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Limits of Debt Repayment Flexibility in Toll-Road Concessions Under Traffic Shortfalls

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Abstract

Traffic shortfalls can impair debt service despite substantial future concession revenues. This study tests repayment flexibility with a normalized financial model informed by public literature. An originally sculpted schedule is compared with a capacity-maximizing repayment rule subject to a debt service coverage ratio (DSCR) floor, current interest payment, and complete amortization before concession expiry. Across 10,980 deterministic scenarios, feasibility depends on near-term interest coverage and lifetime repayment capacity. Under the assumed parameters, a 30% traffic loss lasting three years is accommodated at an 8% coupon, maintaining a 1.20 DSCR floor and repaying debt in year 13. A 15-year loss requires repayment through year 20. Raising the amendment coupon to 10% makes the three-year scenario infeasible under the same coverage floor, regardless of maturity extension. These are conditional model results, not observed project outcomes or default probabilities. The reproducible boundary analysis separates repayment timing, maturity capacity, and creditor pricing to support preliminary screening of debt amendments.

Keywords: infrastructure finance, toll-road concessions, debt sculpting, traffic risk, debt service coverage ratio, debt restructuring, scenario analysis

1. Introduction

Financing a toll road requires more than a positive long-term revenue forecast. Debt obligations fall due on specified dates, whereas actual traffic can depart substantially from expectations. Bain's analysis of international toll-road forecasts documents material forecasting errors and optimism bias [1]. Research covering a broader set of transport projects similarly questions the reliability of demand estimates [2]. These findings motivate financing arrangements that remain workable when a plausible demand trajectory is less favorable than the original forecast. Forecast precision and financial resilience are therefore connected, but distinct, design objectives.

Repayment flexibility is an established response. Castelblanco and colleagues model financial and scope flexibility in two toll-road public-private partnerships (PPPs), identifying repayment period and capital expenditure as influential financial drivers [3]. Debt sculpting aligns scheduled payments with projected cash flow and a target debt service coverage ratio (DSCR) [4]. Pershin examines cash-flow structuring and stakeholder constraints in PPP financing [5]. These approaches establish the usefulness of adjusting repayment profiles; they do not imply that every demand shortfall can be resolved through an extension of maturity.

The distinction matters because concessions and loans have different contractual horizons. Vassallo examines Chilean mechanisms that mitigate revenue risk by changing concession length [6]. Loan repayment constraints require a separate test. Changes also require coordination among parties. A comparative study of six United States highway PPPs identifies macroeconomic shocks, complexity, and institutional conditions among renegotiation triggers [7]. Furthermore, project-finance credit pricing varies with project characteristics and maturity rather than following a universally increasing term structure [8]. A longer repayment period cannot simply be assumed available at the original price.

This article asks: under what combinations of shortfall depth, shortfall duration, amendment coupon, and permitted maturity can a concession repay its outstanding debt while maintaining a specified coverage floor? The working hypothesis, formulated here from repayment-flexibility [3] and sculpting principles [4], is that temporary demand losses can be accommodated without additional public transfers within a bounded region of these variables. Outside that region, repayment flexibility alone is insufficient. The study develops a reproducible screening calculation for this boundary rather than estimating the population-level effectiveness of restructuring. Its contribution is the explicit separation of current-interest feasibility, cumulative repayment capacity, and pricing effects within one auditable model.

2. Methods

2.1 Study design and evidence base

The design is a deterministic numerical experiment. A targeted literature review identified financial-model structure, debt-sculpting principles, traffic-risk mechanisms, and fiscal-risk considerations. Searches combined toll-road finance, traffic shortfalls, repayment flexibility, debt sculpting, and PPP restructuring; publisher pages, institutional repositories, and development-institution publications were consulted through September 6, 2026. The review was purposive, not a systematic review or meta-analysis. No interviews, confidential lender documents, or borrower-level dataset were used.

Table 1. Assumptions at the debt-amendment date. Monetary amounts are normalized units; outstanding principal equals 100.

Parameter	Assumption
Debt; remaining concession life	100; 30 years
Original coupon; original maturity	8%; 15 years
First-year revenue; fixed cash outflows	22; 4
Variable outflows; annual nominal growth	10% of revenue; 2%
Required DSCR; amendment maturities	1.20; 15, 20, 25 years
Traffic loss; duration; amendment coupon	0-60% in 1-point steps; 1-15 years; 6%, 8%, 10%, 12%

The World Bank/Public-Private Infrastructure Advisory Facility (PPIAF) toolkit covers risk assessment and financing [9]. Bull and colleagues link toll revenue, costs, financing, and debt service in financial models [10]. The present implementation follows that general architecture but does not reproduce an institutional workbook or reconstruct a named concession. Every numerical input in Table 1 is a disclosed analytical assumption. Neither the baseline coupon nor the coverage floor is presented as a market estimate. Public sources justify the modeled relationships; they do not establish that the chosen parameter values represent any country or operator.

2.2 Cash flow and the contractual comparator

The model starts immediately before an operating-period debt amendment. Construction financing is outside its boundary. Traffic is reduced by fraction d for L years, then returns to the original trajectory without recovering foregone revenue. Toll levels and vehicle composition are unchanged by the shock. Traffic-dependent revenue and variable outflows decline proportionally, while fixed cash outflows remain. All baseline amounts grow at the assumed nominal rate g. Cash flow available for debt service (CFADS), denoted C_t, is:

$$C_t = [(1-v)R_1 (1 - d\,\mathbf{1}_{t \leq L}) - F_1] (1+g)^{t-1}. \tag{1}$$

Here R_1 is baseline revenue, v is the variable-outflow ratio, and F_1 is a reduced-form fixed allowance for operating, maintenance, and cash-tax requirements. The allowance is held independent of financing; interest tax shields and detailed tax accounting are not modeled. Bull and colleagues discuss toll levels and willingness to pay as influences on traffic and revenue [10]. Equation (1) deliberately isolates traffic volume, so its results should not be interpreted as a tariff-response model.

The original loan is already sculpted to baseline CFADS. With original rate r_0, principal D_0, and maturity N_0, its constant coverage factor q_0 equals the present value of baseline CFADS over N_0 divided by D_0. Scheduled debt service is baseline CFADS divided by q_0. This construction follows established debt-sculpting accounting [4] and avoids comparing flexibility only against an artificially rigid equal-principal loan. Actual CFADS divided by original scheduled service measures the stressed contractual DSCR. Values below 1.20 indicate failure of the modeled covenant; values below 1.00 indicate a cash-payment shortfall before any external intervention.

Normalization permits the numerical example to be rescaled without changing its ratios or feasibility classification. The revenue-to-debt ratio, operating margin, and timing assumptions, rather than the unit of account, determine the results. Growth is an aggregate nominal escalator, not an estimated traffic-growth rate. The recovery assumption means that revenue resumes the contemporaneous baseline level after the shortfall ends; it does not merely resume growing from the depressed level. Consequently, the temporary scenarios contain genuine recovery capacity. A lasting downward revision would need a different cash-flow path even if its first-year loss were identical.

2.3 Admissible repayment flexibility

Let B_{t-1} be opening debt and r the constant post-amendment coupon. Interest is paid currently, principal repayments are nonnegative, and no additional cash borrowing, reserve draw, or public transfer is available. The amendment must repay principal completely by maturity N, which remains within the unchanged concession term. A sensitivity experiment capitalizes an amendment fee f in the opening claim, $B_0 = D_0(1 + f)$, without introducing cash into the project.

If the required coverage floor is k, annual debt service cannot exceed C_t/k. The following rule allocates the greatest permitted payment to creditors:

$$S_t = \min\{C_t/k, (1+r)B_{t-1}\}, \quad B_t = (1+r)B_{t-1} - S_t. \tag{2}$$

The rule is admissible only if S_t is at least rB_{t-1}. Otherwise, even current interest cannot be paid while maintaining k. The remaining cash-flow headroom is unavailable for future debt service in this experiment; no cash accumulation account is modeled. A schedule is feasible if all current-interest conditions hold and B_n is zero within numerical tolerance. Failure is classified as either a current-interest constraint under the coverage floor or incomplete amortization at maturity.

Within these assumptions, the rule is an exact feasibility test. For the same opening balance, any admissible schedule pays no more than equation (2). Its closing balance therefore cannot be smaller. Induction gives the rule the lowest attainable balance in every subsequent year, so it also minimizes subsequent interest. If this balance still cannot meet the next interest condition or reach zero by maturity, another admissible schedule cannot do so. This argument establishes feasibility, not an equity-optimal distribution policy. The creditor receives the maximum permitted early allocation; shareholders may prefer a different feasible allocation.

For the independent linear program, the decision variables are annual principal repayments. Their sum must equal the opening claim, each repayment must be nonnegative, and each year's principal plus interest on the remaining balance must remain below C_t/k. This provides a second computational formulation of the same admissible set. The approach does not assume that a lender will authorize the resulting schedule. Instead, it asks whether any schedule satisfying these specified financial constraints exists before adding negotiation, documentation, and institutional constraints. A negative result is decisive only for that stated admissible set.

Two accounting checks clarify the boundary. First, the initial-year interest condition gives:

$$d \leq 1 - \frac{F_1 + krD_0(1+f)}{(1-v)R_1}. \tag{3}$$

This is a necessary condition, not generally sufficient for complete repayment. Second, discounting a fully amortizing schedule at its own constant coupon gives a payment present value equal to the amended opening claim. Thus nominal principal is preserved and the coupon identity is respected. This is not proof that creditors maintain their economic value: risk-adjusted valuation, funding costs, expected losses, and consent costs may change. In the separate context of public guarantees, Irwin distinguishes maximum exposure from economic cost [11].

2.4 Scenario grid, sensitivity, and verification

The main grid crosses 61 loss depths, 15 durations, four coupons, and three maturities, giving 10,980 scenarios. These combinations have no assigned likelihoods; a feasible-grid proportion is not a success probability. The maximum feasible loss is also calculated by bisection for each coupon-duration-maturity combination. If the no-loss scenario is infeasible, its boundary is recorded as unavailable. Increasing maturity is tested without changing the coupon within each comparison; separate coupon scenarios expose the consequences of repricing.

The continuous boundary is searched between zero and a 95% loss using 45 bisection iterations. The repayment rule uses a 10^{-8} tolerance for balance and interest comparisons. Consequently, reported boundaries are rounded for interpretation; additional decimal places should not be read as evidence of forecasting precision.

Sensitivity calculations vary the coverage floor from 1.00 to 1.30, capitalized fees from zero to 3%, nominal growth from zero to 4%, and fixed cash outflows from two to six units. These are one-factor experiments around the baseline. The implementation uses Python and standard scientific-computing libraries. Independent linear-programming feasibility checks, implemented using SciPy [12], cover 180 seeded grid selections and 38 boundary or baseline checks. Principal conservation, payment present values, monotonic responses, and monetary scaling are also checked. Supplementary Tables S1-S4 and Supplementary File S1 contain the scenarios, boundaries, sensitivity outputs, and code.

3. Results

3.1 Temporary and persistent shortfalls

The original sculpted loan has a baseline DSCR of 1.5161 and first-year debt service of 10.4216 units. A 30% traffic shortfall reduces first-year CFADS from 15.80 to 9.86. For a three-year loss, the original minimum

DSCR falls to 0.9461, and the sum of annual cash-payment deficits is 1.7188 units. That sum excludes unpaid-interest capitalization and subsequent default consequences; it describes the unamended schedule only.

At the unchanged 8% coupon, an adapted schedule accommodates this shock while maintaining the 1.20 floor. It repays debt in year 13, before the original maturity. This outcome reflects lower payments during the three weak years followed by greater allocations after recovery. The adapted rule uses the available coverage headroom more aggressively than the original schedule. Its total interest is 72.5287 units, versus 80.2254 for the original contractual schedule. This numerical difference is not a general restructuring saving: it depends on the assumed recovery and the shift of cash toward creditors after recovery.

When the same 30% loss lasts 15 years, the adapted 15-year schedule leaves 67.1152 units unpaid at maturity. Allowing repayment through year 20 restores feasibility and produces total interest of 125.0538 units. Nominal principal is fully repaid in both successful cases, yet their timing and total interest differ markedly. Table 2 separates these mechanisms. Annual cash-flow paths distinguish payment deferral from accelerated repayment after recovery in the temporary-shock example.

Table 2. Selected scenario results. All cases maintain k = 1.20 and an unchanged 30-year concession. "Interest" failure means incompatibility with the coverage floor, not necessarily inability to pay interest at k = 1.00.

Traffic loss / duration	Coupon / maximum maturity	Outcome	Repayment year or residual
30% / 3 years	8% / 15 years	Feasible	Year 13
30% / 15 years	8% / 15 years	Maturity failure	67.12 unpaid
30% / 15 years	8% / 20 years	Feasible	Year 20
35% / 3 years	8% / 25 years	Interest constraint	Fails in year 1
30% / 3 years	10% / 25 years	Interest constraint	Fails in year 1

3.2 Feasibility boundaries and repricing

Figure 1 shows where maturity extensions help and where they cease to matter. At an 8% coupon, the maximum three-year shortfall is 31.31% for all three maturities. Current-interest coverage binds before additional years become useful. For a 15-year shortfall, however, increasing maturity from 15 to 20 years raises the tolerated loss from 16.64% to 31.25%. Extension to 25 years raises it only slightly further, to 31.31%. The marginal value of additional maturity therefore depends on which constraint is active.

Repricing narrows the feasible region. A 10% coupon reduces the three-year limit to 19.19%. In the worked 30% scenario, available first-year service at the required coverage floor is 9.86/1.20 = 8.2167 units, below the ten-unit interest charge. Additional repayment years cannot repair that mismatch. At 12%, even the no-loss path cannot fully amortize within 15 years at the 1.20 floor. Twenty- and twenty-five-year maturities restore a limited region, with a maximum shortfall of 7.07%. These comparisons concern stated coupon scenarios, not observed rate changes on a floating-rate loan.

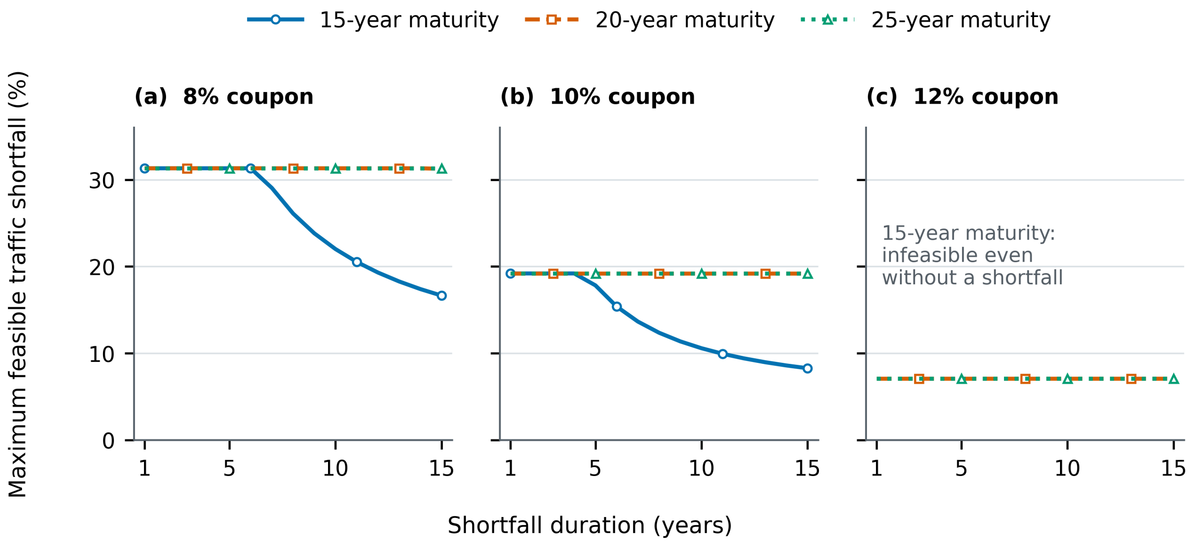

Figure 1. Maximum feasible traffic shortfall by duration, coupon, and permitted maturity. The 15-year curve is absent at 12% because the no-loss scenario is infeasible. All numerical inputs are assumed; curves are deterministic boundaries.

An unavailable boundary at a particular maturity deserves attention even when the immediate-interest test passes. At a 12% coupon, baseline first-year CFADS exceeds the interest charge multiplied by the coverage floor, but repayment over 15 years still falls short. This is the converse of the deep temporary-loss example: favorable current coverage alone does not establish adequate lifetime capacity. Together, the two cases demonstrate why a screen based only on the first year, or only on discounted lifetime receipts, can give an incomplete account of repayment flexibility.

3.3 Sensitivity and numerical consistency

Separating a covenant from a cash constraint changes interpretation. At 8%, reducing k from 1.20 to 1.00 raises the three-year shortfall limit from 31.31% to 39.39%. The 35% scenario in Table 2 can therefore cover current interest in cash but cannot maintain the assumed buffer. Lowering a covenant is a different intervention from extending maturity and changes the protection afforded to creditors. It should be identified explicitly when presenting an apparently successful amendment.

A 1% capitalized fee reduces the baseline three-year limit to 30.83%; a 3% fee reduces it to 29.86%, making the 30% example infeasible. For a 15-year shortfall and 15-year maturity, changing nominal growth from zero to 2% to 4% moves the boundary from 8.99% to 16.64% to 23.72%. Increasing fixed cash outflows from four to six units reduces that baseline boundary to 6.54%. These results demonstrate sensitivity to operating assumptions as well as financing design. They do not establish a recommended tariff escalation or maintenance budget.

All 218 independent linear-programming comparisons agree with the allocation rule. For the checked feasible cases, the largest absolute discrepancy between discounted debt service and opening principal is below 10^{-12} normalized units. The grid also satisfies the expected monotonic responses: greater losses or longer shortfalls do not improve feasibility, and an unchanged-coupon maturity extension does not reduce it. These checks verify the implementation and accounting, not external predictive validity.

Figure 2 illustrates the cash-flow and debt-balance comparison.

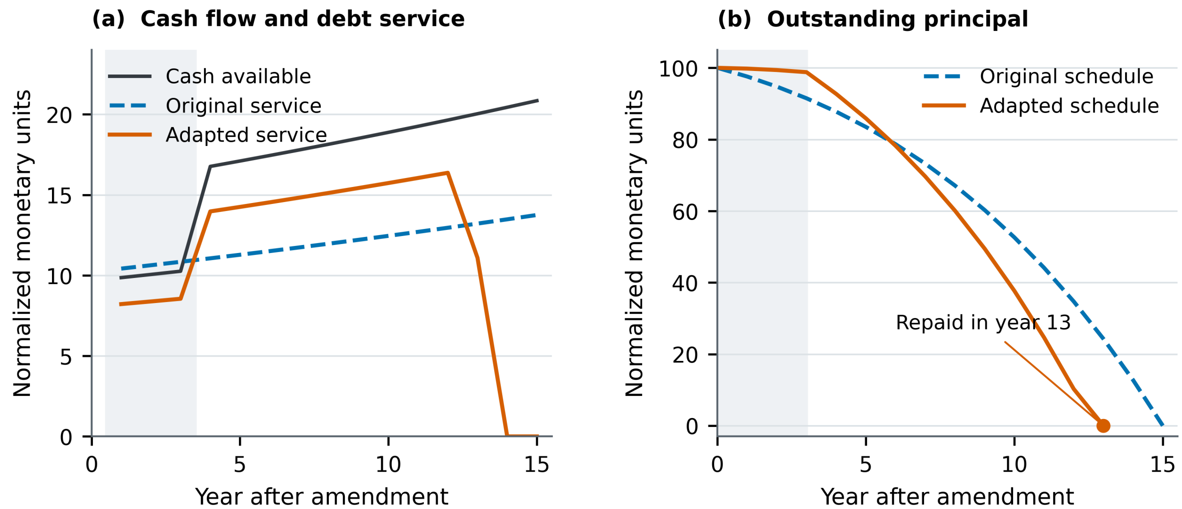

Figure 2. A 30% traffic shortfall lasting three years at an 8% coupon. Adapted service is reduced initially and increased after recovery; debt is repaid in year 13. Shading denotes the shortfall period. The original balance path is the contractual comparator, not a simulated default workout.

4. Discussion

The results support a conditional version of the working hypothesis. Within the modeled constraints, flexibility succeeds when weak near-term cash flow coexists with enough later capacity and affordable current interest. Building on repayment-period sensitivity in earlier work [3], this analysis asks whether improved coverage also satisfies current interest and terminal amortization. The calculation combines established principles rather than claiming to invent debt sculpting. Its useful output is the location and explanation of a boundary for a specified project model.

The distinction between loan maturity and concession duration is essential. Flexible-term concession mechanisms alter the period over which user revenues can be collected [6]. Here, the concession remains unchanged, while creditors may receive a larger share of cash previously available later to shareholders. A successful amendment can therefore redistribute cash and risk even when no public payment is made. In Engel and colleagues' model, avoiding upfront public financing entails forgoing future concession revenues [13]. Feasibility also does not establish social value, affordability to road users, or protection of future maintenance quality.

For investment teams, the proposed sequence is to identify a credible revised traffic path, establish cash available after essential outflows, test current-interest coverage, and then test amortization across acceptable maturity and pricing combinations. Failure of the current-interest test identifies the need to examine liquidity, pricing, capitalization, or other changes. A terminal failure identifies insufficient capacity under the tested horizon. Neither result determines which intervention should be chosen. If public guarantees or payments enter a subsequent proposal, their fiscal implications require separate assessment, as emphasized in the PPP Fiscal Risk Assessment Model (PFRAM) of the International Monetary Fund and World Bank [14].

Several limitations restrict application. The deterministic recovery date is known within each scenario, giving the model a conditional perspective that real lenders do not possess. There is no estimation of traffic probabilities, dependence between macroeconomic variables, or lender risk premiums. A single debt tranche replaces potentially different seniorities and intercreditor arrangements. Annual periods obscure intra-year liquidity pressures. Cash reserves, negative amortization, prepayment restrictions, hedges, and borrowing limits beyond the stated constraints are excluded. Their inclusion could change either the feasible region or the implementability of a modeled schedule.

The reduced-form cash allowance also omits explicit maintenance cycles, handback expenditure, and financing-dependent taxes. These items must be rebuilt before project use. Holding the coupon constant during a maturity comparison is an experimental control, not a claim about lender behavior. Governance and contract-management conditions described in PPP guidance remain relevant even for mathematically feasible amendments [15]. Finally, the normalized input set is illustrative. Future empirical work should test the method against publicly disclosed concession cash flows and amendment terms, and compare predicted boundaries with actual negotiated outcomes without attributing causality from isolated cases.

The figures also separate the effect of deferral from the effect of recovering cash flow. In the short scenario, success does not require using the longest permitted maturity; accelerated repayments after recovery offset the initial postponement. In the persistent scenario, that recovery arrives much later and consumes most of the additional repayment capacity. Reporting only the revised final maturity would hide these differences. A useful amendment assessment should therefore report at least the payment profile, minimum coverage, terminal balance, total interest, and the conditions under which each result changes.

The comparison of capitalized fees illustrates another practical distinction. Adding a fee to the claim avoids an immediate cash payment but increases the amount that future cash flows must support. It is not a source of operating liquidity and does not remove the economic burden of the amendment. Likewise, retaining the original principal while changing the coupon does not hold creditor value constant across scenarios. These distinctions help prevent an apparent improvement in annual coverage from being interpreted as a costless solution. The relevant question is whether the resulting allocation is feasible and acceptable to the affected parties.

Further development could add a reserve account with an explicit initial funding source and withdrawal rules, then measure how the current-interest boundary shifts. Another extension could evaluate the same proposed schedule against several recovery dates rather than redesigning it separately for each known path. That would provide a more demanding test of resilience to forecast uncertainty. Such extensions should preserve a clear distinction between simulated possibilities and observed outcomes, allowing subsequent empirical evidence to assess where the simplified screening model is informative and where its omissions are material.

5. Conclusions

Debt repayment flexibility can accommodate a traffic shortfall only within jointly determined cash-flow, pricing, and maturity constraints. The numerical experiment distinguishes a temporary mismatch that can be reprofiled, an amortization deficit that benefits from additional years, and a current-interest constraint that additional years cannot resolve. Its reproducible implementation supplies an initial screening tool, with explicit assumptions and accounting checks. Application to actual concessions requires project-specific calibration, treatment of reserves and contractual restrictions, and an independent assessment of creditor value and public consequences.

Declarations

Acknowledgments and AI disclosure. OpenAI Codex assisted with literature discovery, drafting, programming, numerical checks, and figure preparation.

Ethics and data availability. The study uses published sources and synthetic scenarios; no human participants, personal records, or animal research are involved. Supplementary File S1 contains code, assumptions, and generated outputs, including Supplementary Tables S1-S4. No borrower-level observations are used.

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