				
id_grid	Yes	Yes	Yes	Yes
year	Yes	Yes	Yes	Yes
provincia_year		Yes		Yes
Fit statistics				
Observations	8,492	8,492	14,839	14,839
R^2	0.55191	0.58427	0.55033	0.58629
Within R^2	0.00409	0.00184	0.00317	0.00130

Clustered (id_grid) standard-errors in parentheses
Signif. Codes: ***: 0.01, **: 0.05, *: 0.1

Ring1 = immediate neighbors (sample_control_1 == 1). Ring2 = second-ring neighbors (d_grid_nb_2 == 1): grids adjacent to Ring1 but not adjacent to treated grids. If the FxS coefficient in Columns (3)–(4) is similar to Columns (1)–(2), coca displacement to Ring1 is not driving the result. Standard errors clustered at the grid level. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

Notes: Donut test for SUTVA: coca displacement from treated grids to first-ring control grids. Columns (1)–(2) replicate the baseline specification (Ring 1 = 526 immediate-neighbor control grids). Columns (3)–(4) replace the control group with 1,103 second-ring neighbor grids (`d_grid_nb_2` = 1): grids adjacent to Ring 1 but not adjacent to treated grids. Displacement would reduce the Ring 2 coefficient toward zero; the larger Ring 2 estimate (-0.527 vs. -0.383) is inconsistent with systematic displacement and suggests the baseline estimate is conservative. All specifications include grid and year fixed effects; even columns add province×year fixed effects. Standard errors clustered at the grid level. Significance: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

Tabla A9

Leave-one-out robustness: FxS $\times$ Placa-Huella interaction coefficient

Grid	Estimate	SE	p_value	Signif
286002.00	-0.21	0.09	0.03	**
286003.00	-0.20	0.09	0.04	**
287032.00	-0.18	0.09	0.06	*
288060.00	-0.19	0.09	0.04	**
289091.00	-0.18	0.09	0.05	*
290119.00	-0.20	0.09	0.03	**
466400.00	-0.20	0.09	0.04	**
467501.00	-0.14	0.08	0.07	*
471884.00	-0.20	0.09	0.03	**
471885.00	-0.19	0.09	0.05	**
471886.00	-0.20	0.09	0.03	**
472985.00	-0.20	0.09	0.03	**
472986.00	-0.20	0.09	0.03	**

Notes: Leave-one-out robustness for the FxS $\times$ Placa-Huella interaction coefficient $\hat{\psi}$. Each row reports the estimate obtained by dropping one doubly-treated grid (grids with both an active FxS title and a Placa-Huella project) from the full sample and re-estimating Equation 6 on the remaining $772 - 1$ treated/control grids. Grid IDs are UNODC numeric identifiers. Baseline $\hat{\psi} = -0.193$ (SE = 0.092, $p = 0.036$) using the full sample of 13 doubly-treated grids. 10 of 13 leave-one-out estimates are significant at the 5% level; the mean is -0.193 (SD = 0.017), confirming that no single grid drives the interaction result. Standard errors clustered at the grid level. Significance: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

Tabla A10

Effects of Land Formalization and Rural Roads on Local Economic Activity and Long-Term Investment:

	Dependent variable:					
	Night Lights		**Deforestation**		**Building**	
	(1)	(2)	(3)	(4)	(5)	(6)
FxS	0.019	0.117^{**}	0.106	0.052	-0.463	0.627
	(0.063)	(0.051)	(0.161)	(0.165)	(1.784)	(1.990)
FxS∗Rural-Roads	0.182^{**}	-0.058	-0.294^{*}	-0.088	7.536^{***}	3.286
	(0.076)	(0.063)	(0.168)	(0.190)	(2.088)	(2.255)
Mean Dep. Var.	1.133	1.133	0.778	0.778	26.821	26.821
N. Treated	246	246	246	246	246	246
N. Control	526	526	526	526	526	526
T.E. (Prov-Year)		✓		✓		✓
Period	2011-2021	2011-2021	2011-2021	2011-2021	2016-2021	2016-2021
Observations	8,492	8,492	8,492	8,492	4,632	4,632

Notes: *** p<0.01; ** p<0.05 ; * p<0.1. This table presents the estimation of equation 6, where *Placa-Huella* is a dichotomous variable equal to 1 if the grid has been exposed to a project aimed at improving rural roads within a distance of 1 kilometer. Night Lights is measured as the logarithm of the nighttime light intensity in the grid/year. Deforestation is defined as the proportion of deforested area in a given grid/year relative to the total forest area in the grid in the year 2000. Building is defined as the number of 10-meter by 10-meter pixels from Sentinel-2 covered by houses or other human constructions. All regressions incorporate year and grid fixed effects. Standard errors are clustered at grid level.

Tabla A11

Effects of Land Formalization and Placa Huella on Local Economic Activity and Long-Term Investment:

	Dependent variable:					
	Night Lights		**Deforestation**		**Building**	
	(1)	(2)	(3)	(4)	(5)	(6)
FxS	0.132***	0.080**	−0.128	−0.023	4.830**	2.984*
	(0.046)	(0.035)	(0.102)	(0.105)	(1.944)	(1.573)
FxS∗Placa-Huella	0.257	−0.058	0.481	0.315	−0.509	−3.478
	(0.219)	(0.114)	(0.472)	(0.456)	(3.364)	(4.067)
Mean Dep. Var.	1.133	1.133	0.778	0.778	26.821	26.821
N. Treated	246	246	246	246	246	246
N. Control	526	526	526	526	526	526
T.E. (Prov-Year)		✓		✓		✓
Period	2011-2021	2011-2021	2011-2021	2011-2021	2016-2021	2016-2021
Observations	8,492	8,492	8,492	8,492	4,632	4,632

Notes: *** p<0.01; ** p<0.05 ; * p<0.1. This table presents the estimation of equation 6, where *Placa-Huella* is a dichotomous variable equal to 1 if the grid has been exposed to a project aimed at improving rural roads within a distance of 1 kilometer. Night Lights is measured as the logarithm of the nighttime light intensity in the grid/year. Deforestation is defined as the proportion of deforested area in a given grid/year relative to the total forest area in the grid in the year 2000. Building is defined as the number of 10-meter by 10-meter pixels from Sentinel-2 covered by houses or other human constructions. All regressions incorporate year and grid fixed effects. Standard errors are clustered at grid level.

Tabla A12

Effects of Land Formalization and Rural Roads on Law Enforcement:

	Dependent variable:			
	Victims of Landmines		**Erradication**	
	(1)	(2)	(3)	(4)
FxS	0.001	0.003	−0.051	−0.071
	(0.002)	(0.002)	(0.126)	(0.123)
FxS∗Rural-Roads	−0.006*	−0.006	−0.126	−0.024
	(0.003)	(0.004)	(0.134)	(0.125)
Mean Dep. Var.	0.003	0.003	0.145	0.145
N. Treated	246	246	246	246
N. Control	526	526	526	526
T.E. (Prov-Year)		✓		✓
Period	2011-2021	2011-2021	2015-2020	2015-2020
Observations	8,492	8,492	4,632	4,632

Notes: *** $p<0.01$; ** $p<0.05$; * $p<0.1$. This table presents the estimation of equation 6, where *Rural-Roads* is a dichotomous variable equal to 1 if the grid has been exposed to a project aimed at improving rural roads within a distance of 1 kilometer. Victims of Landmines is the logarithm of the number of incidents involving law enforcement personnel with landmines and unexploded ordnance in the grid/year. Eradication is the number of hectares of coca crops eradicated in the grid/year. All regressions incorporate year and grid fixed effects. Standard errors are clustered at grid level.

Tabla A13

Effect of Land Formalization and Placa Huella on Law Enforcement:

	Dependent variable:			
	Victims of Landmines		**Erradication**	
	(1)	(2)	(3)	(4)
FxS	-0.003	-0.002	-0.133^{**}	-0.087
	(0.002)	(0.002)	(0.065)	(0.065)
FxS$*$Placa-Huella	0.002	0.005	-0.124	-0.003
	(0.007)	(0.006)	(0.155)	(0.141)
Mean Dep. Var.	0.003	0.003	0.145	0.145
N. Treated	246	246	246	246
N. Control	526	526	526	526
T.E. (Prov-Year)		✓		✓
Period	2011-2021	2011-2021	2015-2020	2015-2020
Observations	8,492	8,492	4,632	4,632

Notes: *** p<0.01; ** p<0.05 ; * p<0.1. This table presents the estimation of equation 6, where *Rural-Roads* is a dichotomous variable equal to 1 if the grid has access to any rural road within a distance of 1 kilometer. Victims of Landmines is the logarithm of the number of incidents involving law enforcement personnel with landmines and unexploded ordnance in the grid/year. Eradication is the number of hectares of coca crops eradicated in the grid/year. All regressions incorporate year and grid fixed effects. Standard errors are clustered at grid level.

Tabla A14

Effects of Land Formalization and Public Goods on Local Economic Activity and Long-Term Investment:

	Dependent variable:					
	Night Lights		**Deforestation**		**Building**	
	(1)	(2)	(3)	(4)	(5)	(6)
FxS	0.171***	0.087**	−0.122	−0.024	3.418*	1.826
	(0.048)	(0.036)	(0.105)	(0.111)	(1.849)	(1.511)
FxS∗Public-Goods	−0.254***	−0.095	0.219	0.175	14.190*	10.388
	(0.095)	(0.081)	(0.216)	(0.194)	(7.471)	(7.068)
Mean Dep. Var.	1.133	1.133	0.778	0.778	26.821	26.821
N. Treated	246	246	246	246	246	246
N. Control	526	526	526	526	526	526
T.E. (Prov-Year)		✓		✓		✓
Period	2011-2021	2011-2021	2011-2021	2011-2021	2016-2021	2016-2021
Observations	8,492	8,492	8,492	8,492	4,632	4,632

Notes: *** p<0.01; ** p<0.05 ; * p<0.1. This table presents the estimation of equation 6, where *Public-Goods* is a dichotomous variable equal to 1 if the grid has been exposed to any public goods Project within a distance of 1 kilometer. Night Lights is measured as the logarithm of the nighttime light intensity in the grid/year. Deforestation is defined as the proportion of deforested area in a given grid/year relative to the total forest area in the grid in the year 2000. Building is defined as the number of 10-meter by 10-meter pixels from Sentinel-2 covered by houses or other human constructions. All regressions incorporate year and grid fixed effects. Standard errors are clustered at grid level.

Tabla A15

Effects of Land Formalization and Public Goods on Law Enforcement:

	Dependent variable:			
	Victims of Landmines		**Erradication**	
	(1)	(2)	(3)	(4)
FxS	−0.004	−0.002	−0.100*	−0.057
	(0.002)	(0.002)	(0.059)	(0.062)
FxS∗Public-Goods	0.005	0.002	−0.410	−0.318
	(0.004)	(0.004)	(0.300)	(0.287)
Mean Dep. Var.	0.003	0.003	0.145	0.145
N. Treated	246	246	246	246
N. Control	526	526	526	526
T.E. (Prov-Year)		✓		✓
Period	2011-2021	2011-2021	2015-2020	2015-2020
Observations	8,492	8,492	4,632	4,632

Notes: *** p<0.01; ** p<0.05 ; * p<0.1. This table presents the estimation of equation 6, where *Public-Goods* is a dichotomous variable equal to 1 if the grid has been exposed to any public goods Project within a distance of 1 kilometer. Victims of Landmines is the logarithm of the number of incidents involving law enforcement personnel with landmines and unexploded ordnance in the grid/year. Eradication is the number of hectares of coca crops eradicated in the grid/year. All regressions incorporate year and grid fixed effects. Standard errors are clustered at grid level.

Figure A7

Placa-Huella en Colombia

Source: Agencia de Renovación del Territorio.

Theoretical Appendix: Two-Period Extension for the Fade-Out (Prediction 1)

The main model in Section 3 is static. To formalize the fade-out in Prediction 1, we extend it to two periods, $t \in \{1, 2\}$, with the same agents and payoff structure.

Setup. At the start of period 1, FxS delivers a land title, reducing the expropriation risk from τ to $\tau' < \tau$. Road quality remains fixed at θ in both periods; Placa-Huella is not implemented in this extension, so $c(\theta)$ is unchanged. The farmer solves a static optimization in each period.

Period 1. With security improved to τ', the optimal legal investment satisfies

$$f'(k_1^*) = \frac{r}{\big(P_L - c(\theta)\big)(1 - \tau')}. \tag{7}$$

The farmer switches to legal cultivation if and only if $\Pi_L(\tau', \theta, k_1^*) > \Pi_C$, i.e., the updated pair $(\tau', c(\theta))$ lies below the threshold curve in $(\tau, c(\theta))$ space implicitly defined by $\Pi_L = \Pi_C$.

Period 2. No further policy change occurs. The farm-gate price for legal crops remains $P_L - c(\theta)$, still depressed by high transport costs. Since the period-2 optimization problem is identical to period 1 given the same $(\tau', c(\theta))$, the farmer's choice in period 2 equals his choice in period 1: the legal-cultivation equilibrium is stationary conditional on $(\tau', c(\theta))$.

Fade-out condition. A farmer who switched to legal cultivation at $t = 1$ reverts to coca at $t = 2$ if and only if $c(\theta)$ is large enough that even the now-titled legal sector cannot compete with coca:

$$\max_k \big(P_L - c(\theta)\big) \cdot f(k) - r\,k \;<\; P_C \cdot f_0. \tag{8}$$

This condition is independent of τ': once the initial security gain is absorbed into k_1^*, high transport costs prevent the legal sector from generating a return that competes with Π_C. The farmer therefore returns to coca within one period of the title delivery, which is the formal content of Prediction 1.

Comparative static. Condition (8) is relaxed (the legal sector becomes viable) when $c(\theta)$ falls. If Placa-Huella is added—lowering $c(\theta)$ to $c(\theta')$—the threshold may be crossed in period 2 even if it was not crossed at $t = 1$ by the title alone. This is the formal basis for the complementarity in Prediction 3: the marginal benefit of reducing $c(\theta)$ is largest when τ has already been eliminated by the title, because the legal-sector gain is fully appropriable when $\tau' = 0$.

Empirical mapping. The fade-out is identified in Figure 4b: the event-study coefficient is negative and significant at $t = 0$ and $t + 1$, then decays toward statistical insignificance by $t + 2$. In the two-period model, this pattern corresponds to the initial title clearing the threshold at $t = 1$ but $c(\theta)$ remaining too high for the switch to persist at $t = 2$. Grids that also received Placa-Huella avoid the fade-out (Table 5), consistent with the complementarity.

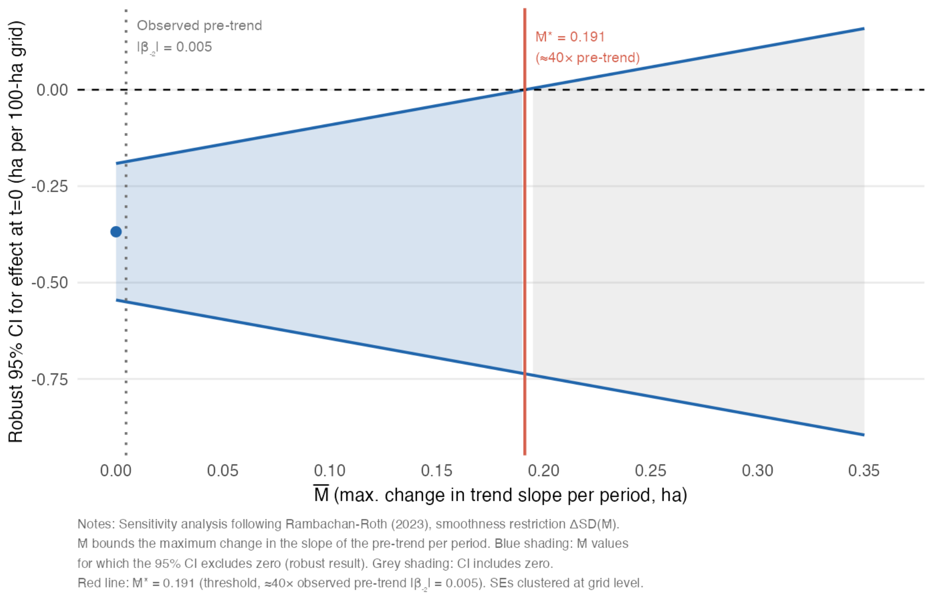
Sensitivity Analysis: Violations of Parallel Trends (Rambachan–Roth 2023)

Following Rambachan and Roth (2023), we assess the sensitivity of the main result to violations of the parallel trends assumption. The Rambachan and Roth framework asks: for how large a deviation from a linear extrapolation of the pre-period trend ($\bar{M}$, measured in percentage-point units of coca per year) does the result remain statistically distinguishable from zero?

Figure A8 presents the sensitivity bounds for the immediate treatment effect ($t = 0$, $\hat{\phi}_0 = -0.364$, SE $= 0.090$). The horizontal axis parameterizes $\bar{M}$ (the maximum allowed deviation from a linear extrapolation of the pre-trend slope, in percentage-point coca units per year); the vertical axis shows the lower and upper bounds of the robust 95% confidence set at $t = 0$ under each $\bar{M}$. The shaded blue region indicates values of $\bar{M}$ for which the CI is entirely below zero (the result is robust). The result remains robust—the 95% CI does not include zero—for all $\bar{M} < 0.190$ percentage points per year. This threshold is 40 times the observed pre-trend at $t = -2$ ($|\hat{\phi}_{-2}| = 0.005$, $p = 0.953$), the period most susceptible to peace-agreement anticipation effects.

Figure A8

Sensitivity to Violations of Parallel Trends: Rambachan–Roth (2023) Bounds



Notes: Sensitivity bounds following Rambachan and Roth (2023). Each point on the horizontal axis represents a value of $\bar{M}$ (the maximum slope deviation from a linear pre-trend extrapolation allowed per period, in percentage-point units of coca coverage). The vertical axis shows the 95% robust confidence interval for the immediate treatment effect ($t = 0$). The shaded region marks the set of $\bar{M}$ values for which zero is excluded from the confidence set (the result is robust). The estimated pre-trend at $t = -2$ (-0.005, $p = 0.953$) is shown as a vertical reference line.