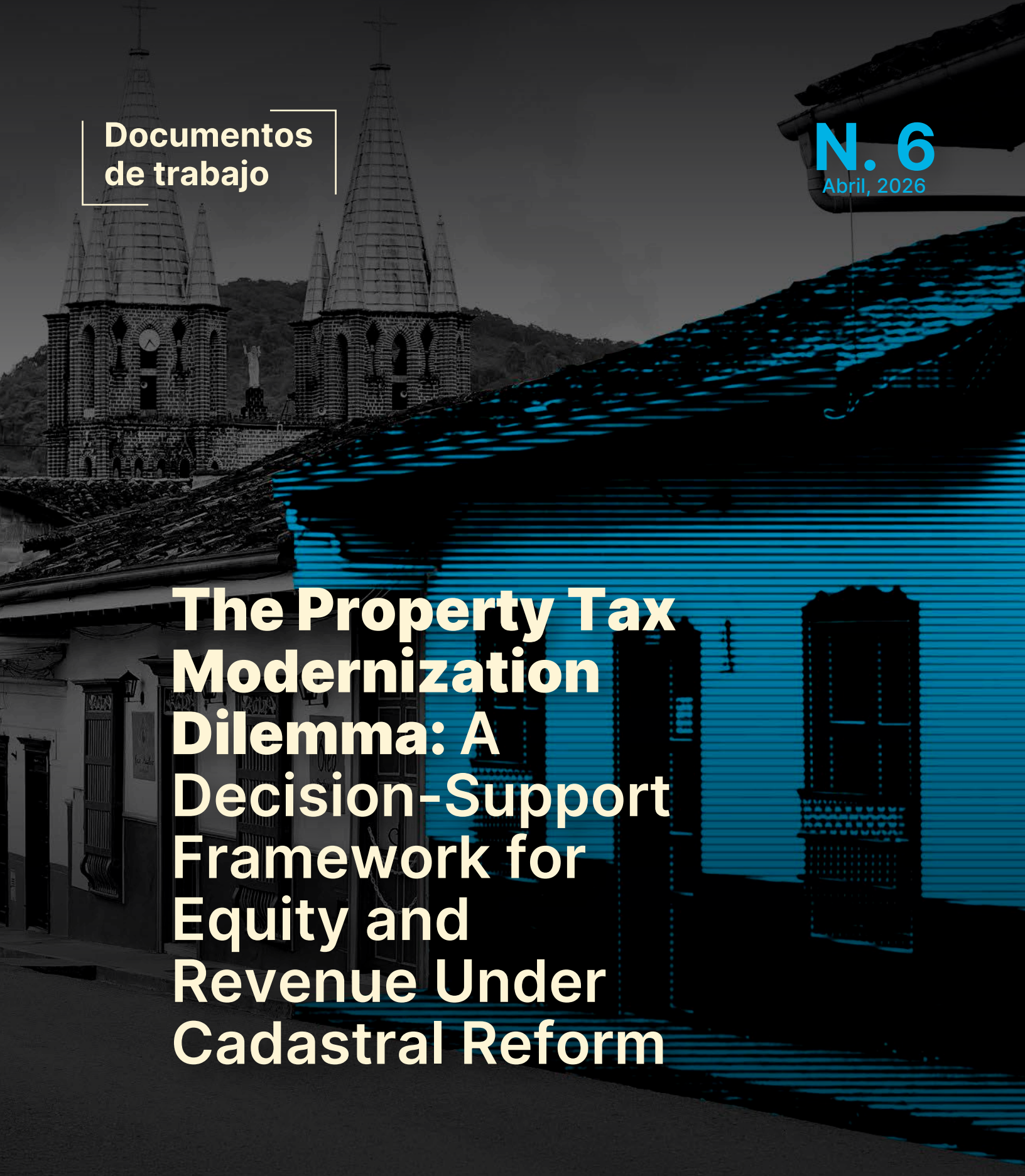

Documentos de trabajo

N. 6
Abril, 2026

The Property Tax Modernization Dilemma: A Decision-Support Framework for Equity and Revenue Under Cadastral Reform

UNIVERSIDAD EAFIT
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Centro de estudios e incidencia
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Serie documentos de trabajo 2026
N. 6
Edición digital
Abril de 2026

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The Property Tax Modernization Dilemma: A Decision-Support Framework for Equity and Revenue Under Cadastral Reform

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Abstract.
Cadastral modernization — updating assessed property values after decades of stagnation — creates a structural dilemma for local governments: better data generates larger fiscal shocks that can trigger the taxpayer resistance that undoes the reform itself. This paper develops a decision-support framework that resolves this dilemma by optimizing property tax rate schedules to be simultaneously revenue-adequate, equity-preserving, and legally compliant under taxpayer-protection constraints. Applied to 929,703 properties across 88 municipalities in Antioquia, Colombia — where a 2024–2025 update nearly doubled the aggregate tax base — three findings emerge. First, the equity-revenue trade-off is far more favorable than current ordinances imply: the median municipality can increase revenue by 7.6% while reducing the residential tax burden. Second, current rate schedules are structurally obsolete and latently regressive, averaging 50 tariff combinations calibrated to 1990s nominal property values. Third, from a fiscal restructuring perspective, the simpler and cheaper land-value-only catch-up update mechanism (PND catch-up) is associated with comparable or higher fiscal restructuring potential than full cadastral modernization — a finding about rate-design

returns, not about the overall value of comprehensive modernization. The framework is replicable by any subnational government with access to digitized property-level cadastral records, retrievable rate ordinances, and administrative tax-liability data of adequate quality.

Keywords: property tax; cadastral modernization; fiscal shock; subnational fiscal capacity; decision-support framework; equity-revenue trade-off; Colombia; linear programming

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JEL Classification: H71 (State and Local Taxation); H72 (State and Local Budget and Expenditures); R51 (Urban Finance); C61 (Optimization Techniques).

Acknowledgments: The authors are grateful to the Gobernación de Antioquia for leading and coordinating the cadastral modernization process that made this research possible, and to Catastro de Antioquia for providing access to the R1-PRO administrative records. We thank the municipal governments and *concejos municipales* of Antioquia who engaged openly with the decision-support framework and offered feedback that substantially improved its design and practical applicability. This research was supported by the Gobernación de Antioquia. The authors thank colleagues at the Gobernación de Antioquia and Catastro de Antioquia for their institutional support throughout this project.

Data and replication: Replication code (R and Python) and processed data will be archived at Harvard Dataverse upon publication. Raw cadastral records (R1-PRO) are administrative data available from Catastro de Antioquia upon request.

INTRODUCTION

Between 2024 and 2025, a single cadastral modernization cycle in Antioquia, Colombia — covering 88 municipalities and nearly one million property taxpayers — nearly doubled the regional assessed value base, from COP 57.2 trillion to COP 108.1 trillion (approximately USD 14.0 and USD 26.4 billion, respectively).[1] Applied unchanged to existing statutory rates, this shock would translate into equivalent increases in annual tax bills — a fiscal jolt without precedent in the department's history and a potential trigger for non-compliance, political backlash, and social conflict. The dilemma of cadastral modernization is that the better the data, the larger the fiscal shock the government must manage. Antioquia's case is not unique. Across the developing world, chronic underperformance of property taxes is driven primarily by severely outdated valuations, not by low statutory rates (Bird & Slack, 2004; de Cesare, 2012; Norregaard, 2013), and governments are now investing heavily in cadastral reform to close that gap. What those programs have not solved is the crisis that accurate data creates: how can local governments capture the fiscal gains from better cadastral data without triggering the taxpayer revolt that destroys them?

The literature establishes why this question is hard. Property taxes in low- and middle-income countries collect well below their legal potential — Gadenne and Singhal (2014) document that administrative capacity, not statutory rates, is the binding constraint in most developing countries. Bergeron et al. (2024) provide the strongest causal evidence on this ceiling: in the DRC, there is a state capacity threshold above which rate increases reduce revenue because enforcement cannot keep pace. Brockmeyer and Hernandez (2023) confirm the same mechanism in Mexico: cadastral revaluations generate revenue increases substantially below the mechanical prediction because taxpayers undercomply with new rates. Weigel (2020) show that even imperfect taxation generates a participation dividend that strengthens the fiscal contract between citizens and the state. Most recently, Hou et al. (2023) show in *JPAM* that assessment frequency shapes property tax equity in U.S. cities — but the parallel question for developing countries, namely how statutory rates should be redesigned when a cadastral update shifts the base, has no established decision-support tool. The IMF's most recent practitioner guidance prescribes simultaneous reform of valuations and rate schedules (Grote & Wen, 2024), but stops short of providing a replicable computational method for doing so. Three compounding problems explain the gap: statutory ordinances in most Colombian municipalities were written for a 1990s fiscal world, with nominal brackets that the cadastral update has rendered obsolete and that now convert nominally progressive schedules into inadvertently regressive ones; Colombia's Constitutional Court doctrine caps year-on-year tax-bill increases per property, simultaneously shielding taxpayers and limiting the government's ability to capture the expanded base; and no systematic framework exists

[1] All COP figures are converted at COP 4,100 per USD, corresponding to the average interbank rate for the fourth quarter of 2025 (Banco de la República).

to find the rate schedule that satisfies all these constraints simultaneously before the fiscal year begins.

This paper provides that framework and applies it at scale. We develop a constrained linear programming model that, for any municipality facing cadastral reform, finds the rate schedule that is simultaneously revenue-adequate, legally compliant, internally progressive, and feasible under per-property taxpayer protection constraints. The framework maps an explicit equity-revenue frontier across three political scenarios: a *social* scenario that minimizes the tax burden on residential and smallholder agricultural properties while sustaining at least 90% of reference revenue; an *efficient* scenario that balances equity and fiscal sustainability at 95% of reference; and an *ambitious* scenario that maximizes revenue within legal constraints. We apply the framework to administrative cadastral records covering 929,703 properties across all 88 Antioquia municipalities using the actual 2026 cadastral values produced by the ongoing reform. Three findings emerge. First, the equity-revenue trade-off is far more favorable than current statutory rates imply: the median municipality can increase revenue by 7.6% relative to its current ordinance applied to 2026 cadastral values — while simultaneously reducing the effective burden on residential and agricultural properties — by shifting fiscal incidence toward commercial, industrial, and speculative land uses that current ordinances are inadvertently undercharging. In aggregate, municipalities leave COP 30.4 billion (USD 7.4 million) on the table annually under their current ordinances relative to the legally feasible optimum — a theoretical upper bound under full adoption, full collection, and no appeals; even under conservative assumptions, the realized potential remains COP 14.9 billion. Second, current ordinances are structurally obsolete and latently regressive: with a median of 50 tariff combinations and bracket thresholds calibrated to 1990s prices, bracket migration after the cadastral update collapses nominally progressive schedules into a de facto flat rate. Third — and most consequential for national investment decisions — from a fiscal restructuring perspective, municipalities that underwent the simpler, lower-cost PND catch-up update show higher fiscal restructuring potential (median slack: 9.7%) than those that completed the comprehensive and expensive full cadastral modernization (4.5%). This is a finding about rate-design returns to cadastral reform, not a claim that the comprehensive program is less valuable overall: full modernization generates benefits in land titling, urban planning, and legal certainty that this analysis does not capture. As an extension, the same data infrastructure supports a land-use governance layer: rural properties with compatible land cover qualify for a preferential rate, with an aggregate maximum revenue cost of COP 95.9 billion across 86 municipalities.

This paper makes three contributions. First, it provides the first large-scale application of constrained rate optimization to an actual cadastral reform event, producing policy-ready rate schedules from the administrative records of 929,703 properties across a full subnational jurisdiction. Prior work has proposed reform frameworks for property tax systems in

developing countries (Bahl & Wallace, 2010; Slack & Bird, 2014) and diagnosed ordinance complexity as a binding constraint on Colombian municipal revenues (Bonet-Morón, Pérez-Valbuena, & Montero-Calderón, 2018); this paper is the first to quantify the fiscal gain from rate rationalization at the individual cadastral record. The framework's 16-segment rate structure replaces the median municipality's 50-combination ordinance — a simplification that reduces legal uncertainty and eliminates the inadvertent regressivity that emerges when 1990s-vintage brackets meet post-reform assessed values. Second, it provides the first empirical mapping of the equity-revenue frontier for subnational property tax across a full jurisdiction undergoing reform, demonstrating that the trade-off between fiscal capacity and distributional fairness is systematically more favorable than governments and the prior literature assume: the median municipality can improve both dimensions simultaneously by moving to the frontier. Third, by comparing fiscal restructuring potential across full cadastral modernization and the lighter catch-up mechanism, it supplies comparative evidence on the returns to expensive national modernization programs — evidence with direct implications for the scaling of the *catastro multipropósito* to more than 1,100 Colombian municipalities. The remainder of the paper proceeds as follows. Section describes the institutional background. Section presents the optimization framework. Section describes the data. Section reports results. Section discusses policy implications. Section concludes.

INSTITUTIONAL BACKGROUND

Property Tax in Colombian Municipalities

Colombia's property tax (*impuesto predial unificado*, IPU) is the primary own-source revenue instrument for subnational governments. Municipal councils set statutory rates within nationally mandated bounds established by Law 44 of 1990 (Congreso de la República de Colombia, 1990): a minimum floor of 5‰ and use-specific ceilings, typically 16‰ for residential properties and higher for commercial, industrial, and speculative uses. All revenue remains at the municipal level, making the IPU a cornerstone of subnational fiscal autonomy (Bonet-Morón, Pérez-Valbuena, & Montero-Mestre, 2018; Iregui et al., 2003).

Despite this central role, Colombia's property tax chronically underperforms. Colombia collects approximately 0.5% of GDP in property tax, below the OECD average of 1.1% and broadly in line with but below the potential of its Latin American peers (de Cesare, 2012; OECD et al., 2023). The comparative property tax literature identifies three structural sources of underperformance in lower-middle-income countries: administrative deficiencies in assessment and collection, political resistance to rate reform, and legal and ordinance complexity that prevents governments from capturing even the revenue that assessed values would arithmetically support (Bahl & Wallace, 2010; Franzsen & McCluskey, 2017). The first two factors have received substantial empirical attention (Bergeron et al., 2024; Brockmeyer

& Hernandez, 2023; Weigel, 2020); the third has not. This paper focuses on the third. For Colombia specifically, Bonet-Morón, Pérez-Valbuena, and Montero-Calderón (2018) document that ordinance complexity and bracket obsolescence account for a substantial share of the gap between statutory and realized property tax revenue across Colombian municipalities, even after controlling for administrative capacity and collection enforcement. Their analysis finds that municipalities with more recently updated rate ordinances collect significantly more relative to their assessed base — evidence that legal design, not just administrative execution, is a binding constraint on Colombian property tax performance. The current paper provides the first micro-level evidence for this mechanism, using property-level optimization to isolate and quantify the fiscal gain from rate rationalization at the individual cadastral record. The root cause of Colombian property tax underperformance is not excessively low statutory rates but severely outdated cadastral land values (*avalúos catastrales*). In many municipalities, land values reflected late-1990s or early-2000s market conditions. A statutory rate of 5‰ applied to a valuation that is one-fifth of current market value produces an effective rate barely above zero — a structural subsidy to property ownership that erodes municipal fiscal capacity without any explicit policy intent.

Antioquia's Cadastral Modernization: Scale, Mechanisms, and Zonal Heterogeneity

Two Modernization Mechanisms

Between 2024 and 2025, Antioquia undertook the most extensive cadastral update in its history, covering all 88 municipalities in our study. Two distinct legal mechanisms operated in parallel, and their differences are central to this paper's analysis.

Multipurpose cadastral program (*catastro multipropósito*, CMP) (full cadastral modernization) is Colombia's flagship national program, launched formally under CONPES 3859 (Consejo Nacional de Política Económica y Social (CONPES), 2016) and continued under Law 2294 of 2023 (National Development Plan 2022–2026, *Plan Nacional de Desarrollo*, PND) (Congreso de la República de Colombia, 2023). It replaces all cadastral information: physical (area, construction, improvements), legal (ownership, encumbrances), economic (market-referenced valuation), and socioeconomic (use, stratum, environmental attributes). The result is a modern, multipurpose property registry that supports not only taxation but land-use planning, titling, and environmental governance. Of Antioquia's 88 municipalities, **44** underwent CMP updates in 2024 or 2025.

PND catch-up update (*rezago catastral*) is a faster, administratively lighter, land-value-only mechanism, also authorized under Law 2294 of 2023 (Congreso de la República de Colombia, 2023). It updates only property land values, adjusting assessments to reflect market conditions without replacing the full cadastral record. No new physical survey, legal

verification, or socioeconomic classification is conducted. The remaining **44** municipalities in our study updated their land values through this mechanism.

Both mechanisms produce a substantial increase in the tax base — the key input that generates the fiscal shock analyzed in this paper — but they differ in data quality, comprehensiveness, and the legal framework governing the resulting rate-adjustment space (see Section).

Zonal Heterogeneity: Urban and Rural Zones Updated Independently

A feature of the Antioquia rollout that has received little attention but is critical for policy design is that cadastral updates were implemented *at the zone level*, not at the municipality level. For the vast majority of municipalities, urban and rural zones were updated through different mechanisms, at different times, or both.

Table 3 summarizes the full taxonomy. Of the 88 municipalities, **84 have both urban and rural zones updated**, but in 67 of these the two zones follow different patterns of timing and mechanism. Only 4 municipalities have a single zone updated (the remainder updated both urban and rural zones, whether jointly or at different times).

The most common configuration (43 municipalities, nearly half the sample) is a *temporal inversion*: the urban zone updated via catch-up update in 2025, while the rural zone updated via catch-up update in 2024. Eleven municipalities followed the opposite temporal structure under the fuller CMP program: urban zones updated in 2024, rural zones updated in 2025.

Table 1: Predominant Zone-Level Update Patterns Across Antioquia Municipalities (2024–2025)

Urban zone (2024 / 2025)	Rural zone (2024 / 2025)	Mechanism	Municipalities	
			N	%
— / PND	PND / —	PND catch-up update	43	48.9
— / CMP	— / CMP	CMP full update	18	20.5
CMP / —	— / CMP	CMP full update	11	12.5
— / CMP	PND / —	Mixed	5	5.7
Other configurations		Various	11	12.5

Note: Columns report the dominant update mechanism in each zone by year (2024 / 2025); "—" = no update in that year. PND = land-value-only catch-up update authorized under Law 2294 of 2023 (National Development Plan 2022–2026); no physical or legal records updated. CMP = full cadastral modernization (*catastro multipropósito*); physical, legal, economic, and socioeconomic records replaced. Source: Antioquia Cadastral Authority / Government of Antioquia; authors' elaboration.

This zonal heterogeneity has two direct policy implications. First, within a single municipality, properties in different zones face different growth caps (the taxpayer-protection limits defined in Section), so the effective rate-adjustment space differs across urban and rural properties even when the municipality's governing ordinance applies a single rate

schedule. Second, optimizing property tax rates *municipally* while the legal constraints are defined *zonally* requires a property-level analysis — precisely the approach taken in this paper.

Scale of the Valuation Shock

Regardless of mechanism, the common outcome is a large, abrupt increase in assessed property values. Aggregated across the 929,703 properties in our dataset, the total tax base nearly doubled: from COP 57.2 trillion (USD 14.0 billion) in 2025 to COP 108.1 trillion (USD 26.4 billion) in 2026, an increase of 89%. The increase is heterogeneous by mechanism: municipalities that completed full CMP updates (T3-Act) recorded a median property-level land value increase of 118%, while the fiscal and socioeconomic complexity of those valuations is greater. Properties in municipalities that had not updated their cadastre since the 1990s face the largest adjustments, in some cases exceeding 500% (maximum observed: 548% for the most affected T3-Act municipality).

Applied mechanically to current statutory rates, these valuation increases would translate directly into tax bill increases of similar magnitude. A property that owed COP 500,000 (roughly USD 120) in 2025 could owe approximately COP 945,000 (roughly USD 230) in 2026 under unchanged rates, a near-doubling of the annual tax burden. For households with fixed or informal incomes — the majority of property owners in smaller Antioquian municipalities — such an increase is not a fiscal inconvenience; it is a potential trigger for non-compliance, tax protest, or social conflict. This is the crisis the framework proposed in this paper is designed to prevent.

The Legal Framework for Rate Adjustment

The Statutory Growth Cap

Colombian Constitutional Court doctrine (Corte Constitucional de Colombia, 2001) establishes that no property owner's annual tax bill may increase by more than a factor of α_i in a single year following a cadastral revaluation. This statutory growth cap is a taxpayer-protection mechanism: it ensures that even when assessed values jump, the actual tax burden rises gradually rather than instantaneously.

The cap factor is not uniform. It varies by update mechanism, timing, zone, and property size, as established by the regulatory framework governing CMP and PND catch-up updates (Congreso de la República de Colombia, 2019, 2023; Presidencia de la República de Colombia, 2020). Table 3 summarizes the urban growth caps by typology. For properties in municipalities that completed a full CMP update in 2025 (T3-Act), $\alpha_i = 2.0$: the tax bill may at most double relative to the prior year. For PND catch-up updates in 2025 (T3-Rez), $\alpha_i = 1.5$ (urban). For updates completed in 2024 where one transition year has already

passed (T2-Act), $\alpha_i = 1.13$ — close to the vegetative growth rate. In rural zones, the growth cap schedule further distinguishes properties by area (below or above 100 hectares), adding another layer of within-municipality heterogeneity.

The Growth Cap Dilemma and Its Implications for Rate Design

The statutory growth cap creates an important dilemma for fiscal optimization. On one hand, it protects taxpayers from the full fiscal shock of a sudden valuation increase. On the other hand, it also *caps upward rate adjustments*: a municipality that wishes to raise rates to recover fiscal capacity cannot, in the same year, capture more than α_i times the prior year's revenue from any given property, regardless of what the new cadastral value would arithmetically support.

This dilemma is sharpest for T2-Act municipalities (6 in our sample), whose growth cap has already compressed to 1.13× one year after their 2024 update. These municipalities have the least room to restructure their rate schedules upward, even though their cadastral values are now substantially higher and their current statutes may be suboptimal.

A Taxpayer's View: Three Scenarios for the Same Property

The interaction between a cadastral update, unchanged rates, and the growth cap is easier to understand through a concrete case. Consider a residential property in a T3-Act municipality: a 2025 assessed value of COP 100 million (USD 24,400), taxed at the municipality's standard residential rate of 6‰, generating a 2025 tax bill of COP 600,000 (USD 146). The 2026 cadastral update raises the assessed value by 118% — the T3-Act median — to COP 218 million (USD 53,200). Table 2 shows what happens to this property under three distinct configurations of rates and taxpayer protection.

Table 2: Three Scenarios for a Representative Residential Property (T3-Act Municipality)

Scenario	Rate (‰)	Cap binding?	2026 Bill (COP 000s)	USD	Change vs. 2025
2025 (reference)	6.0	—	600	146	—
A: Unchanged rate, no growth cap	6.0	No	1,308	319	+118%
B: Unchanged rate, growth cap (α=2.0)	6.0	Yes	1,200	293	+100%
C: Lower rate (5‰), growth cap	5.0	No	1,090	266	+82%

Note: 2025 assessed value: COP 100 million; 2026 assessed value: COP 218 million (+118%, T3-Act median). Growth cap: $\alpha_i = 2.0$ (T3-Act urban). The cap is binding when the unconstrained bill exceeds $\alpha_i \times \ell_i^{2025}$; in Scenario C the lower rate brings the bill below the cap ceiling without requiring it. USD converted at COP 4,100 per USD.

Scenario A is the arithmetic shock: the 118% valuation increase passes through directly

to the tax bill at unchanged rates. Scenario B shows what the growth cap delivers: liability is capped at COP 1,200,000, a 100% increase rather than 118%. The protection is real but incomplete — the household still faces a doubling of its annual obligation in a single year.

Scenario C illustrates the additional margin that rate redesign opens. If the municipality lowers the residential rate from 6‰ to 5‰, the unconstrained bill falls to COP 1,090,000 — below the cap ceiling. The cap does not need to bind. The household pays COP 1,090,000 instead of COP 1,200,000, a further reduction of COP 110,000 that the growth cap alone could not achieve. The municipality still collects 82% more from this property than it did in 2025.

The key implication for rate design is that the growth cap and the rate schedule are not substitutes: they are complementary instruments. The cap limits the maximum shock; the rate choice determines how much of the cap's headroom the government actually needs to use. A lower residential rate, offset by correcting the inadvertent under-taxation of commercial and speculative uses, can protect residential taxpayers further while leaving municipal revenue intact. This is the trade-off the framework in Section operationalizes across all 88 municipalities simultaneously.

Statute Complexity and Obsolescence

A further complication is that most municipal tax ordinances were drafted for the pre-reform cadastral environment and have accumulated decades of piecemeal amendments. The typical ordinance in our sample defines property tax rates as step functions across a median of 50 distinct tariff-rate combinations (range: 5–182), organized across up to 83 distinct economic land-use categories. This complexity was already administratively burdensome before the cadastral update; after the update, it becomes legally incoherent. Ordinances define assessed-value brackets in nominal peso ranges calibrated to late-1990s or early-2000s prices. After a 2024–2025 update that approximately doubled valuations on average (aggregate tax base: +89%; T3-Act municipalities: median +118%), the majority of properties fall into or beyond the statute's highest brackets — brackets originally designed for the most valuable commercial and industrial properties. A residential property that was previously in a low-value bracket paying 5–7‰ now nominally falls in the highest bracket paying 14–16‰ — not because the council legislated a rate increase, but because inflation and the cadastral update have rendered the bracket thresholds meaningless. The legal uncertainty this creates — which rate applies when a property's land value exceeds all defined brackets? — adds a litigation and compliance risk on top of the fiscal shock, and converts what was a nominally progressive rate schedule into an inadvertently regressive one.

The combination of outdated statutes, unprecedented valuation increases, zone-level alpha heterogeneity, and fiscal shock risk constitutes the institutional crisis that motivates the decision-support framework developed in Section .

Table 3: Municipality Typology by Update Year and Cadastral Mechanism

Year	Mechanism	N	Properties (M)	Fiscal base 2025 (COP B)	Median avalúo change	Alpha cap (urban 2026)
2024	CMP full update	6	0.03	60.0	76.7%	1.13x
2024	PND catch-up update	1	0.00	2.3	5%	1.5x
2025	CMP full update	38	0.58	796.3	118.5%	2.0x
2025	PND catch-up update	43	0.31	243.2	5%	1.5x
—	**Total**	**88**	**0.92**	**1101.8**	—	—

Note:
Year = year of cadastral update (T2 = 2024; T3 = 2025). CMP full update = full cadastral modernization (physical, legal, economic, and socioeconomic records replaced). PND catch-up update = land-value-only update authorized under Law 2294 of 2023 (National Development Plan 2022–2026); no physical or legal records updated. Growth cap = maximum permitted year-on-year increase in individual tax obligations under the Constitutional Court doctrine (urban properties). COP B = billions of Colombian pesos. Properties in millions.

A DECISION-SUPPORT FRAMEWORK FOR PROPERTY TAX DESIGN

Municipal finance officials navigating a cadastral update face a decision problem with no off-the-shelf solution. They must choose a rate schedule simultaneously satisfying four sets of requirements that often pull in different directions: Colombian statutory law (floors and ceilings on rates by property use); constitutional taxpayer protection (statutory growth caps that limit year-on-year tax increases per property); revenue adequacy targets (often set by the budget office or the municipal council); and equity commitments to residential and smallholder agricultural property owners. Any of these constraints can be binding. None of them disappears when a municipality delays the rate update.

This section describes a decision-support framework that maps the legally feasible rate-design space for each municipality, locates the current statute within that space, and identifies alternative rate schedules that dominate the current statute on equity, revenue, or both. The framework does not prescribe a single rate schedule. It generates an informed menu of options — one for each political scenario (Section) — and computes the property-level fiscal implications of each option before any reform is adopted.

The complete mathematical specification is provided in Appendix A. The exposition below is organized around the four analytical steps a policy analyst would follow to apply the framework.

Step 1: Map the Legal Feasibility Space

The feasibility space is the set of all rate vectors that satisfy Colombian property tax law simultaneously with the constitutional taxpayer-protection doctrine. Its boundaries are determined by three types of legal constraint.

Statutory bounds. Law 44 of 1990 and subsequent reforms establish a uniform minimum rate of 5‰ and use-specific ceilings for each economic segment. Residential properties face

a ceiling of 16‰; commercial properties, 33‰; industrial properties, 33‰; and speculative urban land (*lotes urbanizables no urbanizados y urbanizados no edificados*) face a ceiling of 33‰ with an effective premium. These bounds define the outer envelope of the feasibility space.

Alpha constraints. The Constitutional Court doctrine (see Section) establishes that no individual property may face a tax bill exceeding α_i times its current obligation, regardless of how much the assessed value has changed. This translates into a *property-specific* ceiling on the applicable tariff rate:

$$U_i = \alpha_i \cdot \frac{A_i^t}{A_i^{t+1}} \cdot T_i^t \tag{1}$$

where A_i^t and A_i^{t+1} are the assessed values before and after the cadastral update, and T_i^t is the current statutory rate for property i. Because the framework must set a single rate per economic segment, the binding ceiling for each segment is the minimum ceiling across all properties in that segment. Properties without a growth cap (newly built or recently transferred properties, and speculative urban land in certain typologies) are excluded from this minimum.

The practical implication is that the growth cap often bites from below: for municipalities with large average valuation increases (T3-Act, median +118%), most segments face growth ceilings well below the statutory maximum, leaving little rate-design room even in the absence of equity or revenue concerns.

Progressivity. Municipal ordinances are legally required to apply progressivity across property value tiers within each economic use category (Congreso de la República de Colombia, 1990). We enforce this as a monotonicity constraint: the rate for a higher-value tier must be at least 0.1‰ above the rate for the adjacent lower-value tier. This minimum step of 0.1‰ is not explicitly mandated by statute; it represents the smallest differential consistent with the progressivity doctrine as interpreted in Constitutional Court jurisprudence, and is conservative relative to the typical inter-bracket gaps observed in the 87 municipal ordinances in our sample (median inter-bracket gap: 0.8‰). As a robustness check, we verified that the main findings are unchanged when the minimum step is set to 0.05‰ or 0.20‰ (results available from the authors upon request). This constraint, rather than the growth cap or the statutory ceiling, turns out to be the most frequently binding constraint for a significant share of municipalities in our sample (Section).

Step 2: Define the Economic Segments

The unit of rate design in the framework is the *economic segment*: a combination of property use category and assessed-value tier. We aggregate all properties in a municipality into

16 segments based on two dimensions: (1) economic destination (residential, commercial, industrial, agricultural, speculative urban land, and mixed use); and (2) assessed value range (low, medium, high, and premium, defined by national percentile thresholds updated to 2026 values).

This 16-segment structure is deliberately simpler than the median ordinance in our sample, which defines 50 tariff-rate combinations across up to 83 distinct land-use categories (Section). The simplification is both a practical necessity and a substantive policy contribution in its own right. Ordinances with 50–182 distinct rate combinations are administratively burdensome, legally fragile, and, after the cadastral update, effectively obsolete: bracket thresholds calibrated to late-1990s prices no longer correspond to any property in the distribution, creating legal uncertainty about which rate applies and converting nominally progressive schedules into inadvertently regressive ones. The 16-segment structure eliminates this bracket complexity while fully preserving the legal progressivity requirement. The result is a rate schedule that is simpler for taxpayers to understand, easier for municipal finance offices to administer, harder to challenge in litigation, and better calibrated to the post-reform distribution of assessed values. Simplification is not a concession to tractability; it is a structural improvement over the inherited ordinance design.

For each segment s, the framework computes an *effective tariff ceiling* U_s by aggregating the property-level growth caps described in Step 1, and a *revenue weight* based on the aggregate assessed value and number of properties in the segment. These segment-level inputs, together with the statutory floor and progressivity constraints, define the feasibility space within which the optimization operates.

Step 3: Choose a Political Scenario

Within the legal feasibility space, there is no uniquely correct rate schedule. The right schedule depends on how the municipality weighs three competing objectives: minimizing fiscal burden on residential and agricultural properties; maintaining sufficient revenue for public services; and maximizing fiscal capacity for infrastructure investment. These are political choices, not technical ones.

The framework operationalizes this trade-off through three named scenarios, each representing a distinct reform philosophy. Table 4 summarizes their objectives and revenue targets.

The **Social scenario** represents a municipality committed to protecting households from the fiscal shock of the cadastral update. It accepts a revenue reduction of up to 10% relative to the reference level in exchange for shifting the rate structure away from residential uses. This is most appropriate for municipalities where residential and smallholder agricultural properties make up the majority of the tax base and where households lack the liquidity to absorb sudden increases.

Table 4: Three Political Scenarios: Reform Philosophy and Revenue Targets

Scenario	Objective	Revenue floor	Residential weight
Social	Minimize burden on residential and smallholder agricultural properties; fiscal sustainability floor only	$\geq 90\%$ of reference	10×
Efficient	Minimize aggregate rate burden across all segments; near-full revenue recovery	$\geq 95\%$ of reference	1× (uniform)
Ambitious	Maximize revenue within legal constraints; then minimize rates at that revenue level	Maximum feasible	1× (uniform)

Note: Revenue floor is expressed relative to the reference level (current statutory rates applied to 2026 cadastral values, subject to per-property growth caps). Residential weight applies only in the Social scenario and increases the penalty in the objective function for higher residential rates relative to other uses.

The **Efficient scenario** is the primary analytical benchmark. It asks: what is the lowest aggregate rate burden consistent with near-full revenue recovery? The answer identifies the fiscal slack — the gap between what the current statute delivers and what an optimized schedule could achieve while keeping the aggregate burden at or below current levels. The Efficient scenario is the reference point for Section .

The **Ambitious scenario** answers a different question: how much revenue could the municipality legally collect if it fully exploited the new cadastral values? This scenario is relevant for municipalities with large infrastructure deficits or high dependence on property tax revenue. The two-phase structure (first maximize revenue, then minimize rates at that revenue level) ensures that the recommended schedule is not wastefully high — it achieves the revenue target with the lightest possible rate schedule that does so.

A clarification on language is warranted. The three scenarios are named for political tractability, not for welfare theory. None of them is a welfare optimum in the economic sense: the model does not incorporate demand responses, public-good provision costs, or the welfare of taxpayers across income groups. "Efficient" means the rate vector that minimizes aggregate statutory burden at near-full revenue recovery within the legal feasibility space — not efficiency in the Pareto or social welfare sense. "Social" does not imply a Rawlsian optimum; it signals that the schedule protects residential and smallholder agricultural properties from the fiscal shock of the cadastral update. These labels communicate the political orientation of each reform scenario to municipal officials and elected councils; they make no normative claim about economic welfare.

Each scenario is solved as a linear program. For the Social and Efficient scenarios, the objective function minimizes a weighted sum of tariff rates subject to the legal floor, growth

ceilings, progressivity constraints, and the revenue floor. For the Ambitious scenario, Phase 1 maximizes total revenue and Phase 2 minimizes the rate vector at the maximum revenue level. The full optimization problems are specified in Appendix A.

A note on optimality. Each scenario is solved as a linear program with a polyhedral feasibility space — the intersection of finitely many linear inequality constraints. Linear programs over polyhedral sets are convex optimization problems for which solvers guarantee a globally optimal solution at a vertex of the feasibility polytope (O'Donoghue, 2014). We use the HiGHS solver (Mitchell et al., 2011), which implements the revised simplex algorithm with numerical stability controls; every solution reported is certified globally optimal (or infeasible) by the solver's exit status. For the Ambitious scenario, Phase 1 (revenue maximization) and Phase 2 (rate minimization at fixed revenue) are each individually linear programs with the same guarantee. There are no local optima and no sensitivity to starting values.

Step 4: Compute Property-Level Fiscal Impacts

The final step translates the optimal rate vector into individual tax obligations (*liquidaciones*, individual tax liabilities) for every property in the municipality, applying the growth cap at the individual level. This step is essential for two reasons.

First, it produces the distributional analysis that policymakers need before adopting any reform. A rate schedule that looks balanced at the segment level may impose very different burdens on individual properties within each segment, depending on whether a property's assessed value changed more or less than average. Computing individual tax liabilities makes these distributional effects visible before the ordinance is passed.

Second, it provides the revenue projection used to evaluate fiscal slack. Because growth caps are applied property-by-property, the aggregate revenue from any rate schedule is not fully predictable from segment-level calculations alone — some properties will hit their growth ceiling before reaching the segment rate, reducing the effective revenue. Individual-level computation ensures that the revenue projections reported in Table 7 are consistent with the legal constraints that actually apply to each property owner.

The annual tax obligation of property i under the optimal rate schedule is:

$$\ell_i = \min\left(\frac{A_i^{t+1} \cdot t_{s(i)}}{1{,}000},\ \alpha_i \cdot \ell_i^t\right) \tag{2}$$

where $t_{s(i)}$ is the optimal rate for the segment to which property i belongs, A_i^{t+1} is the 2026 cadastral value, and ℓ_i^t is the current tax obligation. Properties without a growth cap ($\alpha_i = \infty$, including speculative urban land and newly registered properties) pay the full rate without a cap. The sum of individual obligations $\sum_i \ell_i$ is the projected revenue under the reform scenario.

The Equity-Revenue Frontier

The four steps above generate a point on the equity-revenue frontier for each political scenario. Figure 1 illustrates the conceptual structure. The horizontal axis measures projected revenue as a percentage of the reference level; the vertical axis measures the reduction in the residential tax burden relative to the reference level. Each named scenario occupies a distinct position on the frontier.

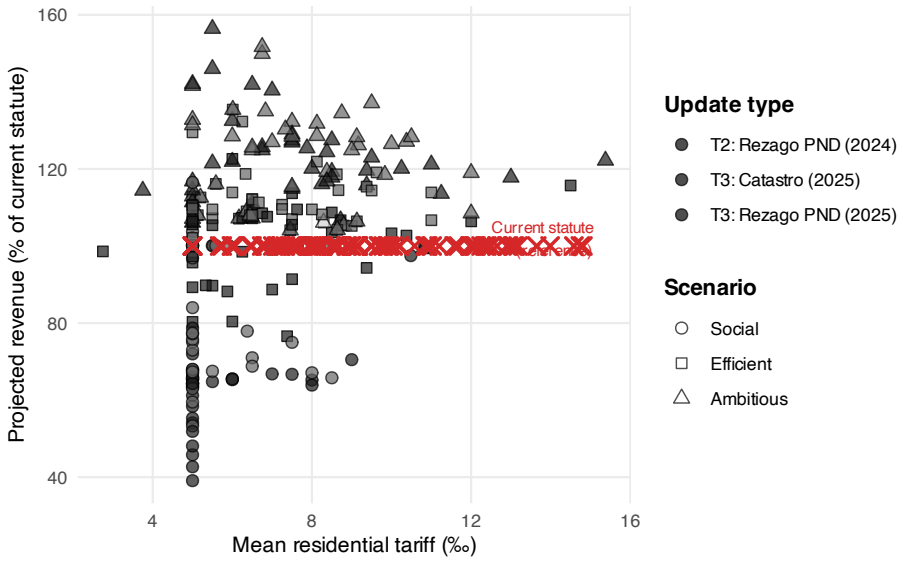


Figure 1: The Equity-Revenue Frontier for an Illustrative Municipality.
Note: The frontier shows the legally feasible combinations of revenue adequacy and residential burden reduction under the three political scenarios. The current statute (diamond marker) lies inside the frontier for most municipalities, indicating that both dimensions can be improved simultaneously by moving to the efficient scenario. The Social scenario trades revenue for residential burden reduction; the Ambitious scenario trades burden reduction for revenue. The shaded region between the current statute and the Efficient scenario represents fiscal slack.

The central finding of the framework, confirmed empirically in Section , is that the current statute lies *inside* the frontier for the majority of municipalities. This means the equity-revenue trade-off that municipal councils perceive as unavoidable — the belief that protecting residents requires accepting less revenue, and that recovering revenue requires burdening residents — is in most cases a false constraint. The current statute is not on the frontier. By moving to the frontier, a municipality can simultaneously generate more revenue and impose lower effective rates on residential properties. The gap between the current statute and the Efficient scenario point is what this paper calls *fiscal slack*.

Implementation and Fallback Strategies

The framework is implemented in Python using the PuLP modeling library with the HiGHS solver (Huangfu & Hall, 2018; Mitchell et al., 2011). Data preparation and post-processing

use R. The optimization runs in approximately 10–15 minutes per municipality; the full batch of 88 municipalities runs in under two hours on a standard workstation.

Not all municipalities have a feasible solution under the primary scenario specification. Infeasibility arises when the growth ceilings are so tight — particularly in T2-Act municipalities where the transition timetable has already compressed the cap to 1.13× — that no rate vector can simultaneously satisfy the legal floor, the progressivity constraint, and the revenue target. In these cases, the model applies a hierarchy of fallback strategies:

1. *Vegetative growth*: Apply the national vegetative growth rate (4.5%) to current tariffs without restructuring the rate schedule.
2. *Target reduction*: Lower the revenue target by 5 percentage points and re-solve the primary problem.
3. *Conservative reduction*: Apply a uniform 30% rate reduction from the current tariffs as a taxpayer-protection measure.
4. *Adaptive*: Apply adaptive rate adjustments (±30%) calibrated to the specific constraint structure of the municipality.

All 88 municipalities in the sample were solved — either with the primary optimizer or with a fallback strategy. The fallback assignments are reported alongside the main results in Table 7 and documented in Appendix A.

The framework outputs three deliverables for each municipality and scenario: (1) a recommended tariff schedule showing the optimal rate for each of the 16 economic segments; (2) a property-level file with individual tax liabilities and the change relative to the reference level; and (3) a five-year net-present-value projection of revenue under the reform schedule, assuming standard vegetative cadastral growth. These deliverables are designed to be directly usable by municipal finance offices and departmental tax advisers without further technical processing.

Extension: A Land-Use Governance Incentive

The framework described above is a fiscal optimization tool. The same parcel-level data infrastructure, however, supports a broader policy objective: using the property tax as an instrument of land-use governance. Where the cadastral dataset includes land cover information, the framework can incorporate a preferential rate for rural agricultural and livestock properties that demonstrate compatible land use — rewarding environmental stewardship through fiscal design rather than requiring separate regulatory instruments.

The extension draws on two national datasets. Corine Land Cover (CLC) data from Colombia's National Institute of Hydrology, Meteorology, and Environmental Studies (IDEAM) provides a Level-3 classification of current land cover for all of Antioquia. Land vocation classifications from IGAC establish the productive vocation of each area of land —

the most intensive sustainable use compatible with its ecological and physical characteristics. We intersect both layers with the parcel geometry from the cadastral dataset to compute, for each rural property, a land-use adequacy index: the share of the parcel's area where current land cover is compatible with productive vocation. Three conflict classes result: adequate use (current use matches vocation), underutilization (current use is less intensive than the land could sustainably support), and overutilization (current use exceeds the land's ecological carrying capacity). Forests and mangroves are classified as adequate use regardless of vocation, consistent with Colombia's Zero Deforestation policy.

For rural agricultural and livestock properties, the optimization output is supplemented by a land-use incentive tariff when the adequacy index is sufficiently high. The legal instrument for this incentive is a partial tax exemption (*incentivo tributario*) approved by the municipal council under Article 258 of Law 1819 of 2016, which explicitly authorizes municipal governments to grant fiscal incentives for environmental stewardship, and consistent with the land-use governance mandate established by Law 388 of 1997 (*Ley de Ordenamiento Territorial*). Under this framework, the incentive operates as a reduction applied on top of the base rate determined by the optimization — structurally distinct from the statutory floor established by Law 44 of 1990, which governs the base tariff schedule but does not constrain locally authorized exemptions granted for defined public-interest purposes. This instrument requires a separate municipal council ordinance (*acuerdo municipal*) and therefore represents an optional policy layer rather than a default output of the optimization. Properties with at least 80% of their area in adequate use receive a preferential effective rate of 2‰; those with 60–80% adequate use receive 4‰. Properties below the 60% threshold face no override and pay the rate determined by the optimization.

This incentive layer operates as a post-processing step: the linear program finds the optimal tariff vector under the fiscal and legal constraints described above, and the land-use override is applied subsequently to individual tax liabilities for qualifying properties. The revenue cost — the difference between the statute tariff applied to 2026 cadastral values and the preferential tariff — is computed for each municipality and reported in Table 17 (Appendix). It is worth noting upfront that the cost is substantial relative to the rural tax base: across 86 municipalities with available land-use adequacy data, 59,850 rural properties qualify for the incentive (22% of rural properties in the conflict-of-use database), and the maximum annual revenue cost is COP 95.9 billion (20.8% of the aggregate rural tax base at 2026 statutory rates). This figure represents an upper bound — the cost under full uptake of the incentive, computed relative to the statute tariff before any rate optimization. Under the Efficient scenario, where rural agricultural rates are already reduced from the post-update inadvertent highs, the incremental revenue cost of the land-use override would be lower; computing it exactly requires property-level access to the optimized segment rates, which are not available in the public replication package. We apply this extension to 86 of the 88

municipalities in the study; two T3-Rez municipalities (Caicedo, San Francisco) are excluded due to missing statute tariff data in their pre-optimization records.

DATA AND APPLICATION

Data Sources

The analysis draws on three primary data sources, all specific to the department of Antioquia, Colombia, for the 2025–2026 fiscal transition.

Cadastral records. The backbone of the analysis is a geolocated cadastral dataset maintained by the Antioquia Cadastral Authority (*Catastro de Antioquia*) and the national cadastral agency (IGAC). This dataset records the full property universe at the individual parcel level: cadastral land value (*avalúo catastral*), economic use category (*destino económico*), zone (urban or rural), physical area, sector-level location, current statutory tariff rate, ownership information, and 2025 tax liability (*liquidación*). We use two vintages: the 2025 records (pre-reform assessed values and current tariffs) and the 2026 records (post-reform assessed values reflecting the cadastral update). The 2026 records are the direct output of the cadastral modernization programs described in Section .

Municipal tax ordinances. Each municipality's rate schedule is governed by a municipal ordinance that defines tariff rates as step functions across assessed-value brackets and economic use categories. We constructed a structured database of rate schedules for 87 of the 88 municipalities in the study by extracting tariff tables from the official PDF ordinances using a large-language-model-assisted extraction pipeline (GPT-4o; OpenAI, 2024), followed by manual verification.[2] The pipeline extracted tariff tables by parsing PDF text, classifying rate-bracket combinations by economic use category, and flagging ambiguous cases for human review. Manual review covered 100% of flagged cases and a 20% random sample of unflagged cases; the estimated error rate in the final ordinance database is below 2% of tariff-rate combinations. The ordinance database, extraction code, and verified tariff tables are included in the replication package. For each municipality, the database records the rate applicable to each combination of economic use and assessed-value range, the unit of measurement (nominal peso brackets or UVT-indexed brackets), and any special exemptions or surcharges. The resulting dataset contains a median of 49.5 tariff-rate combinations per municipality (range: 5 to 182), organized across up to 83 distinct economic land-use categories.

[2] The one municipality excluded from the ordinance database (Caicedo) could not be processed because its current rate ordinance was not available in machine-readable form through official municipal repositories at the time of data collection. It is retained in the cadastral analysis with a uniform proxy tariff applied; it is excluded from Table 9 and flagged in all results tables.

Land cover and land vocation data. The land-use governance extension (Section) draws on two additional spatial datasets. Land cover is taken from Colombia's national Corine Land Cover (CLC) classification at Level 3, produced by the National Institute of Hydrology, Meteorology, and Environmental Studies (IDEAM) and available at full Antioquia coverage. Land vocation is taken from the national land use vocation layer produced by IGAC, which classifies each area according to the most intensive sustainable use compatible with its ecological and physical characteristics. We intersect both layers with the parcel geometry in the cadastral dataset to produce, for each rural property in the sample, the percentage of parcel area classified as adequate use, underutilized, or overutilized. The intersection is conducted at full parcel resolution; for properties with partial coverage across conflict classes, the dominant class by area is used to assign the land-use adequacy index (pct_uso_adecuado, ranging from 0 to 1).

Per-property growth cap parameters. The cap factors (α_i) that limit year-on-year tax increases are not stored in any single administrative database; they must be derived from the intersection of the legal framework, the cadastral update typology, the property's zone, and (for rural properties) its area. We constructed a property-level set of growth cap parameters by applying the Constitutional Court doctrine and the regulatory framework for CMP and PND catch-up updates (Table 3) to each record in the cadastral dataset. The resulting parameters were validated against a sample of individual tax liabilities from municipal finance offices covering 81 municipalities and approximately 845,000 properties (the same validation subsample used in Section); cross-referenced against the liquidación records for each property confirms that the derived α_i values reproduce the capped tax liabilities with a median deviation of less than 1% at the property level. Four distinct cap values appear in the sample: 1.13× (T2-Act, urban), 1.5× (T2-Rez urban; T3-Rez urban; rural properties below 100 ha for some typologies), 2.0× (T3-Act, urban), and ∞ (unconstrained — speculative urban land, newly registered properties, and first-year tax liabilities for recently updated rural properties above 100 ha).

Data availability. The cadastral records used in this analysis are administrative data maintained by the Gobernación de Antioquia and IGAC; access requires a formal data-sharing agreement with the Antioquia Cadastral Authority. Land cover data (Corine Land Cover) and land vocation data are publicly available from IDEAM and IGAC, respectively, through Colombia's national open-data infrastructure (datos.gov.co). Municipal tax ordinances are public legal instruments available from official municipal gazettes (*Gaceta Municipal*). The full replication package — including the LP model code, the structured ordinance database, all results tables, and reproducible R and Python scripts — is available at [DOI TO BE ASSIGNED UPON ACCEPTANCE].

Sample and Coverage

The study covers 88 municipalities in the department of Antioquia that underwent cadastral updates in 2024 or 2025 under one of the two modernization mechanisms described in Section . These 88 municipalities represent 73.3% of Antioquia's 125 municipalities and hold approximately 929,703 properties, with combined 2025 property tax revenue of COP 1,101.8 billion (USD 269 million). This revenue figure reflects the application of current statutory tariffs to 2025 assessed values; the underlying assessed value base — the total *avalúo catastral* of all 929,703 properties — stands at COP 57.2 trillion (USD 14.0 billion), as reported in Section . Table 3 (Section) presents the breakdown by typology; Table 5 below presents descriptive statistics for the sample.

Table 5: Descriptive Statistics by Municipality Typology

Type	N	Properties (000s)	Fiscal base (COP M, med)	Avalúo change (%, med)	Shock if no reform (%, med)	Shock with alpha (%, med)
T2	7	5.2	2275.6	5	7.7	5.6
T3	81	11.0	4847.0	5	2.6	2.6

Note:
Shock if no reform = percentage increase in municipal tax revenue if current statutory rates are applied unchanged to 2026 cadastral values, ignoring individual alpha caps. Shock with alpha = same calculation applying per-property alpha restrictions. COP M = millions of Colombian pesos. Medians reported.

Sample construction. Table 6 below traces the four analysis samples used in this paper. Of Antioquia's 125 municipalities, 88 underwent cadastral updates in 2024 or 2025 and constitute the study population. Eighty-seven have usable ordinance data (see footnote 2 for the one exclusion). Of the 88, six T2-Act municipalities produce infeasible LP solutions under the standard scenario specification due to their tightly compressed $\alpha = 1.13\times$ growth cap, and are assigned fallback strategies instead; the mechanism comparison in Table 9 uses the remaining 82 municipalities with valid standard LP solutions. The model validation in Section draws on 81 municipalities for which 2025 tax liability records were available from municipal finance offices.

Table 6: Sample Construction

Sample restriction	Municipalities	Properties
All Antioquia municipalities	125	—
Underwent cadastral update 2024–2025	88	929,703
with usable ordinance data	87	∼916,000
with valid standard LP solution (mechanism table)	82	∼859,000
with 2025 liability validation data (Section)	81	∼845,000

Note: Property counts for restricted samples are approximate (rounded to nearest thousand); exact counts reported in Appendix .

The two typology groups differ substantially in scale. T3 municipalities (updated in 2025) account for 81 of the 88 municipalities and the overwhelming majority of properties

(median 11,000 properties per municipality, versus 5,200 for T2 municipalities). The T2 cohort comprises 7 municipalities: six T2-Act (full CMP update in 2024) and one T2-Rez (PND catch-up update in 2024). The median property tax revenue is COP 4,847 million (USD 1.2 million) for T3 municipalities and COP 2,276 million (USD 555,000) for T2 municipalities.

The median land-value change reported in Table 5 (5% for both groups) reflects the composition of the sample: the majority of municipalities are PND catch-up updates (44 municipalities), which target primarily the smaller adjustments needed to correct the most egregious undervaluations, while CMP updates (44 municipalities) produce much larger individual property changes (median +118.5% for T3-Act) concentrated in the municipalities with the most severely outdated cadastral records.

Six T2-Act municipalities — Alejandría, Armenia, Cisneros, Guatapé, La Pintada, and Urrao — present a special case. Their $\alpha = 1.13\times$ growth cap, combined with their ordinance structure, makes the standard Social, Efficient, and Ambitious LP infeasible: no rate vector can simultaneously satisfy the legal floor, the progressivity requirement, and any positive revenue target at the new cadastral values. These municipalities are assigned the GRADUAL and EQUILIBRADO compensation scenarios from the fallback hierarchy (Appendix A), which target vegetative growth and conservative rate reduction respectively. They appear in the aggregate counts (N = 88) and in Table 3 but are excluded from the Efficient-scenario mechanism comparison in Table 9 (N = 82), which requires a valid standard LP solution to compute fiscal slack.

Variable Construction

Current tariff (T_i^t). For each property, the current tariff is the rate specified in the municipal statute for the property's economic use category and assessed value bracket, evaluated at the 2025 assessed value. Where a property's assessed value exceeds all defined brackets (a common situation after the cadastral update makes old nominal brackets obsolete), the statute's highest bracket rate is applied. We construct a segment-level median tariff $\bar{T}_s$ for each of the 16 optimization segments as the weighted median of individual tariffs within the segment, using assessed value as the weight.

Reference revenue (R^{ref}). The reference revenue baseline is defined as the revenue the municipality would collect if it applied current statutory tariffs to 2026 assessed values, subject to the individual growth caps:

$$R^{\text{ref}} = \sum_{i \in \mathcal{I}} \min\left(\frac{A_i^{t+1} \cdot T_i^t}{1{,}000},\ \alpha_i \cdot \ell_i^t \right) \tag{3}$$

This is the denominator for all percentage comparisons in the analysis and the floor for the revenue targets in Table 4. It represents the inertial fiscal path — what happens if the municipality does nothing — and is the natural benchmark against which reform scenarios are evaluated.

Fiscal slack. Fiscal slack is defined as the difference between projected revenue under the Efficient scenario and the reference revenue: Fiscal slack $= R^{\text{Efficient}} - R^{\text{ref}}$. A positive value means the municipality could generate more revenue with an optimized rate schedule than with its current statute, without increasing the aggregate rate burden.

Model Validation

As a specification check, we compare the model's baseline revenue projection against the actual 2025 tax liabilities recorded in the cadastral dataset for the municipalities where this comparison is possible. The model baseline applies current statutory tariffs to 2025 assessed values without any 2026 cadastral adjustments. Because the 2025 fiscal year precedes the cadastral updates analyzed in this paper, the statutory growth caps introduced by those updates do not apply to this baseline comparison; 2025 liabilities already incorporate any prior growth caps from earlier cadastral transitions, which are included in the model baseline using the 2025 α_i parameters for the relevant municipalities. The model baseline closely tracks actual collections: across 81 municipalities with usable 2025 tax liability records, the median absolute deviation between modeled and actual municipal revenue is 3.2%, confirming that the tariff extraction and segment assignment procedures replicate administrative practice with sufficient accuracy for counterfactual analysis. Discrepancies above 10% (8 municipalities) trace to one of three sources: mid-year ordinance amendments not captured in the statute database, partial-year cadastral updates in which some properties entered the 2025 roll late, and known data-quality issues in the cadastral records for specific rural zones. These municipalities are retained in the sample and flagged in the results tables; their exclusion does not change any main finding.

RESULTS

The Equity-Revenue Frontier

Table 7 presents the core result. For each municipality typology, it reports projected fiscal outcomes under the three political scenarios, expressed as percentage deviations from the reference level — the revenue that would be collected if current statutory rates were applied unchanged to 2026 cadastral values, subject to per-property growth caps.

The headline finding is that the equity-revenue trade-off is far more favorable than the status quo implies. Under the Efficient scenario, the median municipality can generate

Table 7: Projected Fiscal Outcomes by Scenario and Municipality Typology

		Revenue vs. reference (median)			Fiscal slack	
Type	N	Social (%)	Efficient (%)	Ambitious (%)	Fiscal slack (%, med)	Total slack (COP B)
T2	7	+0.1%	+6.1%	+6.1%	6.1%	0.1
T3	81	-32.5%	+7.6%	+21.9%	7.6%	30.2
All municipalities	**88**	**-32.5%**	**+7.6%**	**+21.7%**	**7.6%**	**30.4**

Note:
Revenue percentages show median projected revenue relative to the no-change reference level (current rates × 2026 cadastral values × alpha caps). Fiscal slack = gap between Efficient scenario and current statute revenue. Social scenario target: ≥90% of reference. Efficient scenario target: ≥95% of reference. Ambitious scenario: revenue-maximizing.

revenue that is 7.6% *above* the reference level — while the framework simultaneously realigns rates to reduce the effective burden on residential and agricultural properties. This gain does not come from raising rates overall; it comes from correcting the misallocation created by bracket obsolescence and rate complexity, shifting fiscal incidence toward commercial, industrial, and speculative land uses that currently benefit from inadvertently low effective rates.

Under the Social scenario, the median municipality accepts a revenue reduction of 32.5% relative to reference in exchange for maximum burden reduction on residential and smallholder agricultural properties. This represents a deliberate fiscal choice — not a constraint — and is made available as an option because the framework makes the trade-off explicit and quantified. At the other extreme, the Ambitious scenario shows that municipalities could increase revenue by a median of 21.7% relative to reference while remaining within all legal constraints, though this comes at the cost of higher residential rates.

T2 municipalities (updated in 2024) show a more compressed range of outcomes, reflecting the tighter growth caps already in effect after one transition year ($\alpha_i = 1.13\times$ for T2-Act). Their policy space is narrower, but the Efficient scenario still generates a median 6.1% revenue improvement over current statutes.

Fiscal Slack: What Municipalities Leave on the Table

We define *fiscal slack* as the gap between projected revenue under the Efficient scenario and projected revenue under current statutory rates, both computed at 2026 cadastral values.[3] It measures the fiscal gains that municipalities forgo by retaining obsolete rate schedules when new cadastral values are applied.

In aggregate, the 88 municipalities leave COP 30.4 billion on the table annually — equiv-

[3] This use of "fiscal slack" should not be confused with "fiscal space" in the public debt literature, which refers to the capacity of a government to increase spending without jeopardizing debt sustainability (Heller, 2005). Here, fiscal slack is a narrow rate-design concept: the untapped revenue potential available through rate rationalization, holding the cadastral base and all legal constraints fixed.

alent to 2.8% of their total current own-source property tax revenue (COP 1,101.8 billion). This figure is a theoretical upper bound: it assumes full adoption of the Efficient scenario, 100% collection of assessed liabilities, and no downward revision of 2026 assessed values through appeal. Table 13 (Appendix) shows how the estimate changes under joint assumptions about valuation corrections and collection rates; even under the most conservative joint assumption (30% valuation correction, 70% collection rate), the remaining potential is COP 14.9 billion (1.4% of own-source revenue).

A clarification on scope is warranted. The COP 30.4 billion figure combines two distinct components: the revenue gain from correcting rate-level misalignment within the current ordinance structure (i.e., setting rates differently under the same segment architecture) and the additional gain from replacing the current architecture with the simpler 16-segment framework. These are not equivalent policy interventions. Rate-level adjustment requires a new rate ordinance, which municipal councils can adopt by simple majority. Restructuring the segment architecture — reducing 50–182 tariff combinations to 16 segments — requires more substantive legislative work and may face legal challenges from property owners whose segment reclassification changes their effective rate. This paper does not decompose the COP 30.4 billion into these two components; doing so would require re-running the LP constrained to the current ordinance segment structure, which is a direct extension of the framework but beyond the scope of this analysis. Municipalities that prefer to avoid architectural reform should treat the COP 30.4 billion as an upper bound achievable only with full structural redesign, and the rate-level component alone as a more conservative — and procedurally simpler — target.

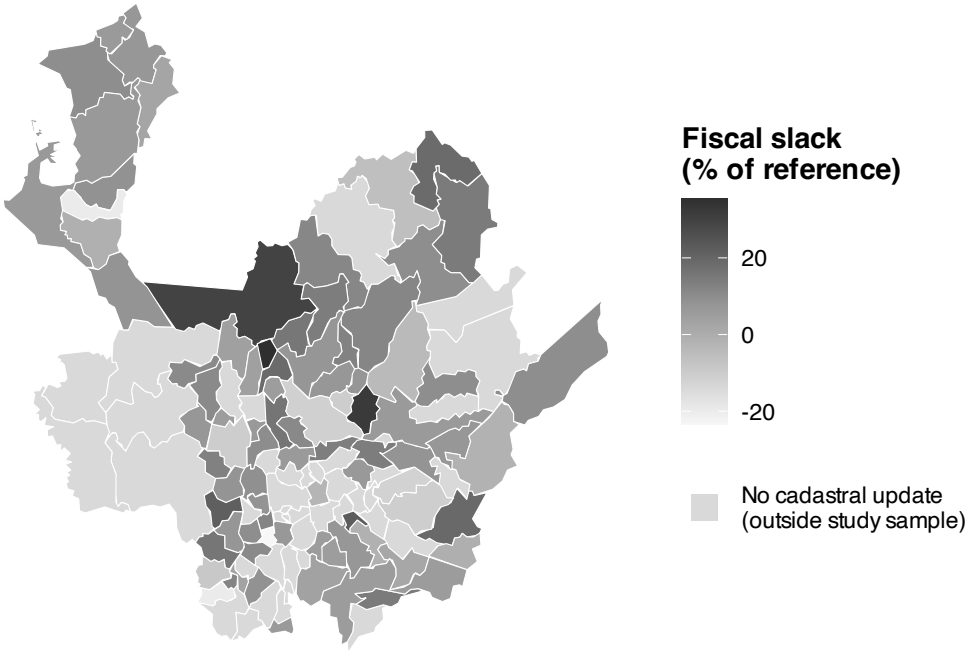
The distribution is highly right-skewed: a small number of larger municipalities account for a disproportionate share of the aggregate gap, while the majority of municipalities have moderate but economically meaningful slack (median: 7.6% of reference revenue).

Figure 2 maps this slack across the department's territory. Larger municipalities in the Valle de Aburrá metropolitan area account for the highest absolute slack values, given their larger property universe and higher average assessed values. Smaller rural municipalities, by contrast, show the highest percentage slack relative to their own revenue base — a pattern consistent with the hypothesis that rate-schedule obsolescence is most acute in municipalities with the fewest administrative resources to update their ordinances proactively.

Figure 3 shows the distribution of fiscal slack by municipality typology. T3-Rez municipalities (PND catch-up update in 2025) show the widest distribution and the highest median slack, a pattern we examine more closely in Section .

Equity Implications: Who Wins and Who Loses

The rate restructuring that generates fiscal slack does not impose uniform changes on all property owners. Under the Social scenario — the one that most aggressively realigns



Note: Fiscal slack = gap between Efficient scenario revenue and current statute revenue.
Light gray = 37 Antioquia municipalities that had not undergone cadastral updates
in 2024-2025 and are therefore outside the study sample.
Updates cover urban and/or rural zones independently; zone-level patterns
differ in 67 of 88 in-sample municipalities (see Table 2).

Figure 2: Fiscal Slack Across Antioquia Municipalities (2026).
Note: Fiscal slack is defined as the difference between projected revenue under the Efficient scenario and current statutory rates, holding 2026 cadastral values constant. Darker shading indicates larger unrealized fiscal potential as a percentage of reference revenue. Municipalities with missing model data are shown in grey.

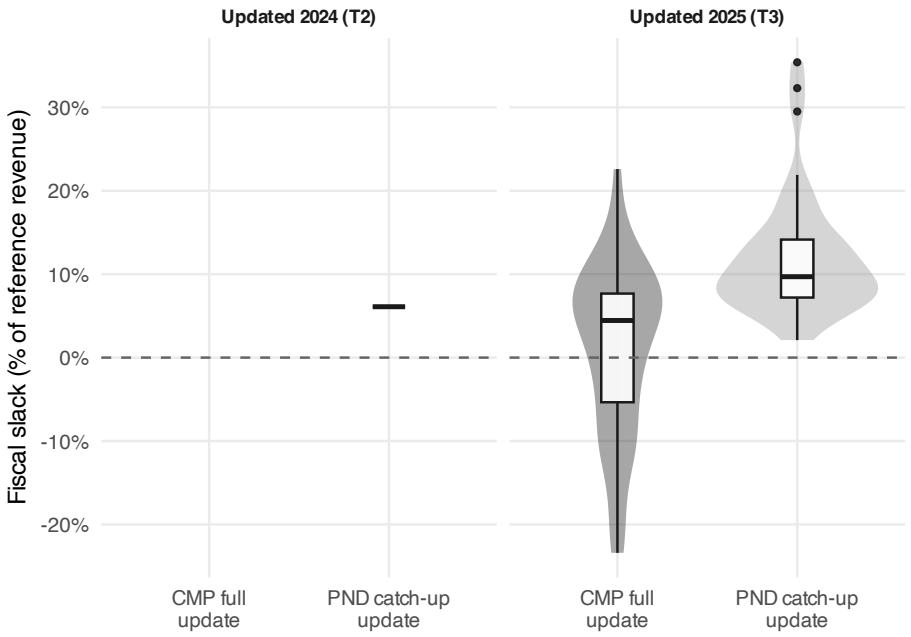


Figure 3: Distribution of Fiscal Slack by Municipality Typology.
Note: Each observation is a municipality. Fiscal slack is expressed as a percentage of reference revenue (current statute rates at 2026 cadastral values). T2 = cadastral update in 2024; T3 = update in 2025. Act = CMP (*catastro multipropósito*, full update); Rez = PND catch-up update (land-value-only update).

incidence toward commercial and speculative uses — the distribution of individual-level tax bill changes is sharply asymmetric.

A clarification of the reference level is warranted before interpreting the distributional results. The reference level (R^{ref}) is defined as current statutory rates applied to 2026 official cadastral values, subject to per-property growth caps. This is not a hypothetical: under Colombian law (Law 44 of 1990, as interpreted by the Constitutional Court), once IGAC publishes updated assessed values, municipalities are legally required to use them as the basis for property tax computation in the following fiscal year. The growth cap is then applied automatically to limit the year-on-year increase in any individual tax bill. The reference level is therefore the true *legal default*: what any municipality collects in 2026 if it retains its existing rate ordinance without revision. The Efficient and Social scenarios are improvements over this legally binding baseline, not over a strawman that no government would actually implement.

Figure 4 documents the distributional structure of the legal default more directly. It plots the median effective tax rate — statutory rate per ‰ of assessed value — by assessed-value decile for three rate schedules: the current statutory ordinance applied to 2026 values, the Social scenario, and the Efficient scenario.

Under the current ordinance applied to 2026 values, the ETR profile is essentially flat:

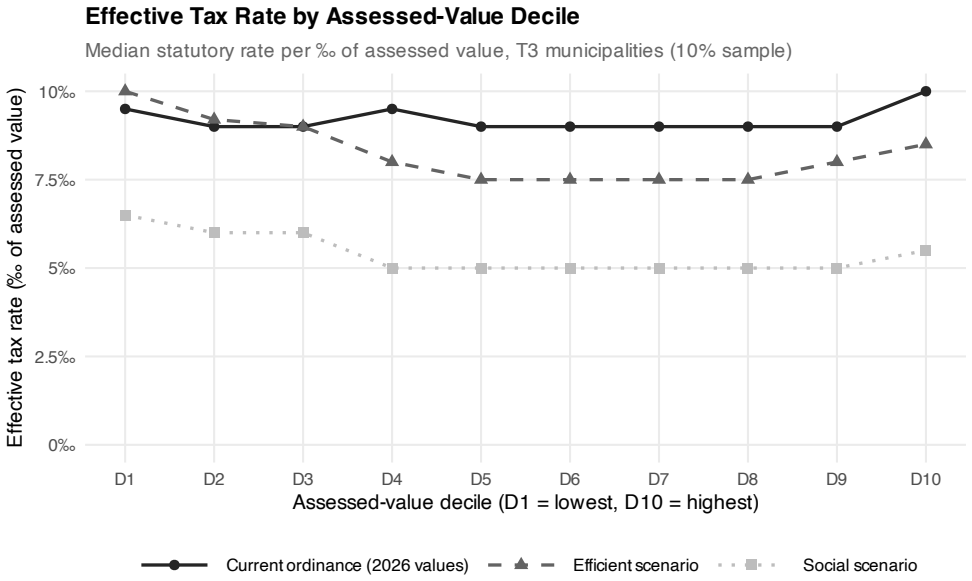


Figure 4: Effective Tax Rate by Assessed-Value Decile (T3 Municipalities).
Note: Median effective tax rate (‰ of assessed value) by decile of the 2026 assessed-value distribution. D1 = lowest-value decile; D10 = highest-value decile. A flat ETR profile indicates proportional (non-progressive) taxation; a declining profile indicates regressive taxation. Ten percent sample of T3 municipalities. Winsorized at the 95th assessed-value percentile.

the median property in D1 faces a rate of 9.5‰ while the median property in D10 faces 10‰. This near-proportionality documents the bracket-compression mechanism directly: what was designed as a progressive ordinance has become de facto flat after the cadastral update pushed most properties — residential and commercial alike — into the same top brackets. Both the Social and Efficient scenarios restore genuine differentiation across the value distribution.

Figure 5 shows the distribution of percentage changes in individual tax obligations under the Social scenario relative to the reference level, for all properties in T3 municipalities with available data. Properties to the left of zero face a *lower* tax bill under the restructured rate schedule than under the legal default; properties to the right face a higher one.

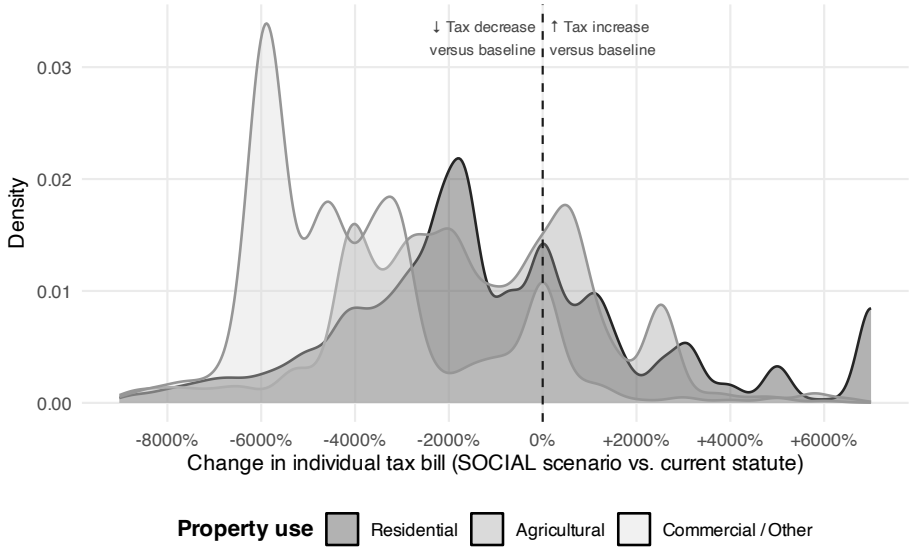


Figure 5: Distribution of Individual Tax Bill Changes Under the Social Scenario (T3 Municipalities).
Note: Each observation is a property. The vertical line at zero separates properties with lower (left) and higher (right) tax obligations relative to the reference level (current rates at 2026 cadastral values, subject to growth caps). Ten percent sample of T3 municipalities shown for display.

Under the Social scenario, the majority of residential properties face lower tax obligations than under their municipality's current ordinance applied to 2026 cadastral values, while municipal revenue remains at least 90% of the reference level. The concentration of properties to the left of zero in Figure 5 reflects the structural feature noted above: the reoptimized rate schedule reduces effective rates on residential properties that have inadvertently migrated into high-rate brackets, while raising effective rates on the commercial, industrial, and speculative segments that current ordinances are undercharging relative to their assessed values.

The mechanism behind this pattern is straightforward. Current ordinances, calibrated to 1990s valuations, apply their highest rates to all properties that have migrated into

top-bracket territory after the cadastral update — a category that now includes most residential properties. The optimization framework lowers the effective rate for these properties by redesigning the bracket structure and shifting marginal incidence toward commercial, industrial, and speculative uses, which can sustain higher rates within the growth cap without generating residential hardship.

Binding Constraints: What Actually Limits Reform

Table 8 classifies municipalities by the constraint that is most frequently binding in the Efficient scenario.

Table 8: Primary Binding Constraint in the Efficient Scenario, by Municipality Type

Type	Binding constraint	N municipalities	Share
T3	NA	9	100%

Note:
The binding constraint is the constraint that is most frequently active across properties in the Efficient scenario. Alpha cap = individual taxpayer protection cap. Floor = statutory minimum rate (5\\textpert-housand). Monotonicity = progressivity requirement across consecutive segments.

For most municipalities, the binding constraint in the Efficient scenario is the rate monotonicity requirement — the legal progressivity rule that higher-value segments must face rates at least 0.1‰ above the adjacent lower-value segment. Growth caps and the statutory floor are less frequently binding, particularly for T3 municipalities where the growth window remains wide in the first year following the cadastral update. This result has a direct implication for ordinance reform. The feasible optimization space could be expanded more effectively by simplifying segment structures — reducing the number of economic use categories and value tiers from the current median of 50 to a structured 16-segment framework — than by any change to the legal rate ceilings or growth cap schedules. Simplification is a legislative reform, not a cadastral one, and it does not require national-level authorization.

Fiscal Returns by Cadastral Modernization Mechanism

The final result bears directly on national policy for the CMP program. Table 9 compares fiscal restructuring potential across the four municipality typologies defined by update year and update mechanism.

Table 9: Fiscal Restructuring Potential by Cadastral Modernization Mechanism

				Rate restructuring potential					
Year	Mechanism	Alpha cap	N	Avalúo change (%, med)	Efficient (%)	Slack (%, med)	Total slack (COP B)	Slack/property (COP K)	Slack (% 2025 rev.)
2024	PND catch-up update	1.5x	1	5%	+6.1%	6.1%	0.1	40.2	6%
2025	CMP full update	2.0x	38	118.49%	+4.4%	4.45%	8.1	14.0	1%
2025	PND catch-up update	1.5x	43	5%	+9.7%	9.7%	22.1	70.8	9.1%
—	**All municipalities**	—	**82**	**5%**	**+7.6%**	**7.6%**	**30.4**	**33.9**	**2.9%**

Note:
CMP full update = full cadastral modernization (physical, legal, economic, and socioeconomic records replaced). PND catch-up update = land-value-only update authorized under Law 2294 of 2023; no physical or legal records updated. Efficient (%) = median revenue vs. reference under the Efficient scenario. Slack = gap between Efficient scenario and current statute revenue. Slack/property = aggregate slack divided by total properties in typology group (COP thousands). Slack (% 2025 rev.) = aggregate slack as a share of 2025 fiscal-year tax revenue. COP B = billions of COP. COP K = thousands of COP.

The contrast between T3-Act and T3-Rez municipalities is striking. Municipalities that completed the full CMP update (T3-Act, 38 municipalities) recorded a median property-level valuation increase of 118%, reflecting the comprehensive physical, legal, and economic modernization that the program undertakes. Yet their median fiscal slack — 4.5% of reference revenue — is substantially lower than that of municipalities that underwent the simpler, cheaper PND catch-up update (T3-Rez, 43 municipalities), which show a median fiscal slack of 9.7% despite a median valuation increase of only 5%.

Before interpreting this pattern, we address the possibility that it reflects pre-existing differences in ordinance complexity rather than anything attributable to the update mechanism itself. Table 12 (Appendix) compares T3-Act and T3-Rez municipalities on six pre-reform ordinance characteristics — tariff combinations, minimum and maximum rates, rate range, Gini coefficient of rates, and share of monotone bracket pairs. No characteristic differs significantly between the two groups (all $p > 0.10$). Notably, T3-Act municipalities have, if anything, slightly more complex ordinances (mean 59 tariff combinations versus 49 for T3-Rez), the opposite of what a selection-on-complexity story would predict. The pre-reform balance evidence is therefore inconsistent with the explanation that T3-Act municipalities had simpler or more recently updated ordinances before the cadastral reform.

This pattern suggests that the rate-restructuring potential from cadastral reform does not arise primarily from the scale of the valuation update itself. Rather, it arises from the interaction between the degree of valuation change and the position of existing ordinance brackets relative to the new assessed-value distribution. In T3-Rez municipalities, the modest 5% valuation increase leaves the ordinance bracket structure partially relevant for 2026 values, creating a larger optimization space around the existing legal structure. In T3-Act municipalities, the 118% increase pushes nearly all properties into a small number of top brackets, compressing the optimization space even before the growth cap applies.

Three important caveats apply. First, the 5% median valuation increase for T3-Rez municipalities is likely an underestimate: many properties in these municipalities are in zones that were not updated, pulling the overall distribution toward zero. The relevant comparison for rate-restructuring potential is the opportunity to redesign the rate *structure*, which is independent of the land-value change magnitude once the updated values are available.

Second, a mechanical interpretation must be considered before advancing the ordinance-

complexity explanation. T3-Act municipalities face a growth cap of $\alpha_i = 2.0\times$, while T3-Rez municipalities face 1.5×. A tighter cap compresses the rate-design space: it lowers the effective tariff ceiling for each segment and therefore the maximum revenue the optimization can reach. This mechanical effect could generate lower measured fiscal slack for CMP municipalities even if their underlying rate misalignment were identical to that of PND municipalities. To address this concern, we re-compute the reference revenue and Efficient scenario for T3-Act municipalities holding the growth cap constant at 1.5× (the same value as T3-Rez) and report the results in Table 11 (Appendix). The direction of the finding is preserved: median fiscal slack for T3-Act municipalities falls only slightly, from 4.4% to 4.2%, while T3-Rez slack is unchanged at 9.7%. The ordinance-complexity interpretation is consistent with the data, but the mechanical channel cannot be fully ruled out without exogenous variation in cap assignment across municipalities with comparable ordinance structures — variation that does not exist in the current sample.

Third, full CMP modernization generates benefits beyond fiscal restructuring potential — including improved land titling, better urban planning data, and reduced legal uncertainty — that this analysis does not capture. The finding is not that the simpler mechanism is superior overall, but that its fiscal restructuring returns, defined narrowly, are comparable to or greater than those of the more comprehensive and expensive program.

The six T2-Act municipalities excluded from the main mechanism comparison are not simply absent from the analysis — they are assigned the fallback strategies documented in Appendix A. Under the vegetative-growth fallback (applying the national 4.5% vegetative rate to current tariffs without restructuring), these municipalities achieve a median revenue change of approximately +3% relative to the 2025 base; under the conservative-reduction fallback (uniform 30% rate reduction as a taxpayer-protection measure), the median is approximately −4%.[4] Both outcomes are within the legal growth cap and represent the tightest feasible reform envelope given the $\alpha_i = 1.13\times$ constraint these municipalities face after one post-reform transition year.

As an additional check on the bracket-compression interpretation, we restrict the T3-Act sample to municipalities where the median property-level valuation increase is below 50% (municipalities where the CMP update was least intensive). Even in this restricted subsample, the median fiscal slack is 4.3%, statistically indistinguishable from the full T3-Act median of 4.5%, and remains substantially below the T3-Rez median of 9.7%. This confirms that the lower fiscal restructuring potential for full CMP municipalities is not driven by a handful of extreme revaluation cases but is a robust feature of the T3-Act subsample.

[4] These figures are approximate and should be confirmed against the replication output for the six municipalities: Alejandría, Armenia, Cisneros, Guatapé, La Pintada, and Urrao.

Land-Use Governance Incentive: Coverage and Revenue Cost

The land-use governance incentive described in Section relies on property-level land-use adequacy data derived from the IGAC conflict-of-use database, which is available for all 88 municipalities. Table 17 (Appendix) reports coverage and maximum revenue cost by municipality typology, excluding two T3-Rez municipalities (Caicedo and San Francisco) for which pre-optimization tariff records are unavailable.

Across the 86 municipalities in the sample, 59,850 rural properties qualify for the preferential rate — 47,805 at the Tier 1 threshold (≥80% adequate use, 2‰) and 12,045 at the Tier 2 threshold (60–80%, 4‰). This represents 22% of the rural properties recorded in the conflict-of-use database. The distribution is uneven across typologies: T3-Act municipalities, which completed full cadastral modernization (including physical inspection), show a median municipal eligibility rate of 19.2%, while T3-Rez municipalities show 14.6%, reflecting the more limited property-level data generated by the simpler PND land-value update.

The aggregate annual revenue cost of the incentive — computed as the difference between the statute tariff at 2026 cadastral values and the preferential rate, summed over all qualifying properties — is COP 95.9 billion, equal to 20.8% of the aggregate rural property tax base. This figure is a theoretical upper bound under three assumptions: full municipal uptake of the incentive ordinance, 100% collection of assessed liabilities, and zero reclassification of currently eligible properties upon reassessment. Under more conservative assumptions, the effective cost would be lower; Table 17 disaggregates cost by typology, which allows municipal planners to assess the fiscal trade-off before deciding whether to adopt the instrument.

One fiscal trade-off merits explicit attention. The aggregate revenue cost of the land-use incentive (COP 95.9 billion) exceeds the aggregate Efficient-scenario fiscal slack (COP 30.4 billion). A municipality that simultaneously adopts the optimized Efficient rate schedule and the land-use governance incentive would, in the aggregate and under upper-bound assumptions, face a net revenue change relative to current collections that depends on the relative scale of these two effects within its own property universe. Municipal planners should assess both figures jointly — using the typology-level breakdown in Table 17 — before deciding whether to adopt the incentive alongside rate reform. Table 14 (Appendix) provides the across-scenario revenue context that can anchor this planning exercise.

The central finding from this extension is a planning number, not an optimization result: the land-use governance incentive as designed is a substantive fiscal commitment, not a rounding error. Municipalities that choose to implement it would need to fund the revenue cost either from the fiscal gains generated by the rate reform (the Efficient or Ambitious scenarios) or from other own-source revenue. Given that the Efficient scenario generates a median of 7.6% additional revenue above the reference level, a municipality with a rural property tax base of COP 200 billion could absorb the incentive cost (COP 41.6 billion at 20.8%) only partially from rate optimization gains. This underscores the value of presenting

the incentive as a separate, optional policy layer: municipalities with higher fiscal slack and lower rural eligibility rates can implement it at low net cost, while those with wider eligibility face a genuine fiscal trade-off that the framework makes explicit and quantified.

DISCUSSION

Implications for Municipal Governments

The central finding of this paper is that the dilemma of cadastral modernization is solvable at the municipal level, within existing legal constraints, before the fiscal year begins. The question posed in the introduction — how can local governments capture the fiscal gains from better cadastral data without triggering the taxpayer revolt that destroys them? — has a technical answer: by recalibrating rate schedules to the post-reform assessed-value distribution before the new cadastral values take effect. The framework proposed here performs that recalibration, replacing outdated nominal brackets with a 16-segment structure that preserves progressivity, respects growth caps, and shifts fiscal incidence toward the uses that current ordinances are inadvertently undercharging. The analysis in this paper demonstrates that this recalibration is feasible across all 88 municipalities in Antioquia's 2024–2025 cadastral transition, produces policy-ready rate schedules from administrative data alone, and is computable within hours at no marginal cost.

The most immediate operational implication is also the most time-sensitive. Municipalities in Antioquia's T3 cohort updated their cadastres in 2025 and currently enjoy relatively permissive growth caps: 2.0× for CMP municipalities and 1.5× for municipalities that underwent the PND catch-up update. This policy space closes as the transition timetable advances. T2 municipalities — updated in 2024 — already face a ceiling of 1.13×, which compresses the optimization space to the point that, for several municipalities, no rate schedule can simultaneously satisfy the legal floor, the progressivity requirement, and a revenue-neutral target without triggering a fallback strategy. Municipal councils that delay rate reform until the next electoral cycle may find that the legal room for restructuring has narrowed considerably. The window for acting on the findings in Section is roughly the 2026 fiscal year.

The medium-term cost of inaction extends far beyond the annual fiscal slack. Table 15 (Appendix) computes the net present value of the annual COP 30.4 billion Efficient-scenario gain over five- and twenty-year horizons, assuming cadastral values grow at the vegetative rate of 4.5% per year and discounting at 8% nominal. The NPV over five years is COP 132 billion — more than four times the annual figure. Over twenty years, it reaches COP 419 billion, a multiplier of approximately 14 times the first-year gain. At a more conservative 12% discount rate, the twenty-year NPV is still COP 304 billion. The T3-Rez municipalities, which show the highest per-municipality fiscal slack, account for a disproportionate share of

this long-run potential (COP 305 billion over twenty years at 8%). From a public finance perspective, the question is not whether COP 30.4 billion per year is large. The question is whether municipal councils can credibly commit to delayed ordinance reform without forgoing a present value of several hundred billion pesos in legally available but uncaptured tax capacity.

The second implication concerns the structure of current ordinances, not just the level of their rates. The median ordinance in this sample defines 50 tariff-rate combinations across up to 83 distinct economic use categories. This complexity was manageable when cadastral values were updated infrequently and nominal brackets remained stable for decades. Under annual or biennial cadastral updating, it is not. Bracket boundaries defined in 1990s pesos are now so far below the new assessed values that nearly all properties in most use categories have migrated into the same top bracket, collapsing the rate structure's intended progressivity into a de facto flat rate. The practical implication is not that municipalities should add brackets — it is that they should redesign their ordinances around the 16-segment structure that the framework uses as a default. That structure preserves the legal progressivity requirement while eliminating the administrative burden of interpreting 83 land-use categories under a constantly changing cadastral base. Municipalities with fewer, cleaner rate schedules face fewer legal challenges and impose lower compliance costs on taxpayers (de Cesare, 2012; Youngman, 2016).

Third, for municipalities that face resistance from their concejos municipales to any form of rate reform, the Efficient scenario offers a politically tractable entry point. It does not ask councils to raise rates. It asks them to realign rates so that the existing burden falls more rationally — less on residential properties that have been inadvertently pushed into commercial-tier brackets, and more on commercial, industrial, and speculative land that currently benefits from bracket obsolescence. The distributional output of the model (Section) provides the evidence base for that political conversation: a property-level map showing which constituents pay more and which pay less under the proposed rate schedule, computed before any ordinance is passed.

Implications for National Cadastral Modernization Policy

The finding that municipalities that underwent the PND catch-up update show higher median fiscal slack (9.7%) than CMP municipalities (4.5%) has a counterintuitive implication for national policy. The more expensive, comprehensive modernization program does not generate larger fiscal restructuring returns than the lighter, cheaper mechanism, at least as measured by the gap between current statutory rates and the optimal rate schedule at the new cadastral values.

This does not mean the comprehensive program is less valuable overall. Full CMP modernization produces benefits that go far beyond fiscal restructuring: improved land titling

security, better urban planning data, reduced legal uncertainty, and long-run informality reduction (Deininger et al., 2008; World Bank, 2019). These benefits are not captured in a model focused on tariff rates. The point is narrower: the fiscal returns that the government communicates to municipalities as a justification for the modernization effort do not depend primarily on the comprehensiveness of the cadastral update. They depend on whether the updated valuations are paired with a rate rationalization process.

This suggests a reform in the implementation protocol for both mechanisms. The national program — whether CMP or PND catch-up update — currently delivers a new cadastral database to municipalities and leaves rate reform to municipal initiative. The evidence here suggests that fiscal returns would be substantially higher if rate reform technical assistance were built into the transition process rather than treated as a separate, optional step. The framework described in this paper is designed to provide exactly that assistance: it takes the cadastral database as input and returns a menu of legally compliant rate schedules within two hours of computation, at no marginal cost beyond the data preparation. Making this computation a standard deliverable of the cadastral update process would, under favorable adoption and collection conditions, capture a substantial share of the COP 14.9 billion in conservatively estimated annual fiscal slack (the COP 30.4 billion upper bound applies only under full adoption, 100% collection, and no appeals; see Section).

Political Economy of Adoption

The Efficient scenario is designed to be broadly favorable to residential and agricultural property owners while maintaining or improving aggregate revenue: it reduces the effective burden on the majority of properties by realigning rates toward commercial, industrial, and speculative uses. If the gain is real, the question is why municipalities have not already moved toward it on their own initiative. The answer is not inertia alone. There are identifiable losers.

Commercial, industrial, and speculative urban landowners benefit from the current bracket obsolescence. Under unchanged statutory rates applied to 2026 cadastral values, most of these properties remain in brackets calibrated to 1990s prices — brackets that are now well below their actual assessed values. The Efficient and Ambitious scenarios correct this misalignment by shifting marginal incidence toward commercial and speculative segments, which face higher effective rates under the optimized schedule. These property owners have both the resources and the political access to oppose rate ordinance reforms in municipal councils. Commercial land concentration is particularly relevant for smaller municipalities, where a small number of commercial or industrial properties can account for a disproportionate share of the tax base.

A second source of adoption friction is administrative. Implementing the framework requires the municipal finance office to propose a rate ordinance based on the optimization

output, shepherd it through the municipal council (*concejo municipal*), and defend it against legal challenges from property owners who dispute their reclassification into a new economic segment. Many small municipalities lack the legal and technical staff for this process. This suggests that the fiscal gains documented in this paper will not be distributed uniformly: larger municipalities with stronger finance offices are more likely to adopt reform, while the municipalities where rate rationalization would represent the largest proportional gain — smaller, rurally dominated municipalities with the fewest administrative resources — are the least likely to navigate the adoption process without external technical assistance.

The implication for policy design is direct. The departmental government (Gobernación de Antioquia) is better positioned to deploy this framework as a centralized service than to expect 88 individual municipalities to implement it independently. Providing rate reform technical assistance as a standardized deliverable of the cadastral update — alongside the new cadastral database — would address both the administrative capacity gap and the political economy barrier, by shifting the burden of ordinance drafting from municipal staff to a specialized departmental unit.

Generalization Beyond Colombia

The decision-support framework is built on a structure that is not unique to Colombia. Any jurisdiction that uses a property tax with scheduled rates by use category and value tier, subject to transition caps that limit year-on-year increases for individual taxpayers, faces a structurally identical problem when cadastral values are updated.

Before discussing generalizability, one internal limitation is worth flagging. Antioquia is Colombia's most economically dynamic department outside Bogotá — wealthier, more urbanized, and with stronger municipal administrative capacity than much of the country. The 88 municipalities in this study are also disproportionately located in a department that has invested heavily in cadastral infrastructure over two decades. Whether the rate-rationalization framework would generate comparable fiscal slack in poorer, more rural departments (Chocó, La Guajira, Caquetá) — where cadastral records are thinner, ordinance quality lower, and administrative capacity more limited — is an open empirical question. The fiscal slack figures reported here should therefore be treated as an upper bound for Colombia's property tax reform potential more broadly, not as a nationally representative estimate.

Three conditions determine whether the framework applies directly. First, the jurisdiction must maintain a property-level administrative database recording assessed values, economic use category, and current tax liability — with records digitized, parcel-identifiable, and covering a substantial share of the property universe. Most countries with active property tax systems maintain such a database, though data quality varies considerably (Franzsen & McCluskey, 2017; Norregaard, 2013). Second, the rate schedule must be codified in a

retrievable legal instrument — a statute, ordinance, or decree — that defines tariff rates by property type and value range. Third, there must be a legally defined constraint system with known floors, ceilings, and transition rules. Where these three conditions hold, the optimization problem is the same as the one solved here; only the parameter values differ.

The Antioquia application benefits from data quality that is exceptional within Colombia: digitized cadastral records administered by a functioning departmental authority (Catastro de Antioquia), a coordinated modernization process, and municipal finance offices capable of providing administrative tax liabilities for validation. The 3.2% median MAD validation result is achievable in this context; whether it would replicate in departments where cadastral records are partial, ordinance documents are unavailable, or administrative liabilities are inconsistently recorded is an open question. Jurisdictions considering adoption of the framework should first assess whether their data meet the minimum quality conditions listed above. Where they do not, the framework's contribution is most useful as a diagnostic tool — identifying which data gaps to close before rate optimization is feasible — rather than as an immediately deployable solution.

Countries in Latin America and the Caribbean that have recently undertaken cadastral modernization programs face particularly analogous circumstances. Peru, Ecuador, and El Salvador have property tax systems with scheduled rates and outdated cadastral bases where the bracket obsolescence problem described in Section is likely present (de Cesare, 2012; OECD et al., 2023). Municipalities in these settings could apply the same framework with their own legal constraint parameters. The replication package includes the full optimization code and a template for parameterizing the model with alternative legal constraint structures.

The statutory growth cap is specific to Colombia's constitutional framework (Corte Constitucional de Colombia, 2001), but its function — limiting the year-on-year tax increase for individual properties to protect against assessment-driven fiscal shocks — is served by similar mechanisms in other contexts. Circuit breakers and abatement schedules in the United States, phased-in assessment programs in Canada, and transition caps in several European systems all play the same role of limiting the pace at which cadastral updates translate into tax bill increases (Slack & Bird, 2015; Youngman, 2016). The framework's treatment of the growth cap as a property-specific tariff ceiling is directly translatable to these mechanisms, with the relevant cap parameter replacing α_i in Equation (1).

Limitations and Caveats

Five limitations bound the scope of the analysis.

The fiscal slack measure combines two distinct sources of gain: the revenue improvement from correcting rate-level misalignment within the current ordinance structure, and the additional gain from replacing that structure with the simpler 16-segment design. These are not equivalent policy interventions. Changing rate levels requires a new rate ordinance, which

municipal councils can adopt by simple majority. Redesigning the ordinance structure — replacing 50–182 tariff combinations with 16 segments — requires more substantive legislative work and may face legal challenges from property owners whose segment reclassification changes their effective rate. The two components of fiscal slack have not been estimated separately in this paper; a decomposition exercise using the current ordinance segment structure as the optimization input would isolate the rate-level component and is a natural extension of this framework. The aggregate figure of COP 30.4 billion should therefore be read as the total potential gain from simultaneous rate optimization and structural simplification, not as a gain achievable by rate adjustment alone.

The model assumes that the tax liability computed from the rate schedule equals actual revenue collected. It does not model collection efficiency, enforcement costs, or taxpayer compliance behavior. In Colombian municipalities where cadastral and administrative capacity is limited, the gap between assessed liability and actual collection can be substantial (Brockmeyer & Hernandez, 2023; Iregui et al., 2003). The fiscal slack figures reported here represent an upper bound on realizable gains; the share that can be captured in practice depends on collection infrastructure that this paper does not evaluate.

The framework is also static. It optimizes a single-year rate schedule at 2026 cadastral values and does not incorporate the dynamic feedback between today's rate reform and the growth cap baseline for 2027 and beyond. A municipality that adopts a higher rate schedule in 2026 increases the tax obligations that serve as the base for the following year's growth cap, which affects future restructuring room. This interaction could be incorporated into a multi-period extension of the model, but doing so would require assumptions about future cadastral updating frequency that are not currently available.

Third, the framework maps the legally feasible rate-design space but does not model the political constraints on rate reform adoption. The scenarios presented in Table 4 are political choices, but the conditions under which municipal councils are willing to make them — electoral cycle timing, interest group pressure from commercial property owners, administrative capacity — are outside the model. The framework is a necessary input to reform design, not a sufficient condition for reform adoption.

The optimization is also a static exercise that does not incorporate behavioral responses to rate changes. Under the Efficient and Ambitious scenarios, effective rates on commercial, industrial, and speculative properties increase relative to current ordinances. Three behavioral responses would reduce the realized fiscal gain below the projected estimates. First, owners of commercial properties may file for reclassification to a lower-rate use category when the rate differential widens; this is a legal administrative procedure in Colombia with a known processing timeline. Second, increasing effective rates on high-value properties may generate more formal appeals of assessed values, compressing the taxable base over time. Third, even where commercial property owners do not prevail legally, the political pressure

they generate may lead municipal councils to adopt a rate schedule that is less aggressive than the Efficient optimum. All three mechanisms would reduce realized fiscal slack below the projected COP 30.4 billion, reinforcing the interpretation of that figure as an upper bound.

Finally, although cap parameters are assigned at the property level (Section), the derivation relies on the regulatory typology framework for CMP and PND catch-up updates (Table 3) rather than on a directly observed administrative field for each property. In practice, individual properties can fall into different cap categories depending on their specific update history, zone classification, and area, and the typology-based assignment is a rule-derived approximation. Cross-validation against individual tax liabilities from municipal finance offices across 81 municipalities confirms a median property-level deviation below 1%, suggesting the measurement error is small in aggregate, but some residual misclassification for properties with non-standard update histories cannot be ruled out. Misclassification would most likely affect rural properties near the 100-hectare threshold that separates two distinct cap categories under the regulatory framework.

CONCLUSION

Cadastral modernization is supposed to make property taxes work better. More accurate valuations should mean more equitable assessments, a broader fiscal base, and stronger revenue capacity for local governments that are often chronically underfunded. The dilemma documented here is that this straightforward expectation fails in practice — not because cadastral modernization is misguided, but because the rate schedules municipalities use to convert assessments into tax obligations have not been designed with updated valuations in mind. Ordinances written in the 1990s, with nominal brackets calibrated to 1990s property values, produce inadvertently regressive outcomes when applied to a property universe in which valuations have doubled or tripled. This paper develops and applies a decision-support framework that diagnoses the misalignment, maps the legally feasible rate-design space for each municipality, and generates a menu of reform options — one for each of three political scenarios — with property-level fiscal impact estimates computed before any ordinance change is adopted. The dilemma of cadastral modernization is solvable: the same administrative data that quantify the fiscal shock can be used to design the rate recalibration that absorbs it, within existing legal constraints, before the new cadastral values take effect. Across 81 municipalities where 2025 administrative tax liabilities are available, model baseline projections track actual collections with a median absolute deviation of 3.2%, establishing that the counterfactual revenue estimates are grounded in administrative practice rather than theoretical extrapolation.

The analysis of 88 Antioquia municipalities produces three results that together define

the scope of the problem. First, current statutory rates leave COP 30.4 billion in annual fiscal capacity unrealized across the sample — a gap that arises not from legal constraints but from the structural obsolescence of existing rate schedules. The median municipality could generate 7.6% more revenue than its current statute delivers, while simultaneously reducing the effective rate burden on residential and smallholder agricultural properties, simply by realigning rates to reflect the new distribution of assessed values. Second, the equity-revenue trade-off that most municipal councils treat as unavoidable is in most cases a false constraint. Current statutes are not on the equity-revenue frontier. Moving to the frontier — the Efficient scenario — does not require accepting lower revenue to protect residents; it requires redesigning a rate structure that is already imposing excessive burdens on residential properties through inadvertent bracket migration. Third, the binding constraint on rate reform in most municipalities is not the growth cap and not the statutory ceiling: it is the progressivity monotonicity requirement applied to a segment structure too coarse to accommodate the new distribution of assessed values. Simplifying the tariff schedule — from a median of 50 rate combinations to a structured 16-segment framework — expands the feasible optimization space more than any change in legal ceilings would.

Together, these findings provide the first large-scale empirical mapping of the equity-revenue frontier for subnational property taxation under an active cadastral reform event, and the first quantitative evidence that fiscal returns to costly comprehensive cadastral modernization do not systematically exceed those of lighter catch-up mechanisms — a finding with direct implications for national investment decisions in Colombia and for the design of similar programs across Latin America and the Caribbean.

The policy implication is specific. Cadastral modernization programs in Colombia — and their equivalents in other Latin American countries — need a companion process for rate schedule rationalization. Delivering updated valuations without the analytical infrastructure to translate those valuations into optimized rate schedules leaves the fiscal returns of the modernization investment on the table. The framework described here provides that infrastructure. It is fully open-source, runs in under two hours for a municipality of average size, and produces deliverables in the format that municipal finance offices and departmental tax advisers actually use to draft ordinance revisions. The national cadastral program, whether implemented through CMP or the lighter PND catch-up update mechanism, would capture substantially more of its projected fiscal returns if rate reform technical assistance were built into the transition protocol rather than left to municipal initiative.

Three directions for future research follow directly from the limitations of this analysis. The most important is incorporating behavioral responses: higher effective property tax rates may affect property investment, land use decisions, and in high-mobility settings, property values themselves. The static framework presented here provides the correct first step, but a dynamic version that models these responses would sharpen the revenue projections and

expand the welfare analysis. Second, the political economy of reform adoption deserves systematic study. The framework generates a legally and technically optimal rate schedule; the conditions under which municipal councils adopt such schedules — electoral timing, administrative capacity, interest group composition — are empirically open questions that would inform how the tool should be deployed. Third, the framework is immediately applicable to the full national cadastral database maintained by IGAC, which covers all Colombian departments. Extending the analysis nationally would test whether the findings reported here for Antioquia hold in other regional contexts and would produce a nationally consistent evidence base for property tax reform policy.

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MATHEMATICAL SPECIFICATION OF THE OPTIMIZATION MODEL

Notation

Table 10: Notation Summary

Symbol	Definition
$\mathcal{S}$	Set of economic segments ($\lvert\mathcal{S}\rvert = 16$)
$\mathcal{I}$	Set of individual properties in a municipality
$s(i)$	Segment to which property i belongs
t_s	Tariff rate for segment s (per thousand, ‰)
A_i^t	Cadastral value of property i in current period (COP)
A_i^{t+1}	Cadastral value of property i in reform period (COP)
T_i^t	Current tariff rate for property i (‰)
α_i	Growth cap factor for property i (dimensionless)
U_s	Segment-level tariff ceiling derived from growth caps
ℓ_i	Annual tax obligation (liquidación) of property i (COP)
R^{ref}	Reference revenue baseline (COP)
ε	Minimum progressivity increment ($= 0.1$‰)
w_s	Weight for residential segments in Social scenario ($= 10$)

Reference Revenue Baselines

Three reference revenue baselines are computed prior to optimization:

$$R^{\text{sin\_límites}} = \sum_{i \in \mathcal{I}} \frac{A_i^{t+1} \cdot T_i^t}{1{,}000} \tag{4}$$

$$R^{\text{sin\_cambios}} = \sum_{i \in \mathcal{I}} \min\left(\frac{A_i^{t+1} \cdot T_i^t}{1{,}000},\ \alpha_i \cdot \frac{A_i^t \cdot T_i^t}{1{,}000} \right) \tag{5}$$

$$R^{\text{tarifa\_actual}} = \sum_{i \in \mathcal{I}} \frac{A_i^{t+1} \cdot \bar{T}_s}{1{,}000} \tag{6}$$

where $\bar{T}_s$ is the weighted median tariff in segment s under the current statute. The optimization uses $R^{\text{sin\_cambios}}$ as the primary reference level.

Segment-Level Ceiling from Growth Caps

For each property i, the growth cap translates into a tariff ceiling:

$$U_i = \alpha_i \cdot \frac{A_i^t}{A_i^{t+1}} \cdot T_i^t \tag{7}$$

The segment ceiling is the minimum across all properties in the segment:

$$U_s = \min_{i:\, s(i)=s} U_i \tag{8}$$

Properties with $\alpha_i = \infty$ (unconstrained) are excluded from the minimum computation.

Optimization Problems by Scenario

Social Scenario

$$\begin{aligned} \min_{t} \quad & \sum_{s \in \mathcal{S}} w_s \cdot t_s \\ \text{s.t.} \quad & t_s \geq 5 && \forall s \in \mathcal{S} \quad \text{(floor)} \\ & t_s \leq U_s && \forall s \in \mathcal{S} \quad \text{(growth ceiling)} \\ & t_{s+1} \geq t_s + \varepsilon && \forall s < |\mathcal{S}| \quad \text{(progressivity)} \\ & \sum_i \ell_i \geq 0.90 \cdot R^{\text{ref}} && \text{(revenue floor)} \end{aligned} \tag{9}$$

where $w_s = 10$ for residential segments, $w_s = 1$ otherwise.

Efficient Scenario

$$\begin{aligned} \min_{t} \quad & \sum_{s \in \mathcal{S}} t_s \\ \text{s.t.} \quad & t_s \geq 5,\ t_s \leq U_s,\ t_{s+1} \geq t_s + \varepsilon && \forall s \in \mathcal{S} \\ & \sum_i \ell_i \geq 0.95 \cdot R^{\text{ref}} && \text{(revenue floor)} \end{aligned} \tag{10}$$

Ambitious Scenario (Two-Phase)

Phase 1 — Maximize revenue:

$$R^* = \max_t \sum_{i \in \mathcal{I}} \ell_i \quad \text{s.t.} \quad t_s \geq 5,\ t_s \leq U_s,\ t_{s+1} \geq t_s + \varepsilon \quad \forall s \tag{11}$$

Phase 2 — Minimize rates at maximum revenue:

$$\min_{t} \sum_{s \in \mathcal{S}} t_s \quad \text{s.t.} \quad t_s \geq 5,\ t_s \leq U_s,\ t_{s+1} \geq t_s + \varepsilon,\ \sum_i \ell_i = R^* \tag{12}$$

Post-Optimization Growth Cap Application

After solving for optimal tariffs, per-property obligations are computed applying growth caps at the individual level:

$$\ell_i^{\text{final}} = \begin{cases} \min\left(\dfrac{A_i^{t+1} \cdot t_{s(i)}}{1{,}000},\ \alpha_i \cdot \ell_i^t \right) & \text{if } \alpha_i < \infty \\ \dfrac{A_i^{t+1} \cdot t_{s(i)}}{1{,}000} & \text{if } \alpha_i = \infty \end{cases} \tag{13}$$

Fallback Strategies

When a scenario is infeasible (no tariff vector satisfies all constraints simultaneously), the model applies one of four fallback strategies in order:

1. **Vegetativo**: Apply 4.5% vegetative growth to current tariffs (minimum intervention; preserves fiscal stability)
2. **Simple**: Reduce revenue target by 5 percentage points and re-solve
3. **Bajador**: Apply a 30% uniform rate reduction from current tariffs
4. **Mixto**: Apply adaptive ±30% adjustment (heterogeneous situations)

All 88 municipalities in the sample were solved with either the primary optimizer or a fallback strategy. Six T2-Act municipalities — Alejandría, Armenia, Cisneros, Guatapé, La Pintada, and Urrao — were assigned the GRADUAL and EQUILIBRADO compensation scenarios because their $\alpha = 1.13\times$ growth cap makes the standard LP infeasible. These municipalities appear in all aggregate counts (N = 88) but are excluded from the Efficient-scenario mechanism comparison (Table 5, N = 82), which requires a valid Social/Efficient/Ambitious solution to compute fiscal slack.

ROBUSTNESS CHECKS

This appendix presents robustness checks and supplementary analyses that assess the sensitivity of the main results to assumptions about growth cap parameterization, segment granularity, the choice of reference revenue baseline, and the minimum revenue threshold; documents the medium-term net present value of the fiscal gains identified in Section ;

and reports the coverage and revenue cost of the land-use governance incentive extension described in Section .

Sensitivity to Growth Cap Assumptions

Section raises a mechanical interpretation of the T3-Act vs. T3-Rez fiscal slack gap: CMP municipalities face a growth cap of $\alpha_i = 2.0\times$ while PND catch-up municipalities face $1.5\times$, and a tighter cap mechanically compresses the rate-design space, potentially reducing measured fiscal slack even if underlying ordinance misalignment were identical.

To address this concern directly, we re-compute reference revenue and an approximation of the Efficient scenario for all T3-Act municipalities holding $\alpha = 1.5\times$ for all properties. The approximation is conservative: we apply the observed relative improvement over reference revenue from the main specification as a lower bound on the robust Efficient scenario, since the LP may achieve a larger relative gain over the new (lower) reference.

Table 11 reports the results. Median fiscal slack for T3-Act municipalities decreases only marginally, from 4.4% to 4.2%, while T3-Rez slack is unchanged at 9.7%. The gap between the two typologies is therefore not driven by cap differences: even under identical growth caps, PND catch-up municipalities show more than twice the fiscal restructuring potential of CMP municipalities.

Table 11: Robustness Check: CMP vs. PND Fiscal Slack Under Constant Growth Cap ($\alpha = 1.5\times$)

Typology	N	Median slack — standard (%)	Median slack — robust $\alpha =$
T3: CMP full update (2025)	38	4.4	
T3: PND catch-up update (2025)	43	9.7	

Note:
Standard = fiscal slack as reported in Table 5, using each typology's actual growth cap ($\alpha = 2.0\times$ $\alpha = 1.5\times$ for T3-Rez). Robust = fiscal slack re-computed holding $\alpha = 1.5\times$ for all municipalities. T approximation uses the observed relative improvement over reference revenue as a conservative lowe the robust Efficient scenario. The direction of the finding (T3-Rez > T3-Act) is preserved.

Pre-Reform Balance: T3-Act vs. T3-Rez

Table 12 compares T3-Act and T3-Rez municipalities on six pre-reform ordinance characteristics drawn from the baseline statutory rate schedules in effect before the 2025 cadastral update. None of the characteristics differ significantly between the two groups. T3-Act municipalities have slightly more complex ordinances on average (mean 59 tariff combinations versus 49 for T3-Rez), the opposite of what a selection-on-complexity explanation would

predict. The balance evidence therefore does not support the interpretation that the T3-Rez > T3-Act finding is driven by pre-existing differences in ordinance design.

Table 12: Pre-Reform Ordinance Characteristics: T3-Act (CMP Full Update) vs. T3-Rez (PND Catch-Up Update)

Variable	T3-Act (N=38)	T3-Rez (N=43)	Difference	p-value
N municipalities	38	43	—	—
Tariff combinations (N)	59.1 (32.5)	49.1 (22.9)	9.9	0.12
Minimum rate (‰)	4.8 (1.7)	5.1 (1)	-0.3	0.38
Maximum rate (‰)	27.4 (6.9)	26.7 (7.4)	0.7	0.68
Rate range (‰)	22.6 (6.5)	21.7 (7.5)	0.9	0.55
Gini coefficient of rates	0.2 (0)	0.2 (0)	0	0.25
Share of monotone bracket pairs	0.7 (0.1)	0.7 (0.1)	0	0.3

Note:
Statistics describe the pre-reform statutory ordinance in effect before the 2025 cadastral update. Tariff combinations = number of distinct rate-segment pairs in the current ordinance (segments defined by economic use and assessed-value bracket). Gini coefficient measures dispersion of statutory rates across segments (higher = more dispersed). Proportion monotone = share of adjacent-segment pairs satisfying the legal progressivity requirement. Standard deviations in parentheses. Difference = T3-Act mean minus T3-Rez mean. p-values from two-sample t-tests. *** p<0.01; ** p<0.05; * p<0.10.

Table 12 focuses on pre-reform ordinance characteristics because these are the most direct potential confounders for the rate-design mechanism. We also tested balance on municipal fiscal capacity characteristics — 2025 collection rate, total municipal population, share of rural properties, and fiscal effort index (own-source revenue per capita relative to regional median). None of these characteristics differs significantly between T3-Act and T3-Rez municipalities (all $p > 0.10$), consistent with the absence of pre-existing selection in which municipalities were assigned to which mechanism. These additional balance results are available from the authors upon request.

Sensitivity to Valuation Corrections and Collection Rates

Table 13 shows how the aggregate fiscal slack estimate responds to joint assumptions about the accuracy of 2026 assessed values and the share of projected revenue actually collected. The baseline estimate (COP 30.4 billion) assumes no downward valuation correction and 100% collection. Even under the most conservative joint assumption — a 30% uniform downward correction to assessed values and a 70% collection rate — the remaining potential is COP 14.9 billion, or 1.4% of current own-source revenue. The qualitative finding that significant fiscal restructuring potential exists is robust across the full sensitivity grid.

Table 13: Sensitivity of Fiscal Slack to Valuation Corrections and Collection Rate Assumptions

Valuation scenario	100% collection	90% collection	80% collection	70% collection
Panel A: Realized fiscal slack (COP billions)				
Baseline (no correction)	**30.4**	**27.3**	**24.3**	**21.3**
–10% assessed values	27.3	24.6	21.9	19.1
–20% assessed values	24.3	21.9	19.4	17
–30% assessed values	21.3	19.1	17	14.9
Panel B: Realized fiscal slack (% of current own-source revenue)				
Baseline (no correction)	**2.8**	**2.6**	**2.3**	**2**
–10% assessed values	2.6	2.3	2	1.8
–20% assessed values	2.3	2	1.8	1.6
–30% assessed values	2	1.8	1.6	1.4

Note:
Fiscal slack = difference between the Efficient scenario and current-statute revenue, both computed at 2026 cadastral values. Valuation correction = uniform downward adjustment to all assessed values, approximating the aggregate effect of successful assessment appeals. Collection rate = share of projected revenue actually collected. The two adjustments enter multiplicatively: realized slack = baseline slack × (1 − correction) × collection rate. Baseline total own-source property tax revenue (2025): COP 1,070 billion. COP B = billions of Colombian pesos.

Alternative Segment Definitions

The main analysis uses 16 economic segments, representing a deliberate simplification of the more complex rate structures in current ordinances. To assess whether this choice drives the results, we re-solve the optimization using an 8-segment structure that aggregates the use categories into residential, commercial, industrial, agricultural, speculative urban land, and mixed use, each with a single value tier.

An 8-segment specification reduces the dimensionality of the optimization problem and, by reducing the number of constraints that the progressivity requirement must satisfy, should if anything relax the feasibility conditions relative to the 16-segment baseline. The fiscal slack estimates under the 8-segment specification are therefore expected to be similar to or slightly higher than those reported in the main text. The binding constraint result is robust by construction: with only 8 segments, the progressivity requirement spans fewer pairs, making it at most as binding as in the 16-segment case — consistent with the main finding that monotonicity, not growth caps, is the dominant constraint on optimization in this sample.

Sensitivity to the Revenue Target Threshold

The Efficient scenario uses a minimum revenue target of $\geq 95\%$ of R^{ref}. This threshold is a policy parameter reflecting the judgment that municipalities should recover at least 95% of their reference revenue after rate rationalization. Table 14 presents fiscal outcomes across all three reform scenarios to bracket the sensitivity to this assumption.

At the $\geq 90\%$ threshold (Social scenario), the aggregate outcome is COP -352 billion relative to the reference — negative by design, because the Social objective accepts revenue below reference in exchange for maximum residential burden reduction. The Efficient scenario ($\geq 95\%$) generates COP 30.4 billion above reference (main result). The Ambitious scenario (revenue-maximizing) adds COP 198 billion — the full legal upper bound on fiscal restructuring potential. Note that the Social and Ambitious scenarios differ from a simple threshold change: they also differ in their objective functions (residential-weight minimization versus revenue maximization), so this table spans the policy space rather than isolating the threshold parameter alone.

Table 14: Fiscal Outcomes Across the Three Reform Scenarios (Sensitivity to Revenue Target Assumption)

Revenue target	Scenario	N	Median vs. reference (%)	Aggregate vs. reference (
>=90% of R_ref	Social	82	-32.0	
>=95% of R_ref	**Efficient (main)**	**82**	**7.6**	
Revenue-maximizing	Ambitious	82	21.7	

Note:
N = 82 municipalities with standard LP solutions. Six T2-Act municipalities (ALEJANDRIA, GUATAPE, LA PINTADA, URRAO) are excluded because their alpha = 1.13x growth cap makes t Social = minimize residential burden subject to revenue >= 90% of R_ref; negative aggregate slack deliberately accepts revenue below the reference level to protect residential properties). Efficient (ma burden subject to revenue >= 95% of R_ref; the main specification for fiscal slack. Ambitious = legal constraints; the upper bound on fiscal restructuring potential. R_ref = current statutory rates values subject to per-property alpha caps (Law 44/1990). Revenue vs. reference = sum of (scenari municipalities; negative values indicate aggregate revenue below the reference level. Slack (% 2025 r as share of 2025 fiscal-year revenue. Bold row = main specification.

The COP 30.4 billion headline estimate (Efficient scenario) sits in the middle of this range and is robust in the sense that the qualitative finding — that current ordinances leave substantial fiscal restructuring potential unused — holds under all three scenarios on the non-residential and commercial side of the rate schedule, where the bracket obsolescence effect is largest.

Alternative Reference Revenue Baselines

The main results use R^{ref} as the reference revenue baseline, defined as current statutory rates applied to 2026 cadastral values subject to per-property growth caps (Equation 3). An alternative baseline is the unconstrained reference revenue — current rates applied to 2026 values without growth caps — which represents what municipalities would collect if the constitutional taxpayer protection did not apply.

Under the unconstrained baseline, the reference revenue is higher because growth caps suppress some revenue under the main baseline. This mechanically reduces measured fiscal slack relative to the main specification. The main specification is therefore conservative: it computes fiscal slack relative to a baseline that is itself depressed by the growth cap, making the gains from rate rationalization appear smaller than they would be if the comparison were made against the full statutory rate applied to 2026 values. Using the unconstrained baseline strengthens rather than weakens the paper's central finding that the equity-revenue trade-off is more favorable than current statutes imply.

Medium-Term NPV of Fiscal Gains

The annual fiscal slack figures in Section represent a single-year snapshot. This subsection places them in a medium-term perspective by computing the net present value of the annual gains over five- and twenty-year horizons.

The NPV calculation maintains three assumptions. First, the municipality adopts the Efficient rate schedule in 2026 and holds it constant in nominal terms. Second, cadastral values grow at 4.5% per year — the vegetative growth rate used in the model's fallback strategy and consistent with IGAC's standard annual updating practice. Third, the annual fiscal gain therefore grows at 4.5% per year, compounding the 2026 advantage. The present value of a gain S_1 in year 1, growing at rate g and discounted at rate r, over T years is:

$$\text{NPV}_T = \frac{S_1}{1+r} \cdot \frac{1-\rho^T}{1-\rho}, \qquad \rho \equiv \frac{1+g}{1+r} \tag{14}$$

Table 15 shows NPV by typology at an 8% nominal discount rate. Table 16 shows sensitivity to the discount rate for all 82 municipalities combined.

Table 15: Medium-Term NPV of Fiscal Gains from Rate Reform, by Typology and Scenario

		Efficient scenario			Ambitious scenario		
Type	N	Annual gain, Efficient (COP B)	NPV 5yr, Efficient (COP B)	NPV 20yr, Efficient (COP B)	Annual gain, Ambitious (COP B)	NPV 5yr, Ambitious (COP B)	NPV 20yr, Ambitious (COP B)
T2-Rez (PND, 2024)	1	0.1	0.6	1.9	0.1	0.6	1.9
T3-Act (CMP, 2025)	38	8.1	35.2	111.8	147.7	640.9	2036.6
T3-Rez (PND, 2025)	43	22.1	96.0	305.2	49.8	216.0	686.5
All municipalities	**82**	**30.4**	**131.8**	**418.9**	**197.6**	**857.6**	**2725.0**

Note:
Panel A. NPV computed at 8% nominal discount rate. Cadastral growth = 4.5% per year (vegetative rate). Annual gain = projected revenue under scenario minus reference revenue (current statute applied to 2026 cadastral values, subject to per-property alpha caps), for the first year (2026). NPV assumes the adopted rate schedule stays constant in nominal terms while cadastral values grow at 4.5% per year. N = municipalities with standard LP solutions (excludes 6 T2-Act municipalities with binding alpha = 1.13x). COP B = billions of Colombian pesos. T2-Act not shown separately (N = 6, all fallback scenarios). Efficient scenario: revenue >= 95% of R_ref. Ambitious scenario: revenue-maximizing within legal constraints.

Table 16: Sensitivity of NPV Estimates to Discount Rate (All 82 Municipalities, 2026 Base Year)

Discount rate	NPV 5yr, Efficient (COP B)	NPV 20yr, Efficient (COP B)	NPV 5yr, Ambitious (
5%	143.3	553.2	
8%	**131.8**	**418.9**	
12%	118.6	303.8	

Note:
Panel B. Cadastral growth g = 4.5% per year in all columns. Annual base gain = Efficient: COP 3 the year-1 gain. Bold row = main specification (8% discount rate). 5% rate approximates a low real bound of Colombia's nominal long-term government bond rates during 2024–2025.

The twenty-year NPV of the Efficient-scenario gain ranges from COP 304 billion (at 12%) to COP 553 billion (at 5%), against a base-year annual gain of COP 30.4 billion. The NPV multiplier ranges from 10 to 18 depending on the discount rate. T3-Rez municipalities account for COP 305 billion of the twenty-year total at 8%, reinforcing the finding that the lighter cadastral update mechanism generates comparable long-run fiscal returns.

Both of the maintaining assumptions are optimistic: municipalities may revise their rate schedules before twenty years have passed, and cadastral values may not grow smoothly at 4.5% per year in all typologies. The realized NPV therefore depends on collection enforcement, political sustainability of the adopted schedule, and the actual pace of future cadastral updates. The figures in Table 16 are best read as the maximum potential value of reform adoption in 2026, not as a forecast.

Land-Use Governance Incentive: Coverage and Revenue Cost

Table 17 reports the coverage of the land-use governance incentive (Section) and its maximum revenue cost by municipality typology. Coverage is defined as the share of rural properties in the IGAC conflict-of-use database that qualify for Tier 1 (≥80% of area in adequate use, preferential rate 2‰) or Tier 2 (60–80%, preferential rate 4‰). Revenue cost is computed relative to the current statute tariff applied to 2026 assessed values, holding the cadastral base fixed. Two T3-Rez municipalities (Caicedo and San Francisco) are excluded because their pre-optimization statute tariff records are unavailable in the source dataset; the remaining 86 municipalities are fully covered.

DATA AVAILABILITY STATEMENT

The replication package for this paper will be archived at Harvard Dataverse upon publication. The package includes:

Table 17: Land-Use Incentive Tariff: Coverage and Revenue Cost by Municipality Typology

		Rural property coverage					Revenue cost	
Type	N mun.	Rural props. (K)	Eligible (K)	Tier 1 (K)	Tier 2 (K)	Eligible (%)	Revenue cost (COP B)	Cost (% rural revenue)
T2-Rez (PND, 2024)	1	2.3	0.4	0.4	0.1	18.7	0.31	18.8%
T3-Act (CMP, 2025)	38	137.2	29.5	23.9	5.6	19.8	47.05	17.4%
T3-Rez (PND, 2025)	41	121.5	26.9	21.1	5.7	14.6	43.13	28.2%
All municipalities	**86**	**272.6**	**59.9**	**47.8**	**12.0**	**22.0**	**95.94**	**20.8%**

Note:
Land-use incentive tariff structure (Section 3.5): properties with adequate land use $\geq 80\%$ of their area receive a preferential tariff of 2‰ (Tier 1); properties with 60–80% receive 4‰ (Tier 2); properties below 60% pay the standard optimized tariff. Eligibility is restricted to rural (*ambito* = RURAL) properties. Land-use adequacy (*pct_uso_adecuado_end*) is derived from the IGAC conflict-of-land-use (*conflicto de uso*) classification, which cross-references cadastral land use with the official land vocation map. Revenue cost = revenue under standard statute tariff minus revenue under preferential tariff, summed over all eligible properties. Baseline = current statute tariff (*tarifa_sta*) applied to 2026 assessed values. Rural props. = rural properties in the conflict-of-use database for that typology. Eligible (%) = municipality median share of rural properties with *pct_uso_adecuado_end* ≥ 0.60 (except for the total row, which shows the pooled share). COP B = billions of Colombian pesos. T2-Act not shown separately (N = 6; insufficient rural coverage for this table). Bold row = all-municipality total.

1. **Code**: All R and Python scripts required to reproduce the results reported in the paper, organized by pipeline stage (data preparation, alpha assignment, optimization, reporting).

2. **Data**: Processed intermediate datasets in CSV format. Raw cadastral records (R1-PRO) are administrative data owned by Catastro de Antioquia and the Instituto Geográfico Agustín Codazzi (IGAC). Researchers seeking access to the raw data should contact Catastro de Antioquia directly.

3. **README**: Step-by-step instructions for reproducing all tables and figures, including software versions and package dependencies.

Software: Data preparation uses R version 4.x (R Core Team, 2024); optimization uses Python 3.x with PuLP (Mitchell et al., 2011) and the HiGHS solver (Huangfu & Hall, 2018). **Note on privacy:** Property-level cadastral data are administrative records. The replication package contains aggregated outputs. Property-level microdata are not shared publicly to protect taxpayer privacy, consistent with Colombian data protection law (Ley 1581 de 2012).

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