Hotelling Meets Laffer: Taxation and the Discovery of Exhaustible Resources*

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February 10, 2026

Abstract

This paper estimates the sensitivity of mining exploration and production to taxation and its implications for optimal tax policy. Using a comprehensive panel of firms' worldwide extraction and exploration expenses, I show that the response to taxation operates almost entirely at the extensive margin through a reduction in exploration expenses. I establish these results by exploiting both global tax variation and four major policy reforms using difference-in-differences designs. Using these estimates, I then characterize the revenue-maximizing sales-based royalty and income tax rates. I find that the revenue-maximizing tax rates exceed currently observed rates, suggesting that mining countries could increase tax revenues from extractive activities.

*I thank Pierre Bachas, Lucie Gadenne, Niels Johannesen, Thomas Piketty, Nadine Riedel, Gabriel Zucman, and seminar participants at the Paris School of Economics for helpful comments.

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1 Introduction

Rising minerals prices have spurred a wave of tax increases in resource-rich countries.[1] However, it remains unclear whether these policies successfully capture rents without distorting the long-run path of production.

Theoretically, the magnitude of the response of mining activity to taxes is ambiguous. On the one hand, the industry is dominated by large multinational corporations that optimize their capital allocation globally (Baumol et al., 1982). Ex-ante, this capital is highly mobile: host countries must compete to attract investment, creating a tax competition dynamic that theoretically disciplines rates (Zodrow and Mieszkowski, 1986; Wilson, 1986). On the other hand, once mines are operational, the ex-post elasticity of production may be low. The location-specific nature of reserves and the massive sunk costs required for extraction suggest states can capture significant rents without triggering immediate distortions, as formalized in the obsolescing bargain model (Vernon, 1971).

Despite the centrality of this trade-off for tax policy, causal evidence on the tax elasticity of mining activity remains scarce. In this paper, I leverage a comprehensive, cross-country dataset of mining production and exploration expenses to provide the first global estimates of the real effects of taxation on mining activity.

To guide my empirical analysis, I begin by developing a conceptual framework of firm production and exploration decisions following a tax rate increase. I extend the canonical model of Pindyck (1978) by incorporating a tax on extraction and sunk investment costs. In the model, exploration serves a dual purpose: it expands the stock of reserves that can be exploited and improves average reserve quality, thereby reducing marginal extraction costs.

My empirical analysis then combines a global cross-country analysis with specific event studies exploiting large tax hikes.

First, I estimate the cross-country semi-elasticity of mineral production and exploration expenditures with respect to profit-based taxes and sales-based royalties. To do so, I construct a

[1] Examples include Colombia (2022), Chile (2023), Mali (2023), Kazakhstan (2023), Finland (2024), and Bulgaria (2025); similar increases are currently under discussion in Peru.

comprehensive global panel (2010–2024) merging firm-level exploration and production data, disaggregated by country and mineral, with a newly compiled database of historical corporate income tax and royalty rates. My identification relies on a within-firm difference-in-differences design. By comparing the same multinational firm's activities across different jurisdictions, I isolate the effect of differential tax changes on capital allocation, while controlling for specific commodity price shocks.

Second, I study more closely four of the largest mining tax reforms of the past two decades: South Africa (2010), Ghana (2012), Mexico (2014), and the DRC (2018). To do so, I rely on an extended panel dataset spanning 1997 to 2024. This dataset tracks aggregate exploration expenses for each firm-country pair, alongside a partial commodity-specific breakdown which I leverage to control for differential mineral price dynamics. These reforms imposed major statutory tax increases in countries where mining accounts for a significant share of GDP. To identify the effects of these reforms, I rely both on a within-firm strategy - tracking a firm's activity across countries - and a between-firm strategy - comparing treated vs. not treated firms - in a difference-in-differences framework.

In both parts, I perform a series of robustness checks, accounting for cross-country spillovers and identification challenges in staggered difference-in-differences settings.

I find that while exploration expenses decline significantly in response to tax increases, production from active mines remains unresponsive. This decline in domestic exploration is gradually compensated by an increase in exploration expenses abroad. Consequently, affected firms reduce their global exploration expenses only temporarily.

I find similar but smaller effects on lower-risk investments (late-stage projects and minesite expansions). This confirms that tax hikes deter investment even when deposits are known and viable. Furthermore, the reforms affect mining activity at the extensive margin: following a reform announcement, the probability of firms conducting exploration in the treated country drops by 33%.

In the final part of the paper, I use these semi-elasticities to derive a revenue-maximizing tax rate. This calculation accounts for the tax's impact on long-term production through the

reduction in exploration expenditures. To link exploration to future output, I estimate the elasticity of reserve additions with respect to exploration expenses and assume that, in the long run, production scales proportionally with the stock of available reserves. I then consider different scenarios depending on the level of profit shifting, with elasticities drawn from Best et al. (2015). At baseline without profit shifting responses, I find that the optimal income and sales tax rates are 37.4% and 7.5% respectively. Adding profit shifting responses considerably changes the results in favor of an increaase in the sales tax and a decrease in the income tax rate.

These findings carry important policy implications, as resource-rich countries revise their mining codes in a context of structural boom in global mineral demand. Overall, the results suggest that increasing the government share in mining rents affects the sector primarily at the extensive margin, affecting mostly long-term production. This highlights a political economy friction (Stroebel and van Benthem, 2013): while governments have a strong incentive to raise taxes to capture short-term revenue from immobile production, doing so erodes the long-run tax base by displacing exploration. My findings imply that countries with mature, fully explored resources can sustain higher tax rates, whereas countries relying on new discoveries risk significantly eroding their future tax base.

Contribution to the literature A large theoretical literature has examined the effects of taxation on the extractive sector, building on Hotelling (1931)'s canonical model of exhaustible resource extraction (see Lund (2009) for a review). Empirically, however, evidence remains scarce and predominantly focused on the oil industry in the United States (Rao, 2018; Brown et al., 2020; Anderson et al., 2018), with the notable exception of Ahlvik et al. (2022), who adopts a cross-country perspective on the oil sector.

This focus on oil limits generalizability to the mining sector due to differences in production functions. As noted by Anderson et al. (2018), geological pressure in oil wells makes it costly for firms to temporally reallocate production or pause extraction. In contrast, mining extraction face fewer geological constraints on stopping and starting extraction, theoretically allowing for greater responsiveness to fiscal shocks.

To the best of my knowledge, this paper is the first to empirically estimate the effects of

taxation specifically on mining activity.

Furthermore, I contribute to the nascent literature on exploration responses. Closest to my work is Ahlvik et al. (2022), who provides cross-country evidence on exploration investment in the oil sector using a similar identification strategy. My results complement their findings by confirming that, in the mining sector as well, taxation significantly impacts the exploration margin while leaving short-run production largely unaffected. These results contribute to the understanding of investment behaviors of firms. As highlighted theoretically by Pindyck (1991), investment expenditures are largely irreversible. I show that this irreversibility affects production dynamics.

The rest of this paper is organized as follows. Section 2 lays out the conceptual framework of the paper. Section 3 describes the data source used. Section 4 studies the effects of taxes on all countries. Section 6 draws implications for the optimal mining tax rate. Section 7 concludes.

2 Conceptual Framework for Exploration and Production Decisions

I begin by developing a conceptual framework to analyze how an increase in sales taxes affects both exploration expenses and production decisions. My framework builds upon Pindyck (1978), which was the first to incorporate exploration decisions into Hotelling (1931)'s canonical model of mineral extraction. However, while Pindyck (1978) focused on the long-run evolution of commodity prices, I adapt his model to derive the comparative statics of a sales tax increase. Compared to Pindyck (1978), I also include fixed infrastructure costs, which are critical for understanding short-to-medium run production dynamic.

2.1 Setup

Production is constrained by two factors: the available stock of reserves and the current level of production capacity, which is determined by the accumulated capital stock.

Reserve dynamics. The stock of reserves evolves according to the firm's exploration history. Let w_t denote exploration expenditures at time t. The stock of reserves R_t is the cumulative sum of discoveries minus cumulative production:

$$R_t = \int_0^t f(w_x, T_x) - q_x \, dx$$

Where $f(w_x, T_t)$ links exploration expenditures w_t to actual discoveries. T_t is the cumulative discoveries made, defined as:

$$T_t = \int_0^t f(w_x, T_x) \, dx = R_t + \int_0^t q_x \, dx$$

I assume that $f_w > 0$, implying positive returns to exploration investment, and $f_{ww} < 0$, implying diminishing returns. Furthermore, $f_T \leq 0$, reflecting the exhaustible nature of mineral resources: as the cumulative stock of discovered resources T_t grows, finding new deposits becomes increasingly difficult.

Capital investment and production capacity. Extraction requires large upfront capital costs. I treat production capacity as a state variable K_t, representing both physical quantity and the monetary value of infrastructure. The capital stock evolves according to:

$$\dot{K}_t = I_t - \delta K_t \tag{1}$$

where I_t is the investment in capital at time t and δ is the depreciation rate. Production is physically limited by this stock of capital: $q_t \leq K_t$.

Marginal production costs. Extraction costs $c(q_t, R_t, K_t)$ depend on production level, reserve size, and capital stock. A larger K_t, representing better infrastructure or equipment, reduces marginal costs ($c_K < 0$), while a higher R_t reflects higher-quality reserves ($c_R < 0$): when reserves are large, the firm has a wider choice of deposits to choose from. This allows the firm to select more high-grade ore, which requires less processing and energy per unit of mineral

produced.

Firm Maximization Problem. Firms choose the paths of production q_t, exploration w_t, and investment I_t. They maximize the net present value of after-tax profits minus investment and exploration costs:

$$\max_{w_t, q_t, I_t} \int_0^T \left[(1-\tau)p_t q_t - c(q_t, R_t, K_t)q_t - w_t - I_t\right] e^{-rt} dt + e^{-rT} V(K_T) \tag{2}$$

Subject to the state equations for R_t, T_t, and K_t, and the capacity constraint $q_t \leq K_t$. The term $V(K_T)$ represents the recovery value of the capital at the end of the mine's life T.

The current-value Hamiltonian is:

$$\begin{aligned} \mathcal{H} = {} & (1-\tau)p_t q_t - c(q_t, R_t, K_t)q_t - w_t - I_t \\ & + \lambda_t[f(w_t, T_t) - q_t] + \mu_t f(w_t, T_t) \\ & + \omega_t[I_t - \delta K_t] + \phi_t[K_t - q_t] \end{aligned} \tag{3}$$

Where λ_t is the shadow price of reserves, μ_t is the shadow cost of cumulative depletion, ω_t is the shadow price of capital, and ϕ_t is the scarcity rent of the current infrastructure.

2.2 Effects of a Sales Tax on Exploration

Applying the first order condition with respect to w_t yields:[2]

$$\lambda_t + \mu_t = \frac{1}{f_w(w_t, T_t)} \tag{5}$$

The firm invests in exploration until the net value of a discovery $(\lambda_t + \mu_t)$ equals the marginal cost of finding a unit $(1/f_w)$.

[2]The firm's optimal exploration expenditure is determined by the first-order condition with respect to w_t:

$$\frac{\partial \mathcal{H}}{\partial w_t} = -1 + (\lambda_t + \mu_t)\frac{\partial f(w_t, T_t)}{\partial w_t} = 0 \tag{4}$$

Differentiating the equilibrium condition with respect to τ yields:[3]

$$\frac{dw_t}{d\tau} = \left[-\frac{(f_w)^2}{f_{ww}}\right] \cdot \left(\frac{d\lambda_t}{d\tau} + \frac{d\mu_t}{d\tau}\right) \tag{8}$$

The term $-\frac{(f_w)^2}{f_{ww}}$ is strictly positive, given the assumption of diminishing returns to exploration investment. The tax reduces the future revenue stream from reserves, implying $\frac{d\lambda_t}{d\tau} < 0$. While μ_t is a negative shadow cost reflecting the penalty of future exhaustion, a sales tax increase has a positive effect on its value, making the depletion penalty less severe in present value terms. However, this effect is generally dominated by the simultaneous decrease in the shadow price of reserves λ_t, leading to a decline in the total incentive to explore. The term $\left(\frac{d\lambda_t}{d\tau} + \frac{d\mu_t}{d\tau}\right)$ is thus generally negative, meaning that exploration expenses decrease as the tax rises.

In the presence of an outside option V^*, the firm follows a participation constraint: $\lambda_t + \mu_t \geq V^*$. If the tax rises sufficiently such that the net domestic value falls below this threshold, w_t drops discontinuously to zero.

2.3 Effects of a Sales Tax on Production

The first order condition with respect to q_t yields:

$$(1-\tau)p_t = MC(q_t, R_t, K_t) + \lambda_t + \phi_t \tag{9}$$

Where MC is the marginal cost of extraction. Rearranging for the shadow value of capacity ϕ_t:

$$\phi_t = (1-\tau)p_t - MC(q_t, R_t, K_t) - \lambda_t \tag{10}$$

[3]

$$\frac{d(\lambda_t + \mu_t)}{d\tau} = \frac{d}{d\tau}\left[\frac{1}{f_w(w_t, T_t)}\right] \tag{6}$$

Applying the chain rule to the right-hand side yields:

$$\frac{d\lambda_t}{d\tau} + \frac{d\mu_t}{d\tau} = -\frac{f_{ww}}{(f_w)^2} \cdot \frac{dw_t}{d\tau} \tag{7}$$

The first order condition with respect to I_t yields:

$$\omega_t = 1 \tag{11}$$

Assuming no adjustment costs, the shadow price of capital is equated to the marginal cost of investment. The equation of motion for the shadow price of capital ω_t is:

$$\dot{\omega}_t = (r + \delta)\omega_t - \left[-\frac{\partial c}{\partial K_t} q_t + \phi_t\right] \tag{12}$$

In the short run, if $\phi_t > 0$, production remains at capacity $q_t = K_t$. However, because τ reduces ϕ_t, the return on capital falls. The firm reduces sustaining investment I_t, leading to a gradual contraction of K_t through depreciation. Thus, production is inelastic in the immediate short run but declines over time.

2.4 Testable Predictions

1. Exploration is highly elastic to tax changes. If the tax τ reduces the net discovery value $(\lambda_t + \mu_t)$ below the global benchmark V^*, exploration expenditures w_t will drop discontinuously to zero as capital is reallocated to more competitive jurisdictions.

2. Production q_t is inelastic in the immediate short run as the firm seeks to capture remaining quasi-rents ϕ_t. However, as the shadow price of capital ω_t falls, the firm reduces sustaining investment I_t. This leads to a secular decline in output as the capital stock K_t depreciates.

3. The tax incidence falls primarily on the scarcity rent of sunk assets (ϕ_t), which narrows the gap between operating profits and the opportunity cost of exit. This accelerates the decision to reach the recovery value $V(K_T)$, leading to earlier mine closure and a decrease in firm entry.

3 Data

Exploration and production data. Data on production and exploration are drawn from the S&P Global Market Intelligence(formerly SNL Metals & Mining) database. It is widely regarded as the best available source of data on mining activity (Aragón and Rud, 2016; Berman et al., 2017), and provides granular annual information at the firm, mine, and commodity levels on exploration and production.

The dataset offers near-universal coverage of global mining activity, spanning 140 countries and over 4,000 firms. It captures more than 90% of the sales revenue of the listed mining universe represented in Compustat (see Table A.1),[4] and accounts for more than 60% of global minerals production, with some heterogeneity by type of mineral (see Table A.2).

The panel covers the period 1997 to 2024. While aggregate exploration expenses are available for the full period, a comprehensive commodity-level breakdown is available only from 2010 onwards. However, for some major commodities (such as gold, copper, nickel, and diamonds) the breakdown exists since 1997. I leverage this sub-sample in Section 5 to conduct robustness tests, specifically controlling for differential commodity price dynamics to ensure that my results are not driven by minerals-specific shocks.

I primarily exploit data on exploration expenditures and commodity production, aggregated at the firm-country-commodity level. I also use data on reserve levels to compute the revenue-maximizing tax rate in Section 6. Table 1 summarizes the sample, which includes over 4,100 unique firms with aggregate annual exploration expenditures averaging $7.7 billion.

Exploration expenses are also disaggregated by project stage, serving as a proxy for investment risk. I exploit this breakdown in Section 5 to assess heterogeneous treatment effects. Specifically, the data distinguish between grassroots exploration (high-risk greenfield projects) and late-stage or minesite exploration (lower-risk expansion of existing mines).[5]

[4]Compustat covers the universe of listed firms globally.

[5]Grassroots exploration targets greenfield sites where no prior drilling has occurred; it represents the earliest, highest-risk stage and accounts for one-third of total expenses. Late-stage exploration occurs after a discovery to delineate the deposit's size and feasibility. Minesite exploration takes place near existing operations to extend the mine's productive life.

Table 1: Summary Statistics

	Exploration		Production		
	Nb Firms	**Amount** $M	**Nb Firms**	**Unit**	**Amount** M
Gold	3,343	3,840.1	1,023	Ounce	71.4
Copper	2,256	1,771.7	547	Ton	16.2
Silver	1,089	486.4	597	Ounce	557.2
Uranium	632	428.7	76	Pound	112.1
Nickel	974	400.0	170	Ton	1.3
Diamonds	441	375.9	109	Carat	93.6
Lithium	556	247.2	62	Ton	0.3
Potash	158	200.5	25	Ton	22.1
Lanthanides	342	97.6	13	Ton	0.1
Molybdenum	246	50.8	98	Ton	0.2
Cobalt	283	42.8	102	Ton	0.1
Total	**4,134**	**7,782.4**	**3,547**		

Notes: This table presents descriptive statistics for the sample, disaggregated by commodity. It reports the number of unique firms, average total annual exploration expenditures (in million USD), and average total annual global production volume (in million units). It includes a panel from 1997 to 2024 for gold, copper, nickel, diamonds, and the total, and from 2010 to 2024 for all other commodities.

Tax data. Royalties are payments for the extraction of state-owned resources. They are typically calculated ad valorem (on sales) or on mining income (after deducting production expenses), and are generally deductible from the corporate income tax base. To capture the full fiscal burden on mining firms, where royalties often constitute a significant layer of taxation on top of regular corporate income taxes, I construct a novel dataset combining multiple sources.

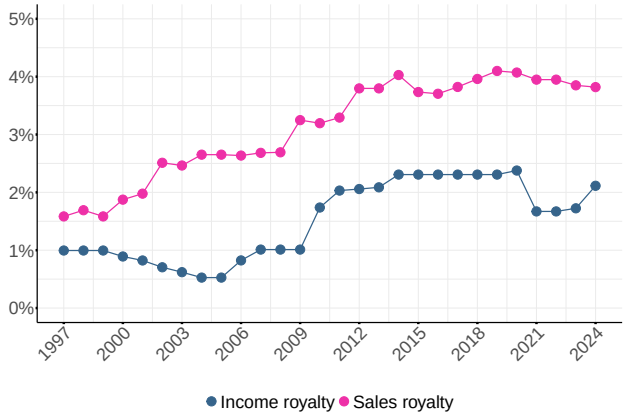
I build upon the dataset provided by Laporte et al. (2019), which covers 21 African countries, and complement it with manual data collection from national mining codes for all other countries with active exploration. I exclude country-year observations governed by ad hoc or negotiated regimes without a centralized statutory framework, noting that such regimes have increasingly been replaced by standardized systems. For nations with decentralized fiscal regimes, I assign the tax rates of the region hosting the largest share of non-coal mining activity (Nevada for the United States, Ontario for Canada, and Western Australia). While this approach proxies the national environment, I acknowledge it introduces measurement error for firms operating in other regions.

Figure 1a illustrates the evolution of these rates. The data reveal a clear upward trend in statutory royalty rates tracking the commodity boom, followed by a stabilization after the 2015

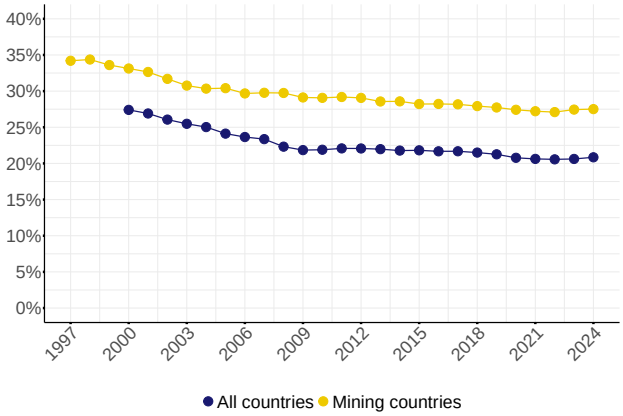
demand shock in China. In contrast, corporate income tax rates in the sector largely mirror the general global decline.

Figure 1: Evolution of Tax Rates

(a) Royalties on sales and income



(b) Taxes on income



Note: Figure 1a shows the non-weighted average of royalty rates on income and sales since 1997. It includes 50 countries in which there is an exploration activity in a given year. Data is taken from the Ferdi dataset for 22 Subsaharan African countries, and author's online searches for other countries. Figure 1b shows the evolution of the non-weighted average tax rate on income for mining countries and in all countries, including non-mining countries. Data for non-mining countries come from the OECD corporate income tax dataset.

4 Worldwide semi-elasticity

In this Section, I first estimate the effects of tax rate changes on exploration expenses and production using a global cross-country analysis, before analyzing specific major fiscal reforms in Section 5.

4.1 Empirical Strategy

My empirical strategy relies on a within-firm identification design, exploiting variation in the tax rates faced by the same multinational firm across different countries. I rely on the 2010-2024 panel providing a full commodity breakdown. I estimate the following linear regression model:

$$\log(y_{fict}) = \beta_1 \tau_{it}^{income} + \beta_2 \tau_{it}^{sales} + \log(p_{ct}) + \mu_{fic} + \gamma_{ft} + \epsilon_{fict} \tag{13}$$

where y_{fict} denotes either production or total exploration expenditures for commodity c by firm f in country i at time t. The independent variables of interest are τ_{it}^{income}, the statutory corpo-

rate income tax rate, including potential royalties on mining income, and τ_{it}^{sales}, the royalty (or turnover tax) rate. Including the price p_{ct} allows to control for mineral-specific price shocks.

To ensure causal identification, the model includes the following fixed effects structure. First, firm $\times$ country $\times$ commodity fixed effects (μ_{fic}) absorb all time-invariant unobserved heterogeneity specific to a firm's project in a given country. It controls for factors such as the geological quality of the specific deposit or the firm's historic infrastructure in that country.

Second, firm $\times$ year fixed effects (γ_{ft}) control for all time-varying shocks common to the firm globally. It absorbs global commodity price shocks, firm-level credit constraints, or shifts in corporate strategy. By including γ_{ft}, I effectively compare how a specific firm reallocates its exploration expenditures between its subsidiaries in response to a relative change in tax rates, holding its global exploration budget constant.

In alternative specifications, I replace the commodity price control $\log(p_{ct})$ with Commodity $\times$ Year fixed effects, which absorb all global price dynamics and demand shocks specific to a mineral. Finally, to capture responses at the extensive margin, I re-estimate the model aggregating the data to the country-commodity level.

4.2 Results

The results are displayed in Tables 2 and 3.

Exploration Expenditures. Both results at the firm and at the country level shows a sharp distinction in how different tax instruments affect investment behavior. I find that sales-based royalties have a clear negative impact on exploration expenses across all specifications. Specifically, a one percentage point increase in the royalty rate is associated with a 5.4 to 7.4% reduction in exploration expenditures.

In contrast, the response to corporate income taxes is smaller and only weakly significant at the firm level, with a semi-elasticity ranging from -1.1 to -2.1%. While standard economic theory suggests that pure profit taxes should be neutral regarding investment decisions (Diamond and Mirrlees, 1971), these findings indicate that in practice, statutory corporate taxes remain

Table 2: Tax Semi-Elasticity of Exploration and Production

	Exploration (log)		Production (log)	
	(1)	(2)	(3)	(4)
Income Tax Rate	-0.011*	-0.011	-0.005	-0.003
	(0.007)	(0.007)	(0.008)	(0.008)
Sales Royalty Rate	-0.054***	-0.058***	0.016	0.013
	(0.019)	(0.020)	(0.028)	(0.028)
Price (log)	0.052		0.240***	
	(0.058)		(0.066)	
Observations	41,833	41,833	14,074	14,074
R^2	0.91053	0.91298	0.97869	0.97929
Firm-Country-Commodity fixed effects	✓	✓	✓	✓
Year-Firm fixed effects	✓	✓	✓	✓
Year-Commodity fixed effects		✓		✓

Notes: This table summarizes coefficents estimated from equation (13). The outcome variable is the log of annual exploration expenses made by each firm in each country for columns 1-2, and production by country for columns 3-4. Standard Errors are clustered at the firm level.

Table 3: Tax Semi-Elasticity of Exploration and Production, Country Level

	Exploration (log)		Production (log)	
	(1)	(2)	(3)	(4)
Income Tax Rate	-0.019**	-0.021***	-0.003	-0.0006
	(0.008)	(0.007)	(0.008)	(0.008)
Sales Royalty Rate	-0.074**	-0.059*	-0.005	-7.02×10^{-5}
	(0.034)	(0.033)	(0.022)	(0.023)
Price (log)	0.230***		0.083	
	(0.080)		(0.085)	
Observations	2,849	2,849	4,980	4,980
R^2	0.85020	0.87433	0.95689	0.96169
Country-Commodity fixed effects	✓	✓	✓	✓
Year fixed effects	✓		✓	
Year-Commodity fixed effects		✓		✓

Notes: This table summarizes coefficents estimated from equation (13). The outcome variable is the log of total annual exploration expenses made in each country for columns 1-2, and production by country for columns 3-4. Standard Errors are clustered at the country level.

partially distortionary. This deviation from theory likely stems from real-world frictions, such as imperfect deductibility of costs.

Production. I find no statistically significant evidence that tax increases affect production levels in the short run. The coefficients for both royalties and income taxes are statistically insignificant. This short-term inelasticity is consistent with the industry's cost structure: once a mine

is operational, the capital is sunk, and the long lead times between discovery and extraction prevent firms from rapidly adjusting output in response to fiscal shocks.

My results are close to the results of Ahlvik et al. (2022), who find a semi-elasticity of exploration of -0.03 for production taxes, and of -0.009 for income taxes in the oil sector, and no significant effect on oil extraction.

4.3 Robustness

Staggered difference-in-differences. Recent advances in econometric theory highlight that standard two-way fixed effects estimators can yield biased estimates in staggered adoption designs when treatment effects are heterogeneous or vary over time (Sun and Abraham, 2021; Callaway and Sant'Anna, 2021). To address this concern, I implement a stacked difference-in-differences approach following Cengiz et al. (2019) and Ahlvik et al. (2022).

This method reconstructs the dataset by creating separate sub-samples for each reform event. Within each sub-sample, treated units are paired exclusively with never-treated controls (i.e., countries with no tax changes), thereby eliminating the 'forbidden comparisons' that generate bias. The estimates from this specification confirm my baseline results: I find a significant decrease in exploration expenses following an increase in sales taxes, with an elasticity of -0.13 (see columns (1) and (2) of Table 4), while the effect of income taxes disappears.

Cross-border spillovers. I conduct sensitivity analyses to rule out cross-border spillover effects. A potential concern is that the estimated effect is inflated by reallocation of expenses: multinational firms might reallocate exploration budgets from treated countries to the control group, artificially widening the difference. To address this violation of SUTVA, I restrict the sample to firms operating in a single country. The results hold and the magnitude even increases, as shown in columns (3) and (4) of Table 4. Single-country firms appear significantly more sensitive to taxes, likely due to tighter financial constraints compared to larger, diversified multinationals.

Table 4: Tax Semi-Elasticity of Exploration Expenses, Robustness

	Exploration Expenses (log)			
	Stacked regression		One country	
	(1)	(2)	(3)	(4)
Income Tax Rate	0.0008	-3.08×10^{-5}	0.002	-0.001
	(0.004)	(0.005)	(0.009)	(0.009)
Sales Royalty Rate	-0.133***	-0.135***	-0.243***	-0.250***
	(0.043)	(0.041)	(0.067)	(0.066)
Price (log)	0.141***		0.090	
	(0.036)		(0.057)	
Observations	566,861	566,861	14,270	14,270
R^2	0.73341	0.74140	0.67415	0.68774
Firm-Country-Commodity-Indicator fixed effects	✓	✓		
Year-Indicator fixed effects	✓			
Year-Indicator-Commodity fixed effects		✓		
Firm-Country-Commodity fixed effects			✓	✓
Year fixed effects			✓	
Year-Commodity fixed effects				✓

Notes: This table reports the results of two robustness tests: the stacked regression in columns (1) and (2), and with a sample composed only of firms operating in one country in columns (3) and (4).

5 Case Study on Large Tax Changes

In this section, I analyze large-scale mineral tax reforms in four key jurisdictions: South Africa, Ghana, Mexico, and the Democratic Republic of the Congo.

5.1 The reforms

Selection. From the universe of mining tax reforms implemented over the past twenty years, I restrict the sample to episodes that satisfy three identification criteria ensuring a clear and sustained shock to firm incentives. First, the reform must lead to an unambiguous increase in the statutory tax burden. For instance, I exclude the 2011 reform in Peru, which switched from a production-based to a profit-based system, rendering the net impact on the effective tax rate unclear. Second, the policy change must be persistent. Consequently, I exclude short-lived experiments such as Australia's 2012 Mineral Resource Rent Tax, which was repealed after just two years despite implying a significant rate hike. Third, the reform must impose a significant increase in the tax rate faced by mining firms.

Based on these criteria, I identify four major episodes: South Africa (2010), Ghana (2012),

Mexico (2014), and the DRC (2018). These reforms represent the only clear, significant, and sustained tax hikes in the sector during this period. As illustrated in Figure A.1, they were implemented against the backdrop of the commodity super-cycle which provided the political leverage for resource-rich states to capture a larger share of rents.

Mexico (2014). Prior to 2014, the Mexican mining sector was subject only to the standard corporate income tax. The reform introduced a specific mining regime with three key components. First, it implemented a 7.5% Special Mining Duty levied on EBITDA. Second, it introduced a 0.5% royalty on gross revenues from gold, silver, and platinum. Third, it eliminated the immediate deductibility of pre-operative exploration expenses. Firms must now amortize these costs at an annual rate of 10%, significantly increasing the after-tax cost of early-stage investment. Additionally, a new duty on unused concessions was introduced to discourage speculative hoarding.

Democratic Republic of the Congo (2018). The 2018 Mining Code represented the first major revision of the liberal 2002 regime. The reform broadened the fiscal base and raised rates. Royalties on copper increased from 2% to 3.5%, and on gold from 2.5% to 3.5%. The code introduced a 10% royalty rate on strategic strategic minerals (cobalt, germanium, and coltan). The tax base was also redefined to "Gross Commercial Value," eliminating deductions for transport and marketing that existed under the previous system. Furthermore, the code introduced a 50% super-profits tax triggered when commodity prices exceed feasibility study projections by 25%. Finally, the state's free-carried interest was doubled to 10%, and the stability clause guarantee was reduced from 10 years to 5 years.

Ghana (2012). The 2012 reform increased the statutory corporate income tax (CIT) rate for mining companies by 10 percentage points, from 25% to 35%. Simultaneously, the royalty regime was harmonized: the previous sliding scale (3% to 6%) was replaced by a flat royalty rate of 5% on production value. A proposed windfall tax was discussed during this period but ultimately not implemented.

South Africa (2010). The Mineral and Petroleum Resources Royalty Act, passed in 2008 and implemented in 2010, implemented for the first time a state-level royalty system. The new royalty rate is calculated based on profit margins, with rates sliding between 0.5% and 5% for refined minerals, and between 0.5% and 7% for unrefined minerals, applied to the value of the sales.

Table 5 provides a summary of the fiscal terms before and after each reform.

Table 5: Summary of Tax Reforms

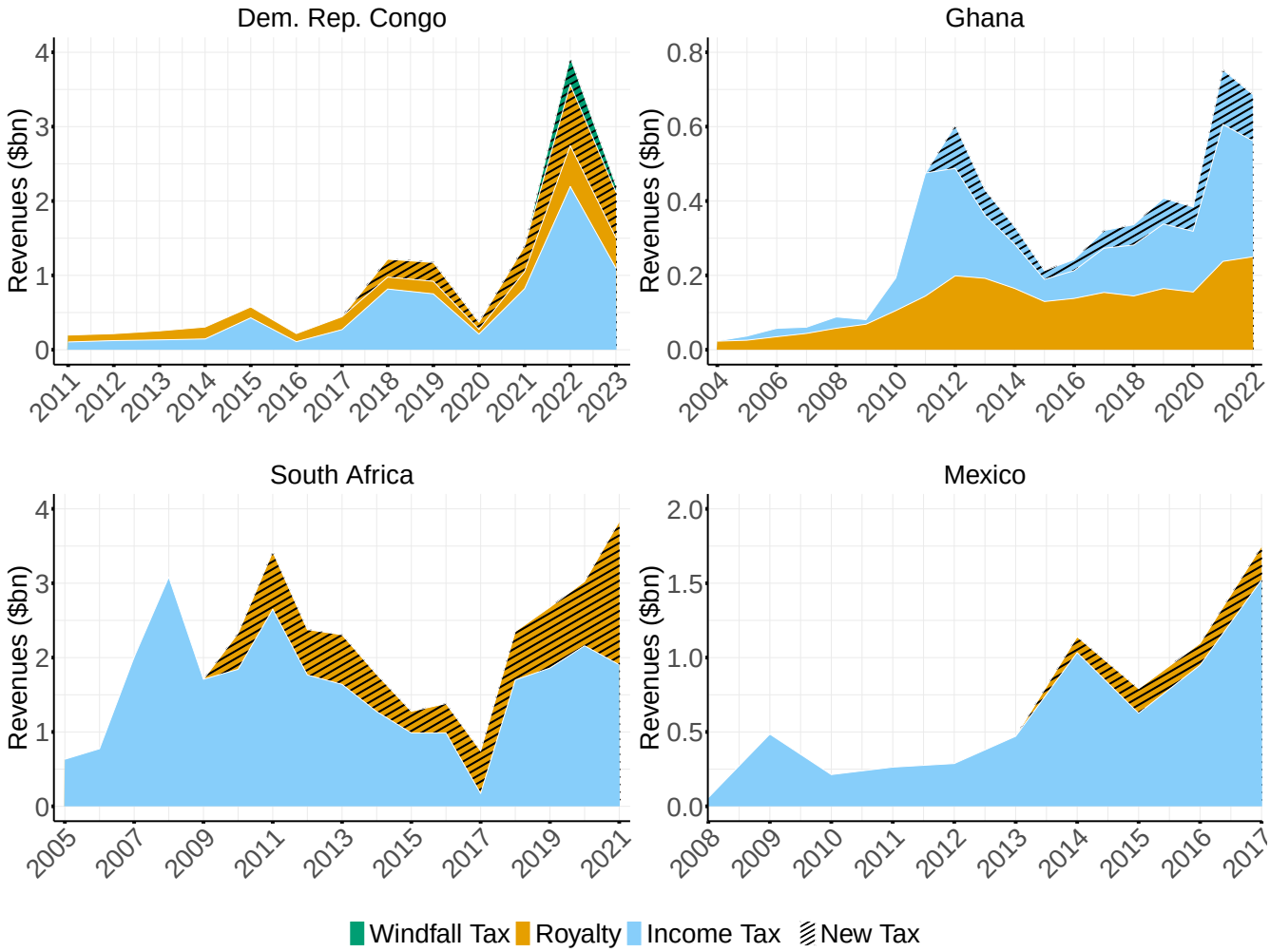
Country	Voted	Implemented	Rate on income	Rate on sales	Other changes
South Africa	2008	2010		+0.5–5 or 6%	
Ghana	2012	2012	+10pp		
Mexico	2013	2014	+7.5pp	+0.5pp	End of full deduction of pre-operative expenses
Dem. Rep. Congo	2018	2018		+1pp	Broadening of the tax base +50% excess profit tax

Impact on Government Revenues. The fiscal reforms represent a significant share of total mining sector collections. The incremental revenues generated by these tax increases account for 17% of post-reform revenues in Ghana, 27.5% in the DRC, 31.1% in South Africa, and 13.5% in Mexico. Figure 2 shows descriptively the evolution of corporate income tax, royalties, and windfall taxes across the four jurisdictions. The figure specifically isolates the revenue directly attributable to the reforms—represented by the striped areas—based on official government and agency reports.

5.2 Background

Table 6 reports descriptive statistics for the 11-year window surrounding each reform. The sample covers significant exploration activity, ranging from 49 active firms in Ghana to 256 in Mexico, the vast majority of which are foreign-headquartered. Figure A.2 plots the evolution of exploration shares for each country's main commodities. Descriptively, exploration activity was often already trending downward prior to the reforms. This volatility, driven by the entry and exit of a few large firms, underscores the need for an identification strategy going beyond simple time-series observation.

Figure 2: Evolution of Tax Revenues from the Mining Sector



Notes: These four graphs show the evolution of revenues from corporate income taxes, royalties, and windfall taxes in the mining sector, in billion USD. Striped areas denote revenues from new tax instruments as well as the incremental portion of revenues resulting from statutory rate increases in existing instruments.
Sources: Data are compiled from various publicly available government and agency reports. **Democratic Republic of the Congo:** Data are sourced from annual ITIE-RDC reports. "Windfall Tax" corresponds to the *Impôt Spécial sur le profit Excédentaire*, "Royalties" to the *Redevance Minière*, and "Income Tax" to the *Impôt sur les bénéfices et Profits* (or *Impôt Spécial Forfaitaire*). **Ghana:** Data are obtained from the annual reports of the Ghana Extractive Industries Transparency Initiative (GHEITI). The significant spike in corporate income tax revenues in 2010 is attributable to major mining projects reaching the end of their capital allowance recovery periods. As these firms exhausted their investment-linked tax credits and carried-forward losses, a larger share of their operating income became subject to the statutory tax rate. **South Africa:** Data are sourced from the South African Revenue Service (SARS) annual Revenue Collection Reports. **Mexico:** Data are retrieved from the fourth-quarter reports (*Informes sobre la Situación Económica, las Finanzas Públicas y la Deuda Pública*) under the chapter *Indicadores de Recaudación*. The new royalties introduced by the 2014 reform combine the *derecho especial*, *derecho extraordinario*, and *derecho adicional*. Prior to 2015, reports for Mexico do not disaggregate corporate income tax (CIT) between the mining and oil sectors. To estimate mining-specific CIT for this period, I estimate oil-sector CIT by assuming the ratio between CIT payments and total payments from the oil sector remains constant at the average level observed post-2014.

The four countries are globally significant producers with mining sectors that are central to their domestic economies. As detailed in Table A.5, they hold dominant market positions: Mexico is the world's leading silver producer (22% of global output), the DRC dominates cobalt (69%), South Africa leads in platinum (72%), and Ghana is a top-tier gold producer (4.3%).

Table 6: Summary Statistics - Exploration by Country

Country	Year	Nb Firms	Share foreign firms (%)	Amount per year ($M)
South Africa	2005-2015	109	100	193.0
Ghana	2007-2017	49	100	49.0
Mexico	2009-2019	256	97	350.7
DRC	2013-2013	54	100	60.3

Notes: This table shows the annual total expenses in grassroots exploration made by firms on average for each country during the 11 years around the reforms, in $ million. The number of firms is the total number of firms carrying out an exploration activity at least once in the country during the period. Foreign firms are defined based on the ultimate owner of the company. The share is defined based on the number of firms.

Consequently, the mining sector accounts for a substantial share of GDP, ranging from 2.3% in Mexico to 19.7% in the DRC, and fiscal revenue.[6]

Figure A.3 maps the location of industrial mines, illustrating that all four nations are bordered by other major mineral producers. This geographic proximity creates plausible channels for cross-border capital leakage. For instance, the DRC borders the copper belts of Zambia and Angola; Ghana shares the West African gold belt with Burkina Faso and Ivory Coast; and South Africa neighbors the diamond and platinum deposits of Botswana and Zimbabwe. Note that this analysis is restricted to industrial mining, which represents approximately 80% of total production, and excludes the artisanal sector.

5.3 Empirical Strategy

To identify the causal effects of tax reforms on exploration and production, I employ a dynamic difference-in-differences framework. My baseline analysis focuses on grassroots exploration (investments aimed at discovering new fields, which represents more than a third of total investments). I then extend the analysis to late-stage exploration (extensions of known deposits) and total expenses to capture the full spectrum of exploration activity.

Between-firm strategy. I first compare exploration expenses made by firms with substancial activity in treated countries with firms not affected by the reforms. More specifically, the treatment group consists of firms that incurred more than 10% of their total exploration expenses in

[6] In 2022, mining taxes contributed 42% of total revenue in the DRC and 13% in Ghana (UNU-WIDER Government Revenues Dataset).

a treated country during the five years prior to the tax increase. The control group consists of all remaining non-exposed firms. I estimate the following event-study specification:

$$y_{ft} = \sum_{k \neq -1} \beta_k \cdot \mathbb{1}(D_{ft} = k) \cdot Treated + \mu_f + \mu_t + \varepsilon_{ft} \tag{14}$$

where y_{ft} denotes the logarithm of exploration expenses for firm f in year t. The term $\mathbb{1}(D_{ft} = k)$ is an indicator equal to one if firm f is k years away from the reform implementation year, and the $Treated$ dummy indicates whether a firm was treated or not. μ_f and μ_t represent firm and year fixed effects, respectively, absorbing time-invariant firm heterogeneity and global shocks to exploration demand. Standard errors are clustered at the firm level.

The coefficients β_k characterize the differential evolution of exploration expenses for treated firms relative to the control group. To disentangle the mechanisms driving the total effect, I estimate Equation (14) using two separate dependent variables: exploration expenses incurred within the treated jurisdictions ("Local Expenses"), and (ii) exploration expenses incurred in non-treated jurisdictions ("Foreign Expenses").

Within-Firm Reallocation. In a second step, I exploit the granular nature of the data to compare exploration expenses within the same firm across treated and non-treated countries. The unit of observation is the firm-country-year (f, c, t). This specification allows me to control for firm-specific shocks that simultaneously affect exploration decisions across all locations. I estimate the following equation:

$$y_{fit} = \sum_{k \neq -1} \gamma_k \cdot \mathbb{1}(D_{ct} = k) \cdot Treated + \mu_{fi} + \mu_{ft} + \varepsilon_{fit} \tag{15}$$

Here, y_{fit} is the log of exploration expenses by firm f in country i at year t. The specification includes firm-by-country fixed effects (μ_{fi}) to control for time-invariant comparative advantages, and firm-by-year fixed effects (μ_{ft}) to absorb time-varying firm-level shocks. The inclusion of firm-by-year fixed effects (μ_{ft}) absorbs all time-varying firm-level shocks. This is advantageous for identification as it controls for the firm's global expenses and isolates changes in the geo-

graphic composition of exploration expenses. However, if the reform causes a firm to reduce its aggregate global exploration budget rather than merely reallocating funds, μ_{ft} will absorb this mechanism. Therefore, I also estimate an alternative specification replacing μ_{ft} with year fixed effects (μ_t). Comparing these two specifications allows me to disentangle pure reallocation from net reductions in exploration activity.

The coefficients γ_k capture the diversion of investment away from treated countries relative to other countries within the same firm. It is important to note that if firms substitute exploration capital from treated to non-treated affiliates, the control group in this design is positively affected by the treatment. This estimator will thus likely overestimate the magnitude of the negative effect on the treated jurisdiction. This internal reallocation bias is not present in the between-firm strategy (Equation 14), where the control group consists of non-exposed firms whose investment decisions are independent of the tax reform.

Extensive Margin. I next examine the extensive margin—the decision to explore in a treated country. I construct a balanced firm-country-year panel, excluding firms that never explored in a treated country during the sample period. I estimate a Linear Probability Model (LPM) as follows:

$$\mathbb{1}(Explore_{fct} > 0) = \sum_{k \neq -1} \delta_k \cdot \mathbb{1}(D_{ct} = k) + \mu_{fc} + \mu_t + \varepsilon_{fct} \tag{16}$$

The dependent variable is a dummy equal to one if firm f reports positive exploration expenses in country c at time t. This specification tests whether the tax reforms alter the probability of maintaining active exploration projects. I complement this with a country-level aggregation, regressing the count of exploring firms on the treatment indicators to capture aggregate entry and exit dynamics.

Production Response. Finally, I analyze the effects on the intensive margin of extraction using mine-level data. This allows for a precise identification of the supply elasticity with respect to tax rates, conditional on global commodity price cycles. The estimation relies on the following

specification:

$$y_{mct} = \sum_{k \neq -1} \theta_k \cdot \mathbb{1}(D_{ct} = k) + \alpha \ln(P_{ct}) + \mu_m + \mu_t + \varepsilon_{mct} \tag{17}$$

where y_{mct} is the log metric ton production of mine m extracting commodity c in year t. The term μ_m denotes mine fixed effects (which absorb mine-specific geology and commodity type), and μ_t denotes year fixed effects. Crucially, I control for $\ln(P_{ct})$, the global price of the specific commodity extracted by the mine, to isolate the tax effect from commodity price booms. Standard errors are clustered at the mine level.

5.4 Results

5.4.1 First Stage

Figure 3 provides the visual evidence for the first-stage relationship between the tax reforms and royalty payments, estimated at the mine level. The results show a sharp and immediate increase in royalty payments in the year of adoption, with the effect persisting throughout the post-treatment window. The point estimates in Figure 3a indicate that, on average, royalty payments increased by approximately 0.26 million USD. I make sure that these estimates are not driven by an increase in mining activity by alternatively using the ratio between royalty payments and gross revenues in Figure 3b. I find an increase of this ratio of around 1.5pp on average post reforms. The stability of this intensive-margin response confirms that the increase in payments is driven by the policy change rather than changes in production scale. For both outcomes, the pre-reform coefficients are precisely estimated and statistically indistinguishable from zero, providing strong empirical support for the validity of the parallel trends assumption.

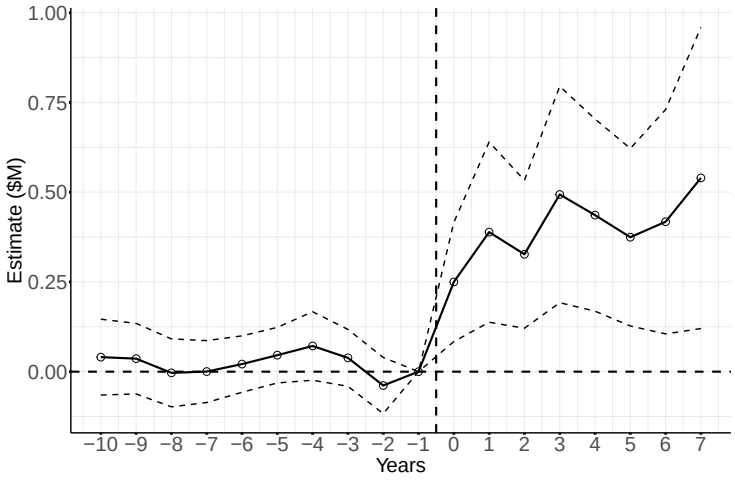
5.4.2 Exploration Responses

Between-firm Strategy. Figure 4 presents the dynamic evolution of exploration expenses for exposed firms relative to non-exposed firms.

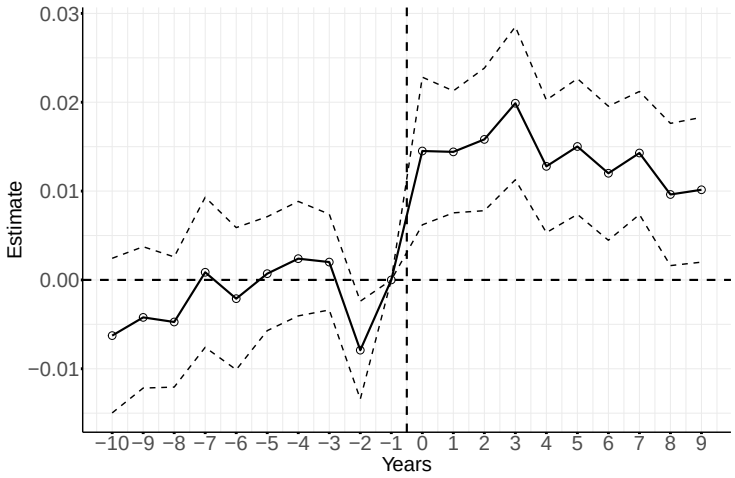
Subfigure 4a shows the results of two regressions with two outcome variables: one with 'foreign expenses' made by treated firms, or expenses made outside treated countries, and one

Figure 3: First Stage: Effects of the Reforms on Royalty Payments

(a) Effects on Tax Payments



(b) Effects on Tax Payments-to-Revenues Ratios



Note: This figure plots event-study coefficients for the impact of tax reforms on firms payments. Figure 3a reports effects on total royalty payments (in million USD). Figure 4b reports effects on the royalty-to-gross-revenue ratio.
Dashed lines represent 95% confidence intervals. Standard errors are clustered at the mine level.

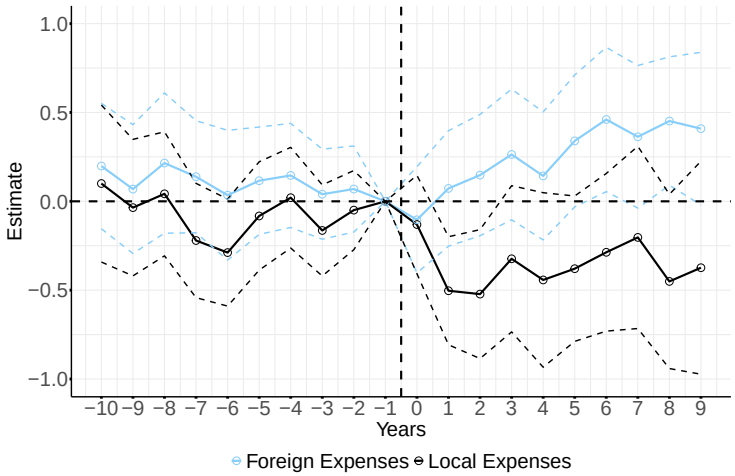
with 'local expenses' made in treated countries as an outcome. The results document a strong substitution effect: immediately following the tax increase, treated firms significantly reduce exploration expenses in the treated jurisdictions while simultaneously gradually increasing investment in non-treated jurisdictions.

Table B.1 (Columns 1-4) reports the corresponding event-study coefficients. On average, exposed firms reduced their local exploration expenses by 29.3% in the post-reform period (Table 7). Figure B.1 confirms that this pattern is not driven by a single outlier; all four implementing countries exhibit similar trends of domestic contraction and foreign expansion.

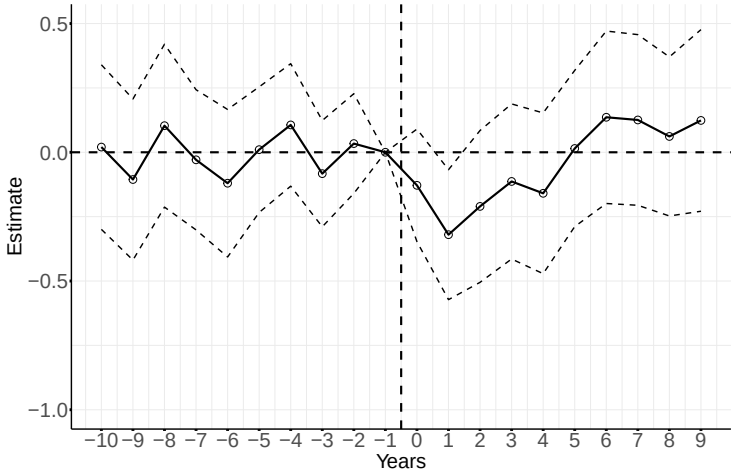
Figure 4b plots the evolution of total exploration expenses for treated firms. In the immediate aftermath of the reform (years $t = 0$ to $t = 2$), total global expenses decline, suggesting that firms cannot instantly reallocate capital to foreign subsidiaries—likely due to search frictions or adjustment costs. However, by year $t = 5$, total expenses recover to pre-reform levels. This implies that in the long run, the tax reform affects the location of exploration activity rather than the global volume of expenses.

Figure 4: Impact of Tax Reforms on Exploration Expenses - Between-Firm Strategy

(a) Local vs. Foreign Expenditures



(b) Overall Expenditures



Note: This figure plots event-study coefficients for the impact of tax reforms on exploration expenses using the between-firm strategy. Figure 4a decomposes expenses into "Local Expenses" (incurred in the treating jurisdiction) and "Foreign Expenses" (incurred by the same firms in non-treating jurisdictions). Figure 4b plots the impact on the firm's total global exploration budget. Time 0 indicates the reform implementation year. Dashed lines represent 95% confidence intervals. Standard errors are clustered at the firm level.

Appendix Figure B.3 presents the results for exploration expenses that also include late-stage

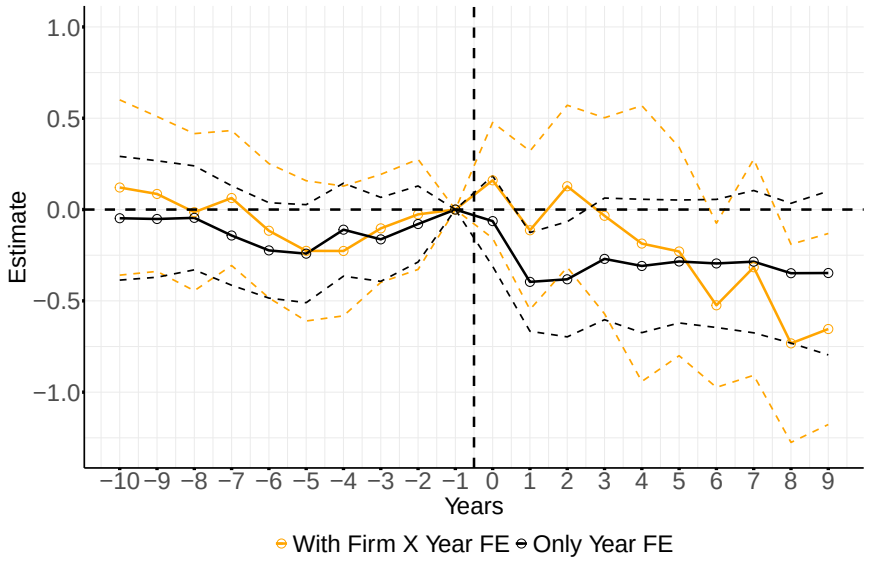
mine extension expenditures. The results confirm a reduction in local investment and a concurrent increase in foreign spending. However, the response of total expenses is more gradual, likely reflecting the longer time horizons and rigidity associated with late-stage projects.

Within-firm Strategy. Figure 5 presents the results from the within-firm strategy. To disentangle the scale of investment from its geographic distribution, I estimate the model with two different fixed effect structures.

First, when including only year fixed effects (absorbing global trends but leaving firm-level scale shocks visible), we observe a sharp and immediate drop in exploration expenses in treated countries. This indicates that firms react quickly to the tax hike by cutting local budgets.

In contrast, when including firm-by-year fixed effects—which controls for the firm's total global budget and isolates the share allocated to each country—the decline is notably more gradual. This lag suggests that while firms can cut local spending immediately, the process of reallocating that capital to foreign jurisdictions faces frictions. It takes time for firms to identify new targets and ramp up exploration elsewhere, resulting in a progressive rather than instantaneous shift in the firm's geographic portfolio.

Figure 5: Impact of Tax Reforms on Exploration Expenses - Within-Firm Strategy



Note: This figure presents estimates from the within-firm specification (Equation 15). It compares the standard specification (controlling for year FE) against the reallocation specification (controlling for firm-by-year FE). Time 0 indicates the reform implementation year. Dashed lines represent 95% confidence intervals.

Table 7 summarizes the results for the between and within-firm strategies. As expected, the within-firm coefficient is significantly smaller than the between-firm estimate. This confirms that the within-firm strategy acts as a lower bound due to spillover effects, whereas the between-firm strategy remains robust to SUTVA violations.

Table 7: Exploration expenses - Pre-Post

	Between Firms			Within Firms	
	Total Expenses (log)	Local Expenses (log)	Foreign Expenses (log)	Expenses (log)	
	(1)	(2)	(3)	(4)	(5)
Treated X Post	-0.070	-0.293***	0.146	-0.341***	-0.165
	(0.086)	(0.096)	(0.113)	(0.086)	(0.140)
Observations	26,402	25,415	25,629	13,334	13,334
R^2	0.57638	0.57090	0.57621	0.63566	0.82959
Within R^2	9.33×10^{-5}	0.00086	0.00027	0.00289	0.00053
Firm fixed effects	✓	✓	✓		
Year fixed effects	✓	✓	✓	✓	
Firm-Country fixed effects				✓	✓
Firm-Year fixed effects					✓

Notes: This table summarizes our estimates of the effects of the reforms on exploration expenses. The outcome variable is the log of annual exploration expenses made by each firm, overall (1), only in treated countries for treated firms (2), only in non-treated countries for treated firms (3), and exploration at the firm-country level in column (4). Standard Errors are clustered at the firm level.

Finally, I study the effects of the reforms on less-risky "Late Stage" investments, made to expand of existing mines. I hypothesize that higher taxes should disproportionately deter high-risk, marginal investments. Consistent with this view, Figure B.4 shows that late-stage investments declines by only 25% post-reform, compared to the 50% collapse observed in grassroots exploration.

Comparison with results from Section 4. To compare my estimates with the worldwide semi-elasticity derived in Section 4, I first calculate the average tax increase, weighted by the number of treated firms in each jurisdiction. To ensure comparability, I convert income tax rates into equivalent sales tax rates using a profit-to-sales ratio of 0.47 (see Section 6 for the detailed derivation). I find a semi-elasticity with respect to sales of 8.4. This estimate is slightly higher than, but quantitatively consistent with, the results obtained in Section 4.

Robustness tests. A potential concern is that tax reforms might coincide with commodity price shocks that differentially affect exploration incentives. To address this, I restrict the sample to the

subset of commodities for which S&P Global provides granular price data (copper, diamonds, gold, nickel, platinum, and zinc). By running the analysis at the firm-by-commodity level, I can explicitly control for commodity-specific price trends. As shown in Figures 6a and 6c, the negative impact on local exploration remains robust and statistically significant, both for the within and the between-firm strategies.

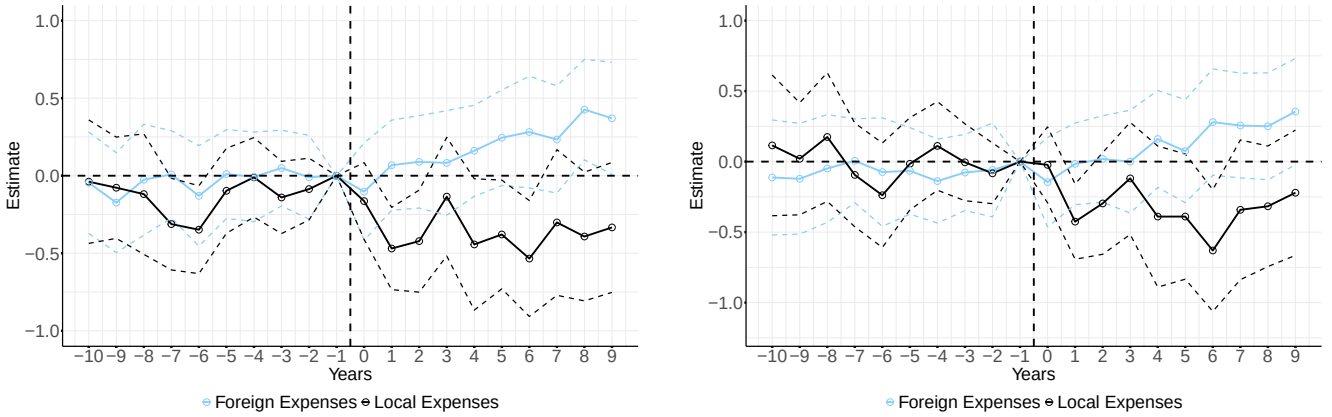
I then make sure that my results are not biaised by including treated units in the control group, as detailed in Sub-section 4.3. I implement a stacked difference-in-differences approach detailed in Sub-section 4.3. Over

The results are displayed in Figure 6.

Figure 6: Event Study - Robustness Tests

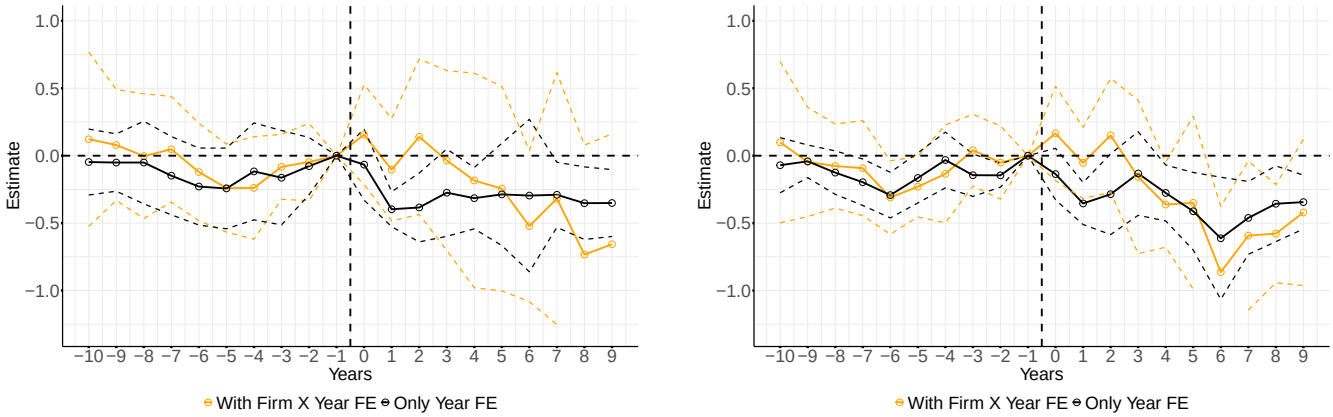
(a) Between - Stacked Regression

(b) Between - Controlling for Commodity Prices



(c) Within - Stacked Regression

(d) Within - Controlling for Commodity Prices



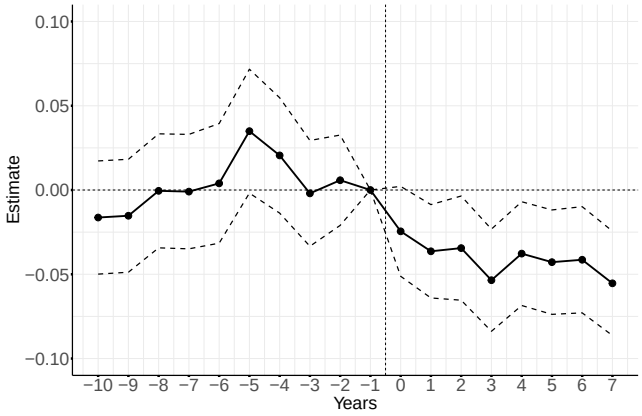
Notes: These figures show estimates of the impact of the reforms on exploration expenses. Time 0 indicates the year of implementation of the reform. Dashed lines represent 95% confidence interval. Standard errors are clustered at the firm level.

Extensive Margin. On the extensive margin, I find a decline of the probability of firms to explore in treated countries just before the implementation of the reforms. Figure 7a shows that firms that carry out an exploration activity at least once in one of the treated country in my dataset see a reduction of 5pp in the probability that they invest in treated countries. Given that the baseline probability of these firm to invest pre-reform is 0.15, this reduction of 5pp amounts to a decrease by a third of the probability to invest in treated countries. Figure B.5 shows the results for each country. Table B.3 shows the coefficients associated with the event study graph, while Table B.2 shows the coefficients for the pre-post regression.

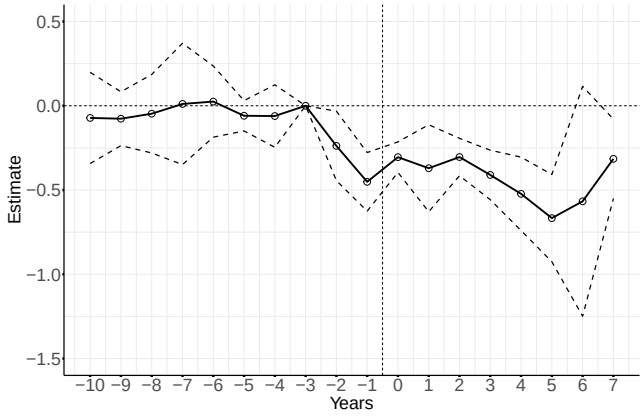
I also find a reduction in the number of firms exploring. Figure 7b shows that the number of firms starts declining two years prior to the reform, with a coefficient ranging between 0.3 and 0.4 in the three years following the reform.

Figure 7: Extensive margin

(a) Probability to explore



(b) Number of Firms



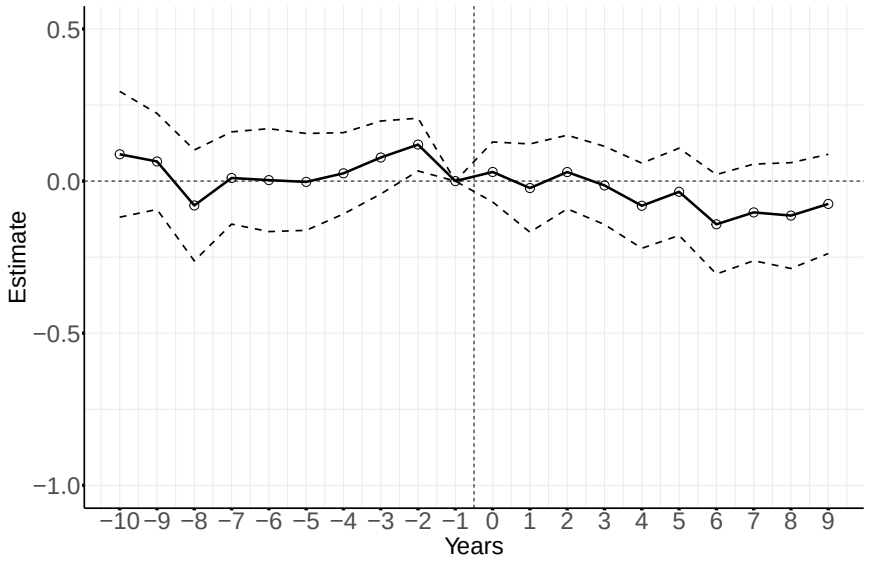
Note: Figure 7a shows the coefficients of our OLS estimation with the outcome variable being a dummy equal to one if the firm is currently making exploration expenses in the country. The results should be interpreted in percent point change. Figure 7b shows the evolution of the number of firms exploring in treated countries, with the outcome variable being the log of the number of firms. Time 0 indicates the year of implementation of the reform. Dashed lines represent 95% confidence interval. Standard errors are clustered at the firm level for Figure 7a and at the country level for Figure 7b.

5.4.3 Minerals Production

Results on production are displayed in Figure 8. The event study coefficients remain relatively stable and statistically indistinguishable from zero in the decade preceding the reform, providing support for the parallel trends assumption. While there is a slight upward trend in produc-

tion estimates two years prior to implementation (Time -2), the effect is not statistically significant at the 95% level. Following the reform (time 0), we observe a modest, though generally non-significant, downward trend in production volumes, suggesting that firms did not drastically alter their extraction levels in response to the tax rate increase.

Figure 8: Effects on Minerals Production



Note: This figure shows estimates of the impact of the reforms on the amounts of mineral production made in treated countries. The outcome variable is the log of the volume of production of each commodity in each mine. Time 0 indicates the year of implementation of the reform. Dashed lines represent 95% confidence interval. Standard errors are clustered at the mine level.

Table B.4 shows the results for the pre-post analysis, while Table B.5 shows the event study coefficients. Figure B.6 shows the country-by-country results.

6 Revenue-Maximizing Tax Rates

I now draw implications for the optimal tax rate for mining states, using the semi-elasticities derived in Sections 4.

6.1 Revenue-Maximizing Formula

I model the government's revenue maximization problem as a trade-off between rate and base, accounting for cross-elasticities between instruments. I normalize total production value to 1. The tax base for royalties (B^{sales}) is a function of real output, which is eroded by both the sales tax and the income tax. The corporate income tax base (B^{income}), defined as a proportion of the profit margin π, is subject to these same real output distortions but faces an additional erosion channel: profit shifting. Captured by the semi-elasticity σ_{τ^i}, this term reflects the firm's increased incentive to engage in tax avoidance as the statutory income tax rate rises. The government thus solves for the pair (τ^i,τ^s) that maximizes total collections G.

The sales tax base will be equal to:

$$B^{sales} = \underbrace{(1 - \epsilon_{y,\tau^s} \times \eta_{res,explo} \times \tau^s)}_{\text{erosion due to } \tau^s} \times \underbrace{(1 - \epsilon_{y,\tau^i} \times \tau^i)}_{\text{erosion due to } \tau^i}$$

The income tax base will be equal to:

$$B^{income} = \pi \times \underbrace{(1 - \epsilon_{y,\tau^i} \times \tau^i)}_{\text{erosion due to } \tau^i} \times \underbrace{(1 - \epsilon_{y,\tau^s} \times \eta_{res,explo} \times \tau^s)}_{\text{erosion due to } \tau^s} \times \underbrace{(1 - \sigma_{\tau^i})}_{\text{erosion due to profit shifting}}$$

Government revenues write:

$$G = B^{sales} \times \tau^{sales} + B^{income} \times \tau^{income}$$

Maximizing G with respect to both rates yields a closed-form solution.

In the absence of profit shifting ($\sigma = 0$), the maximization problem simplifies to a system of linear functions. The analytical solution is given by:

$$\tau^{s*} = \frac{2}{3\epsilon_{y,\tau^s}\eta_{res,explo}} - \frac{\pi}{3\epsilon_{y,\tau^i}} \tag{18}$$

$$\tau^{i*} = \frac{2}{3\epsilon_{y,\tau^i}} - \frac{1}{3\pi\epsilon_{y,\tau^s}\eta_{res,explo}} \tag{19}$$

This result illustrates a substitution effect: the government weighs the relative distortion of each instrument. If the income tax is highly distortive (high ϵ_{y,τ^i}), the optimal policy shifts the tax burden toward royalties (τ^{s*} increases), and vice versa.

6.2 Estimation of the Parameters

Output elasticities ϵ_{y,τ^s} and ϵ_{y,τ^i}. I use the results from Section 4 displayed in Table 2, column (1): the output response for an increase in 1pp of the income tax is estimated to be -1.1%, and -5.4% for the sales tax.

Profit margin π. I use data from S&P on net pretax cash flows, capital expenditures, and gross revenues from the sale of commodities for each mine to estimate the profit margin of minerals extraction. I find a ratio between pretax profits and gross revenues of 0.47, with some heterogeneity across minerals and over the years, as shown in Figure B.8. I consider an alternative scenario of an increase in the profit margin to 0.6, in the likely case of future increases in mineral prices.

Estimation of reserve elasticity η. Decriptive evidence suggests that the amounts spent in exploration are indeed positively correlated with an increase in reserves in the same year, as shown by Figure A.4 for the main commodities in my sample.

I estimate an elasticity between exploration expenditures and new reserves by running this regression at the country level:

$$log(\Delta_{ict}) = log(exploration_{ict}) + log(p_{ct}) + \mu_{ic} + \mu_t \tag{20}$$

With Δ_{ict} new reserves found in metric tons in each country i of each commodity c in year t.[7] It is equal by definition to reserves at the end of year t minus reserves at the end of year $t-1$ plus

[7] It is important to note that the reserves that I use include both economically viable reserves (what is usually called *reserves* in the industry), and resources, which are discoveries that are not defined as profitable yet, but which could be in the future. I have made this choice because this variable is less tied to the price of the commodity - "reserves" are highly fluctuant, while the *reserves plus resource* which I use will be less determined by the level of prices.

production in year t. $exploration_{ict}$ are all exploration expenditures made by all firms in country i and commodity in year t. μ_{ic} controls for the fact that the easiness of finding resources differs across countries. Running this regression at the country level rather than at the firm level allows to take into account potential sales of reserves between firms. The results are displayed in Table B.6 in the Appendix. I find a coefficient of 0.57, which is an expected order of magnitude.

Shifting elasticity σ_{τ^i}. I include a scenario with profit shifting responses. To estimate the share of profits that will be shifted for each income tax rate, I use the results from Best et al. (2015). In this study, the authors exploit a reform in Pakistan that allows them to disantangle real responses from shifting responses to an increase in income tax rate. They find that a sizeable share of profits is shifted by Pakistanese firms: 66.7% for a rate of 35%. For my scenario, I make the hypothesis that the share of shifted profits is linear with the income tax rates, going from 0 for a 0% rate, and equal to 66% for a rate of 35%.[8] I make an alternative scenario of moderate shifting where this share is divided by two.

6.3 Results

The results are displayed in Table 8. In the baseline scenario with no shifting response, I find that the optimal rates on sales and income are 7.5% and 37.4%. These baseline optimal rates are substancially above the average actual tax rates in mining countries, which is more of around 4% in sales-based taxes and 27.5% in income taxes. Including the large shifting responses estimated by Best et al. (2015) considerably changes the results, yielding a very low income tax rates and increasing the sales tax rate significantly.

Taking into account the likely future rise in mining profitability, the last two lines suggest that governments can further increase the tax burden. Whether they should favor higher income taxes or production taxes depends on their administrative capacity to enforce profit-based taxation.

Figure 9 shows the revenues associated with the different tax rates mix associated with the

[8]The authors do find a smaller share of shifted profits for firms taxed at a lower rate: this share is 17.1% for firms taxed at 20%, which makes this share close a proportional share with respect to the income tax rate.

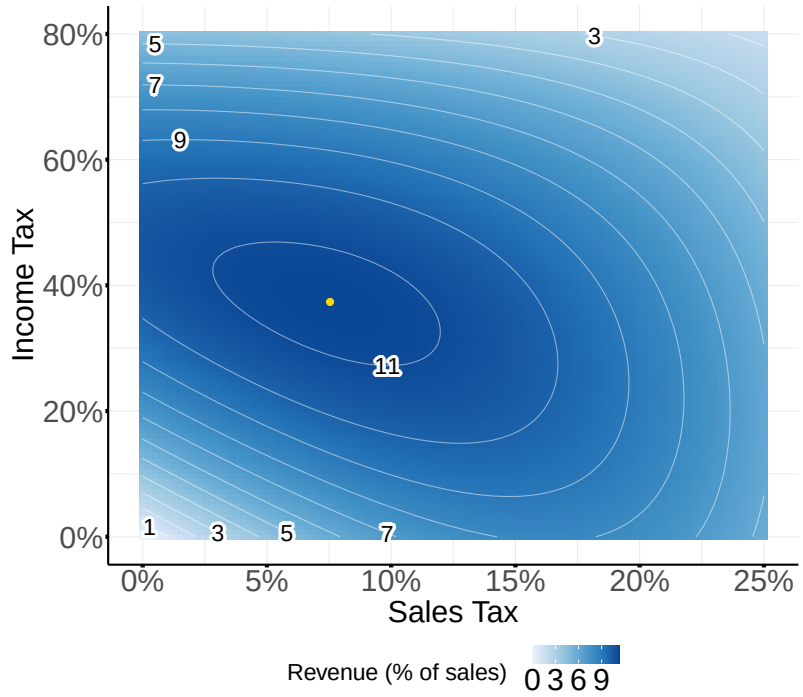
Table 8: Revenue-Maximizing Rates

Method	τ^{sales} (%)	τ^{income} (%)	Revenues (% of Sales)
Baseline	7.5	37.4	11.3
With Shifting	14.0	12.8	9.0
Moderate Shifting	12.4	20.4	9.6
$\eta = 0.8$	1.3	44.0	10.6
$\eta = 0.8$ with Moderate Shifting	7.1	25.0	8.0
$\pi = 0.6$	3.5	42.6	13.8
$\pi = 0.6$ with Moderate Shifting	10.7	23.9	10.8

Notes: This table shows the optimum sales and income tax rates which optimize the revenues of the government, as well as the revenues as a percentage of total sales. Across countries, the average actual tax rate is approximately 4% on sales and 27.5% on income.

baseline estimation.

Figure 9: Iso-Revenue Curves and Optimal Tax Rates Mix



Note: This figure shows government revenues (as a percentage of sales) as a function of the income tax rate (y-axis) and the sales tax rate (x-axis), in our baseline scenario without shifting responses. The contour lines represent iso-revenue curves: every point along a single curve generates the same level of total revenue. The numbers overlaid on the curves indicate the specific revenue yield (in % of sales) associated with that tax combination. The yellow point is the optimum tax rates mix.

7 Conclusion

In this paper, I study the effects of the four largest tax increases on mining exploration and production. I find a small effect on production of existing mines, and a large effect on exploration expenses and firm presence in treated countries, which might affect long-run output. These results echo Anderson et al. (2018) study on the oil sector while the mechanisms are different. Firms are more likely to adjust at the extensive margin, opening fewer new projects, than at the intensive margin, where they have already incured important investment in exploration and development of the mine.

These results have important policy implications, at a time when mineral prices and mining rents are expected to increase. Many resource-rich countries have recently increased their tax rates on mining activity, and others are currently discussing it. From a government perspective, increasing tax rates might be especially interesting in a context of resource depletion, when the return on exploration might be declining and a large number of mines are already being exploited, while it might deter the opening of new mines.

Further research is needed to have a better understanding of the enforcement of these reforms. Many resource-rich countries are opening their administrative data to researchers. Taking advantage of this new data availability is key to understanding whether these reforms implied any avoidance effects.

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A Additionnal Descriptive Evidence

Table A.1: Coverage of Listed Firms by S&P

	Worldwide Mining Activity			Share Covered		
	Profits ($bn)	**Sales** ($bn)	**Employees** (K)	**Profits** (%)	**Sales** (%)	**Employees** (%)
1999	11.2	87.6	750.1	107.2	70.4	87.9
2000	16.5	107.3	798.9	103.8	80.2	90.5
2001	16.8	117.8	681.3	105.2	84.1	89.3
2002	15.6	120.7	521.9	105.7	85.4	86.2
2003	25.4	140.8	580.5	92.2	85.5	84
2004	44.6	198.6	584.8	92.3	86.7	85
2005	75.3	274.4	723.4	96.5	89.6	88
2006	128.8	349.1	1,054.2	94.8	90.3	90.5
2007	145.9	429	1,128.5	94.7	89.9	89.7
2008	103.3	542.8	1,355.8	102.7	91.5	89.2
2009	86.5	453.1	1,406.3	100.8	91.5	90.9
2010	203	606	1,383	95.9	91.5	90
2011	235.6	745	1,448.7	95.5	91.8	90.3
2012	113.2	747.3	1,497.2	97.5	92	90.4
2013	21.8	661.8	1,251.3	134.3	91.7	89.8
2014	51.6	613.2	1,246.1	113.3	92.5	90.8
2015	-63	478.1	1,206.2	79.2	92.2	90
2016	24.6	453.9	1,118.8	102.1	91.7	89.3
2017	108.4	538.1	1,082.7	97.8	92.1	89.8
2018	112.1	570.4	1,118.3	98.2	92.2	89.9
2019	75.1	514.6	1,129.6	97.7	91.2	89.5
2020	111	558.4	1,164.1	96.3	91.8	87.5
2021	246.7	746.3	1,023.8	94.9	91.7	86.4
2022	179.1	728.2	1,072.3	95.7	91	85.1
2023	121.1	699	1,006.4	98	91.2	85.4
1999-2023	**88.4**	**459.3**	**1,053.4**	**98.1**	**91**	**89**

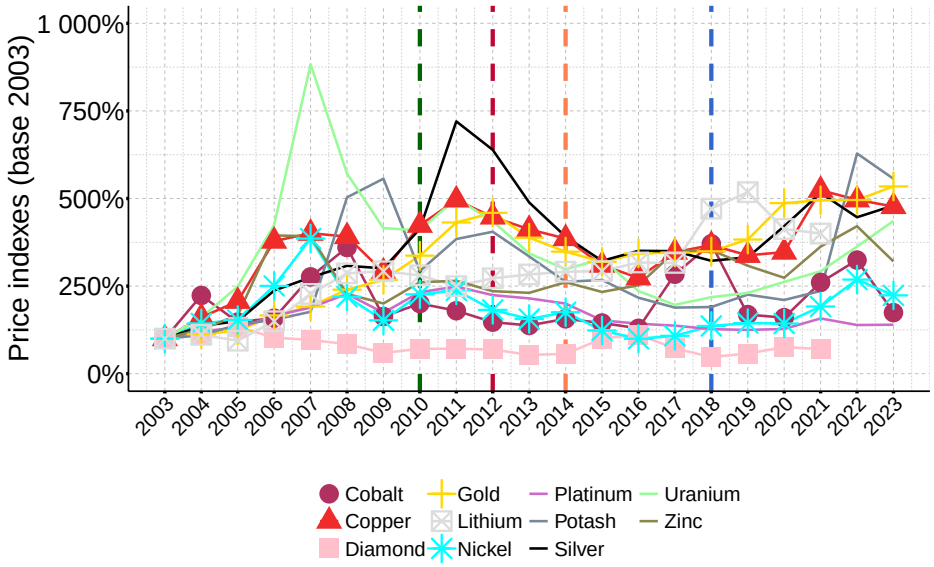
Notes: This table shows figures on worldwide activity of mining firm from Compustat and the share that our sample drawn from S&P covers. Mining firms in Compustat are defined as firms which NAICS4 codes is 2122, *Metal Ore Mining*. The last line shows the average annual figures for columns 2 to 4 and the weighted average figures for the last three columns

Table A.2: Coverage of Minerals Production by S&P

Mineral	**Unit**	**Prod.** thousand	**Share** (%)
Iron Ore	Ton	1,447,943	64.8
Silver	Ounce	535,028	68.9
Bauxite	Ton	160,263	77.8
Diamonds	Carat	81,172	62.5
Gold	Ounce	73,438	78.0
Phosphate	Ton	42,226	53.5
Manganese	Ton	20,718	59.9
Copper	Ton	15,211	93.9
Zinc	Ton	7,889	39.2
Platinum	Ounce	6,114	71.6
Palladium	Ounce	6,055	77.7
Lead	Ton	2,190	57.5
Nickel	Ton	1,329	42.0
Titanium	Ton	1,223	30.3
Tin	Ton	237	51.2
Molybdenum	Ton	171	81.0
Lithium	Ton	157	27.2
Antimony	Ton	74	35.6
Cobalt	Ton	54	58.7
Graphite	Ton	22	88.7

Notes: This table shows figures on annual average worldwide minerals production as reported by the United States Geological Survey (column 1), and the share that S&P data covers (column 2). It covers the years 1999 to 2023.

Figure A.1: Evolution of Minerals Prices and Timing of the Reforms



Source: IMF & USGS.

Note: This graph shows the evolution of mining prices since 2003 and the year of implementation of the four reforms under study. The green bar indicates the 2010 reform in South Africa, dark red the 2012 reform in Ghana, orange the 2014 reform in Mexico, and blue the 2018 reform in DRC.

Table A.3: Coverage of Minerals Production by S&P

		Dem. Rep. Congo		Ghana		Mexico		South Africa	
	Unit	**Prod** thousand	**Share** (%)	**Prod** thousand	**Share** (%)	**Prod** thousand	**Share** (%)	**Prod** thousand	**Share** (%)
Antimony	Pound					35.6	93.3		
Antimony	Ton							2.1	107.1
Bauxite	Ton			535.2	107.9				
Cobalt	Ton	22.6	55.6					0.4	50.8
Copper	Ton	293.0	82.1			318.0	90.3	70.6	69.0
Diamonds	Carat	1,807.7	15.3					8,721.5	28.4
Gold	Ounce	169.7	53.1	2,190.4	80.8	1,616.7	83.5	6,402.6	89.3
Iron Ore	Ton					7,689.0	58.0	40,919.2	96.2
Lead	Ton					127.6	88.5	36.9	79.4
Manganese	Ton			999.0	99.4	302.5		4,664.7	74.2
Molybdenum	Ton					6.7	93.6		
Nickel	Ton							30.6	38.1
Palladium	Ounce							1,842.8	85.9
Phosphate	Ton							703.1	102.0
Platinum	Ounce							3,741.9	70.1
Silver	Ounce	471.2	76.5	3.3	34.7	90,442.3	78.0	456.5	34.6
Tin	Ton	0.2	51.7						
Titanium	Ton							107.2	39.3
Zinc	Ton	6.0	86.0			385.0	56.7	30.3	11.2

Notes: This table shows figures on annual average worldwide minerals production as reported by the United States Geological Survey in metric tons in each country of interest, and the share that S&P data covers. It covers the years 1999 to 2023.

Table A.4: Summary Statistics - Exploration by Country

Commodity	**RDC**		**Ghana**		**Mexico**		**South Africa**	
	Amount ($M)	**Share** (%)	**Amount** ($M)	**Share** (%)	**Amount** ($M)	**Share** (%)	**Amount** ($M)	**Share** (%)
Gold	4.39	14.57	23.92	97.66	100.30	57.20	12.30	6.80
Diamonds	0.05	0.15	0.05	0.22	0.00	0.00	15.70	8.67
U3O8	0.00	0.00	0.02	0.07	0.00	0.00	2.22	1.23
Silver	0.00	0.00	0.00	0.00	38.44	21.92	0.03	0.02
Copper	22.21	73.72	0.00	0.00	21.57	12.30	2.95	1.63
Zinc-Lead	0.38	1.27	0.00	0.00	10.11	5.76	1.73	0.95
Lithium	0.77	2.56	0.00	0.00	0.39	0.22	0.43	0.24
Molybdenum	0.00	0.00	0.00	0.00	0.38	0.22	0.05	0.03
Nickel	0.06	0.21	0.00	0.00	0.23	0.13	2.55	1.41
Platinum	0.00	0.00	0.00	0.00	0.12	0.07	136.76	75.56
Cobalt	1.32	4.38	0.00	0.00	0.02	0.01	0.02	0.01
Potash	0.59	1.96	0.00	0.00	0.00	0.00	0.20	0.11
Lanthanides	0.03	0.09	0.00	0.00	0.00	0.00	0.67	0.37
Other	0.33	1.09	0.50	2.04	3.81	2.17	5.40	2.98
All	**30.13**	**100.00**	**24.49**	**100.00**	**175.36**	**100.00**	**136.18**	**100.00**

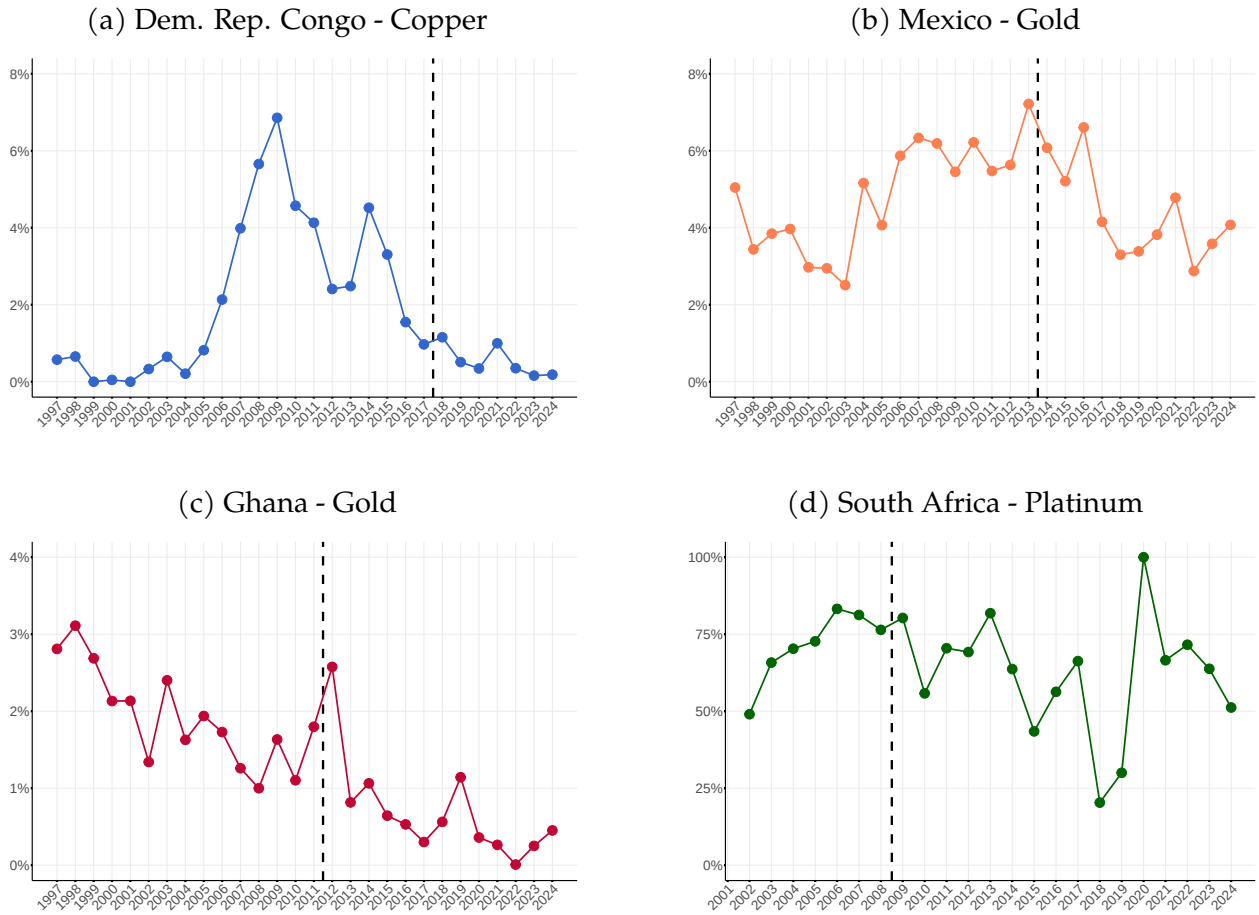
Notes: This table shows, for each type of commodity, the annual total expenses in grassroots exploration made by firms, in $ million and as a share of total exploration expenses made in the country. The period for each country is 11 years around the year of the reform: 2005-2015 for South Africa, 2007-2017 for Ghana, 2009-2019 for Mexico and 2013-2023 for DRC.

Table A.5: Minerals Production and Mines by Country

Commodity	Unit	Dem. Rep. Congo		Ghana		Mexico		South Africa	
		Nb Mines	Prod. thousand	Nb Mines	Prod. thousand	Nb Mines	Prod. thousand	Nb Mines	Prod. thousand
Bauxite	Ton	0	0.0	1	400.1	0	0.0	0	0.0
Cobalt	Ton	7	54.4	0	0.0	0	0.0	1	0.2
Copper	Ton	40	812.5	0	0.0	34	440.8	26	98.8
Diamonds	Carat	0	0.0	0	0.0	0	0.0	25	6,526.3
Gold	Ounce	3	775.2	11	2,977.8	64	3,340.2	64	6,317.2
Lead	Ton	0	0.0	0	0.0	28	220.9	1	49.1
Molybdenum	Ton	0	0.0	0	0.0	3	12.1	0	0.0
Nickel	Ton	0	0.0	0	0.0	0	0.0	17	31.0
Palladium	Ounce	0	0.0	0	0.0	0	0.0	32	2,523.1
Phosphate	Ton	0	0.0	0	0.0	0	0.0	1	2,390.0
Platinum	Ounce	0	0.0	0	0.0	0	0.0	32	4,775.2
Silver	Ounce	0	0.0	0	0.0	66	152,573.2	0	0.0
U3O8	Pound	0	0.0	0	0.0	0	0.0	5	2,750.0
Zinc	Ton	0	0.0	0	0.0	30	570.4	1	28.2

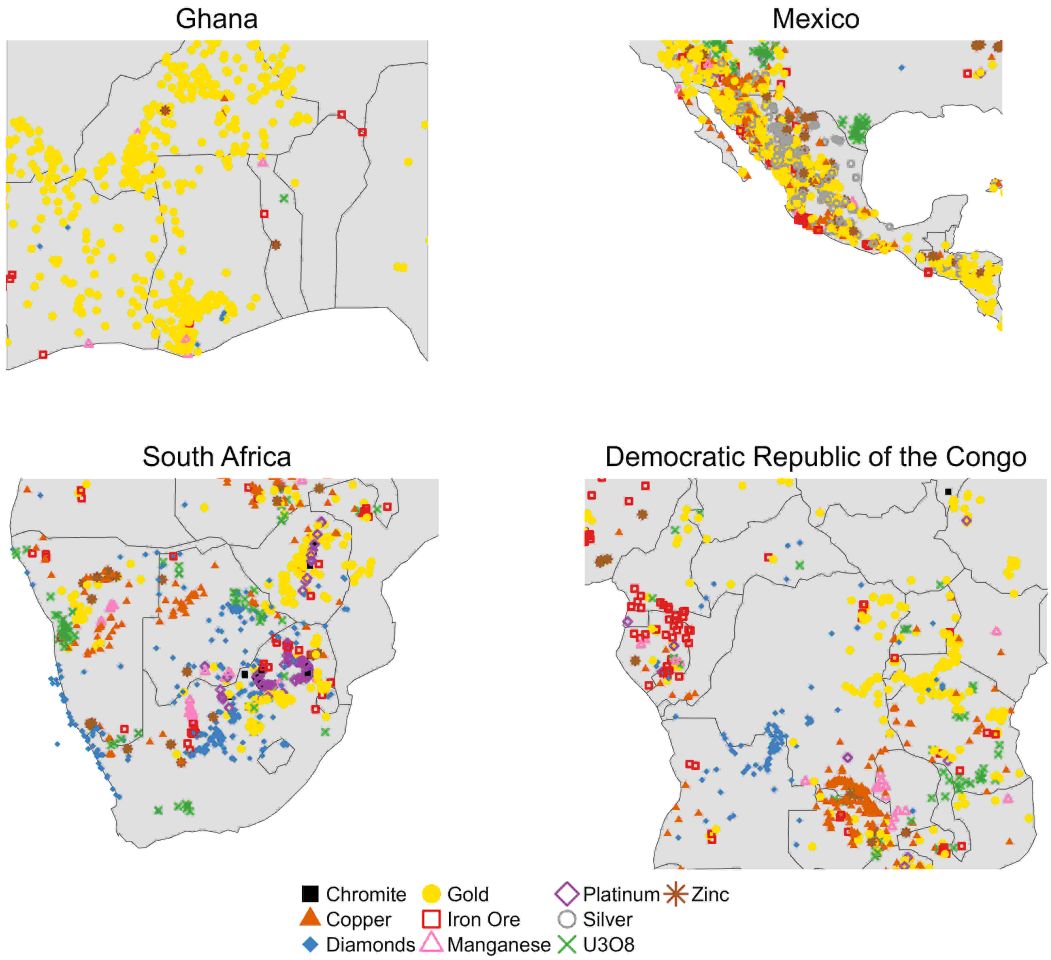
Notes: This table shows figures on the number of mines and the value of total production by country for the year preceding the reform. The unit value of production is indicated on the second column. It covers the year preceding the implementation of the reform: 2009 for South Africa, 2011 for Ghana, 2013 for Mexico and 2017 for DRC.

Figure A.2: Share in world exploration expenses



Notes: These figures show the share of global exploration expenses made in DRC, Mexico, Ghana and South Africa. It only includes explorations targeted at the main commodity of the country in terms of country production value.

Figure A.3: Map of mining activity

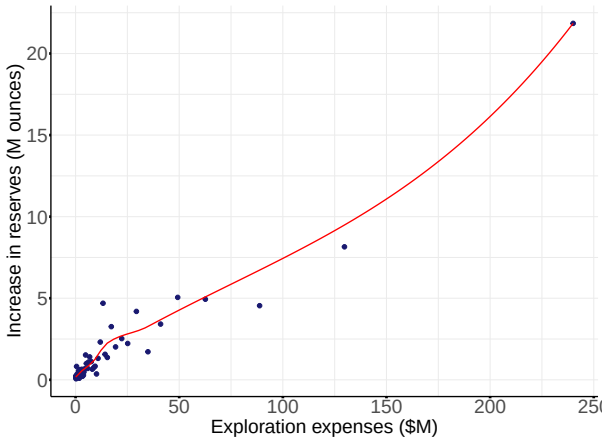


Source: S&P Metals and Mining dataset.

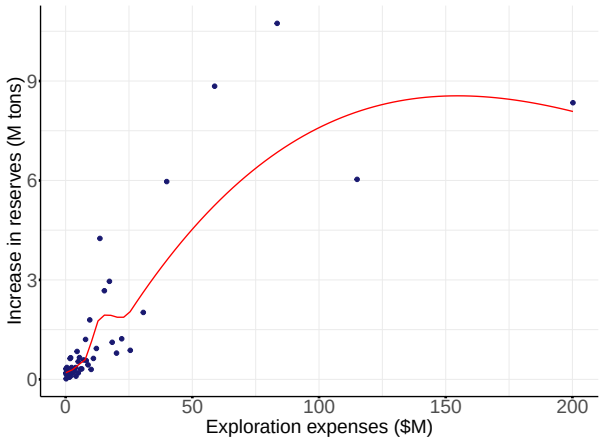
Note: This map shows the location of mines in the four countries under study and neighboring countries. The commodity is the primary commodity produced by each mine.

Figure A.4: Link between exploration expenditures and new reserves

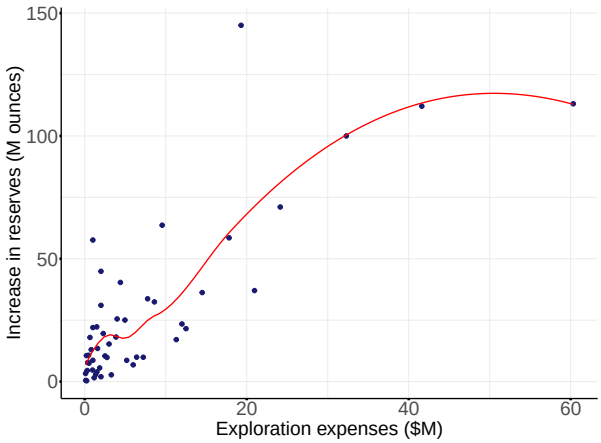
(a) Gold



(b) Copper



(c) Silver



B Additionnal Results

B.1 Price Effects of an Increase in Taxes

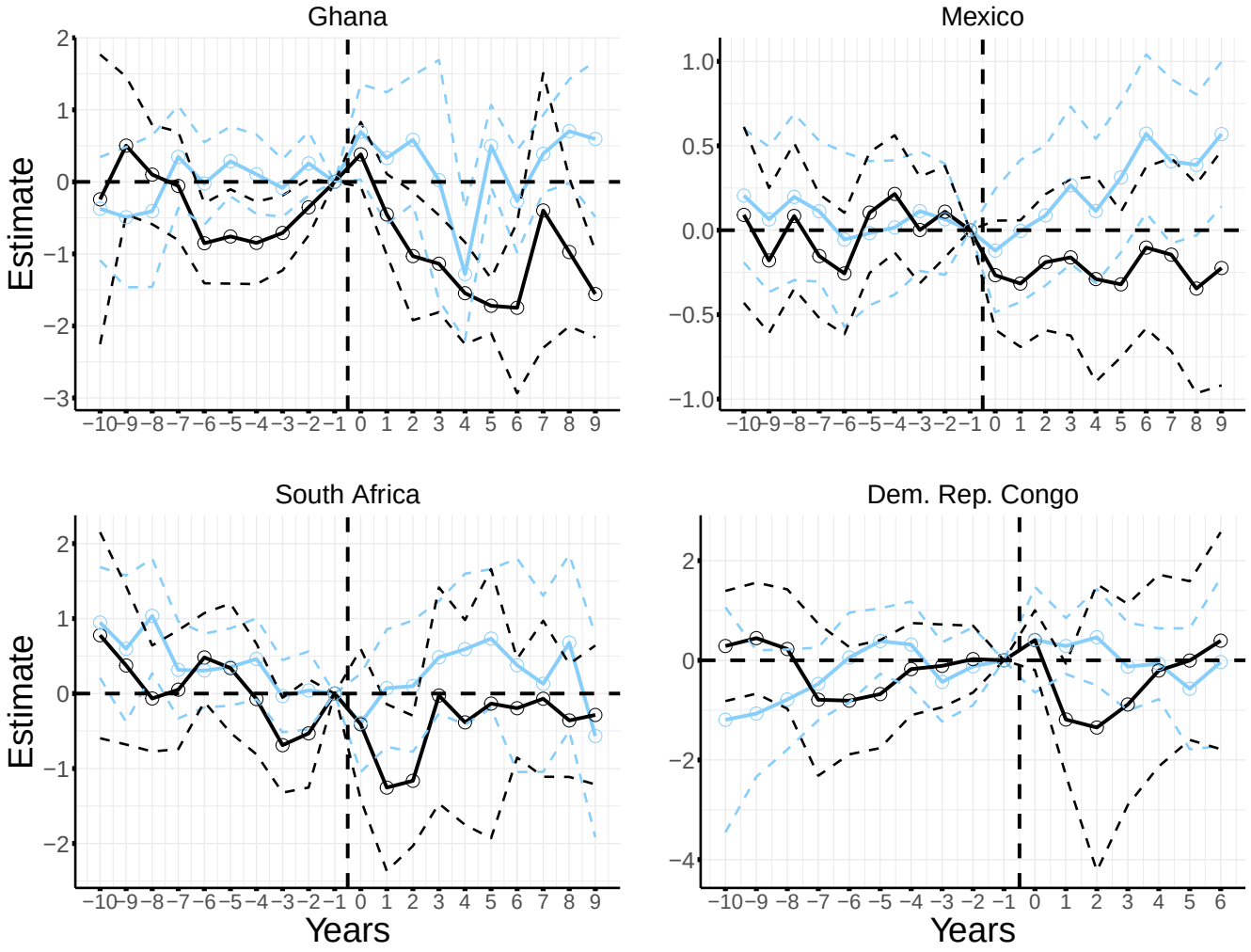
If a country concentrates a large share of the production of a given commodity, a tax increase might influence prices. To model this, I define global inverse demand as $p_t(Q_t)$, where $Q_t = q_t + Q_{row}$. The domestic country holds a market share $s = q_t/Q_t$. The government then internalizes the effects that domestic production might have on global prices and the effective marginal revenue becomes $p_t(1 - \frac{s}{\epsilon})$, where ϵ is the price elasticity of demand.

The revised first order condition for production is:

$$(1-\tau)p_t\left(1-\frac{s}{\epsilon}\right) = MC(q_t, R_t) + \lambda_t + \phi_t \tag{21}$$

In the short run, since $q_t = K$ and $\frac{dq_t}{d\tau} = 0$, aggregate supply remains unchanged. The global price p_t does not react to the tax, regardless of the level of the market share s. The tax is fully absorbed by the scarcity rent ϕ_t. In the long run, if exploration falls ($\frac{dw_t}{d\tau} < 0$), domestic supply decreases. If s is large, this contraction significantly raises the global price ($dp_t/d\tau > 0$), shifting a portion of the tax burden to consumers.

Figure B.1: Between Firms - Local versus Foreign Expenses



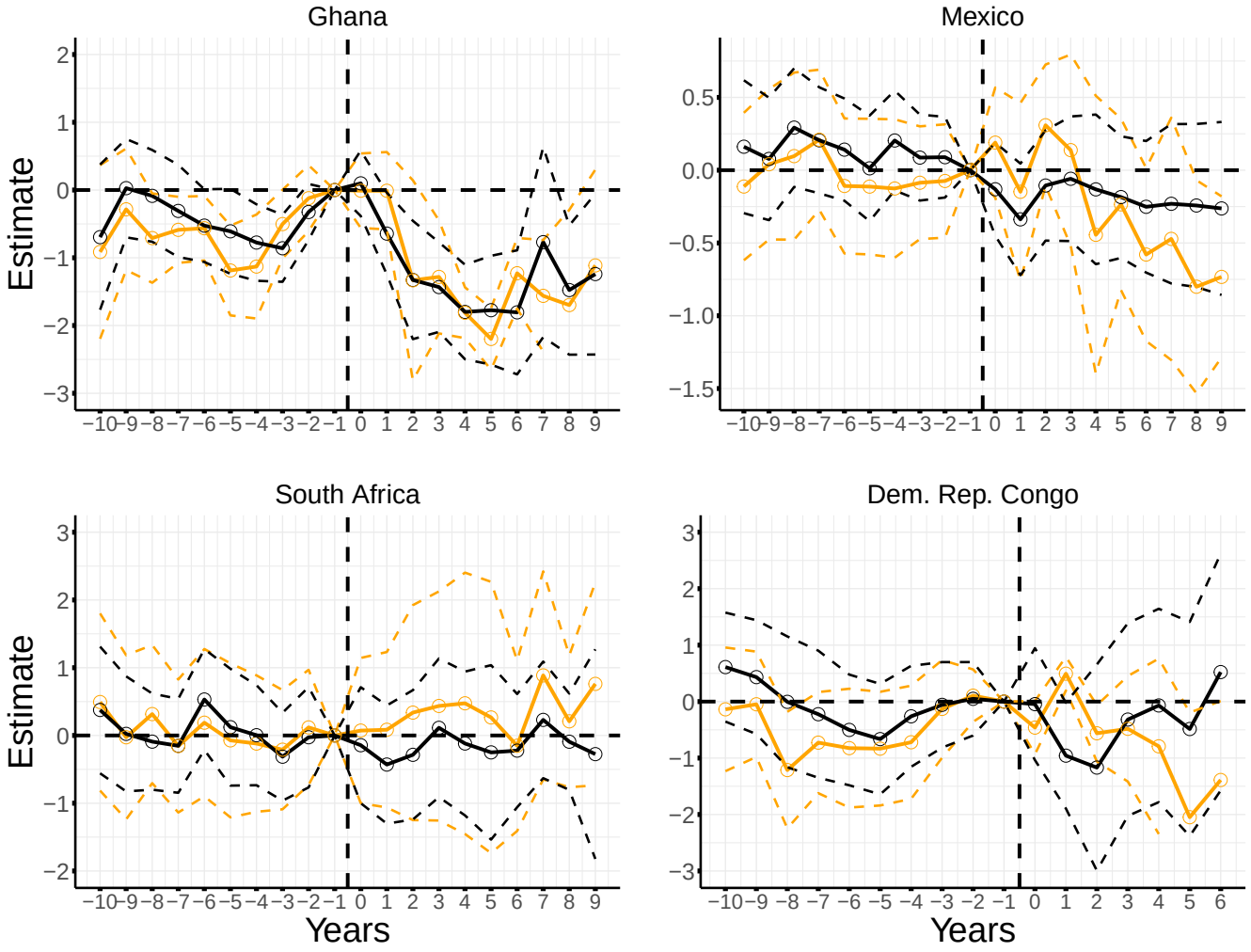
Notes: This figure shows estimates of the impact of the reforms on exploration expenses from our between-firm estimation for each country. Time 0 indicates the year of implementation of the reform. Dashed lines represent 95% confidence interval. Standard errors are clustered at the firm level.

Table B.1: Exploration Expenses - Event Study Results

	Between Firms			Within Firms	
	Total Expenses (log)	Local Expenses (log)	Foreign Expenses (log)	Expenses (log)	
	(1)	(2)	(3)	(4)	(5)
Time = -10	0.009	0.149	0.144	0.291	0.079
	(0.165)	(0.222)	(0.183)	(0.182)	(0.239)
Time = -9	-0.120	-0.004	0.035	0.224	0.138
	(0.161)	(0.194)	(0.186)	(0.166)	(0.207)
Time = -8	0.096	0.069	0.187	0.248	0.010
	(0.163)	(0.179)	(0.202)	(0.151)	(0.227)
Time = -7	-0.035	-0.193	0.115	0.129	0.033
	(0.140)	(0.161)	(0.162)	(0.142)	(0.186)
Time = -6	-0.130	-0.271*	0.014	0.072	-0.083
	(0.145)	(0.150)	(0.186)	(0.135)	(0.186)
Time = -5	0.008	-0.060	0.095	-0.081	-0.260
	(0.123)	(0.153)	(0.153)	(0.142)	(0.198)
Time = -4	0.112	0.038	0.125	0.074	-0.231
	(0.121)	(0.142)	(0.150)	(0.130)	(0.182)
Time = -3	-0.080	-0.154	0.015	-0.062	-0.114
	(0.105)	(0.130)	(0.130)	(0.117)	(0.151)
Time = -2	0.026	-0.059	0.057	-0.033	-0.035
	(0.099)	(0.111)	(0.124)	(0.108)	(0.149)
Time = 0	-0.126	-0.138	-0.131	-0.079	0.119
	(0.112)	(0.142)	(0.152)	(0.131)	(0.154)
Time = 1	-0.322**	-0.498***	0.062	-0.427***	-0.069
	(0.129)	(0.154)	(0.167)	(0.143)	(0.206)
Time = 2	-0.212	-0.520***	0.138	-0.354**	0.125
	(0.151)	(0.185)	(0.175)	(0.175)	(0.244)
Time = 3	-0.119	-0.333	0.231	-0.230	-0.030
	(0.153)	(0.208)	(0.188)	(0.184)	(0.282)
Time = 4	-0.154	-0.444*	0.143	-0.232	-0.352
	(0.160)	(0.250)	(0.184)	(0.220)	(0.418)
Time = 5	0.014	-0.386*	0.339*	-0.406**	-0.476
	(0.156)	(0.208)	(0.190)	(0.187)	(0.290)
Time = 6	0.133	-0.292	0.469**	-0.428**	-0.661***
	(0.173)	(0.226)	(0.209)	(0.194)	(0.225)
Time = 7	0.115	-0.237	0.380*	-0.279	-0.487
	(0.170)	(0.260)	(0.208)	(0.228)	(0.324)
Time = 8	0.047	-0.471*	0.458**	-0.335	-0.773***
	(0.159)	(0.251)	(0.187)	(0.222)	(0.293)
Time = 9	0.127	-0.393	0.428*	-0.371	-0.600**
	(0.181)	(0.303)	(0.225)	(0.262)	(0.268)
Observations	26,402	25,415	25,629	13,334	13,334
R^2	0.57687	0.57126	0.57666	0.63639	0.83036
Within R^2	0.00125	0.00170	0.00132	0.00489	0.00507
Firm fixed effects	✓	✓	✓		
Year fixed effects	✓	✓	✓	✓	
Firm-Country fixed effects				✓	✓
Firm-Year fixed effects					✓

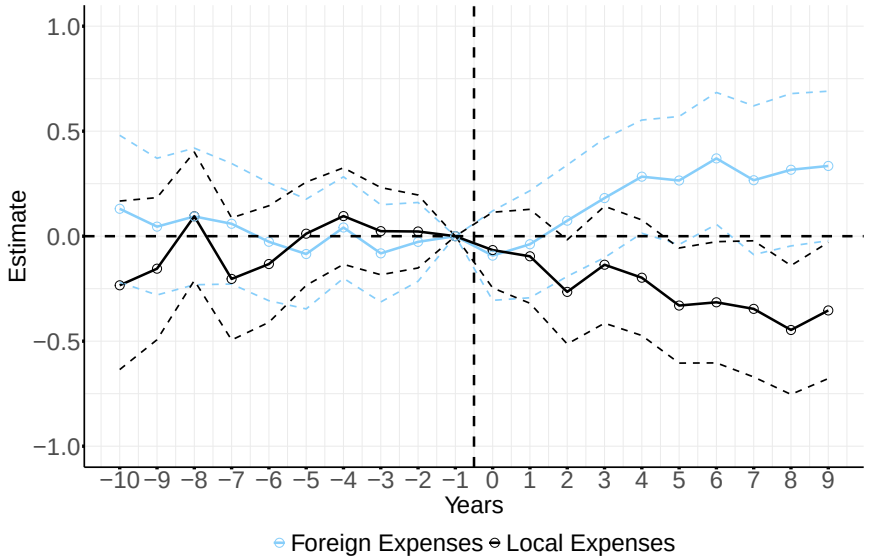
Notes: This table summarizes our estimates of the effects of the reforms on exploration expenses. The outcome variable is the log of annual exploration expenses made by each firm overall in column (1), only in treated countries for treated firms in column (2), only in non-treated countries for treated firms in column (3) and exploration at the firm-country level in column (4). Column (1) to (3) displays the results for the between firm strategy, while column (4) shows the results for the within-firm strategy. Standard Errors are clustered at the firm level.

Figure B.2: Within Firms



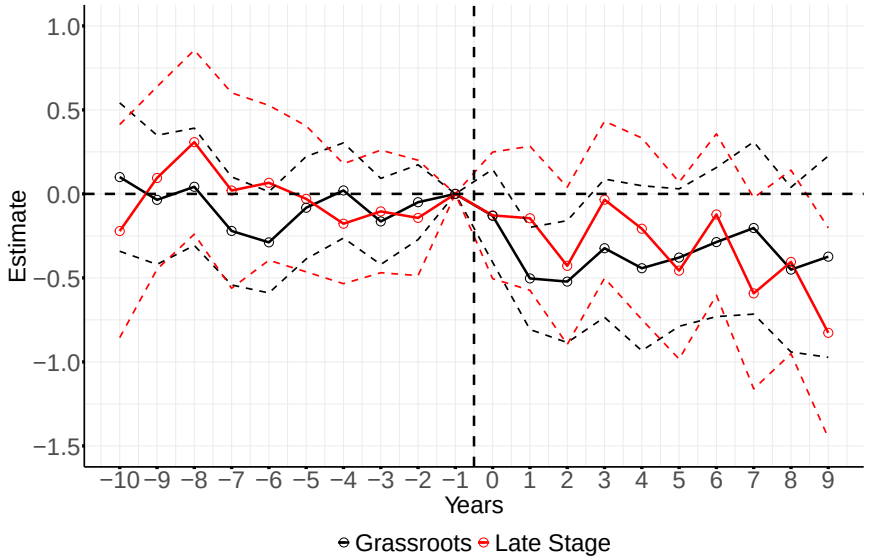
Notes: This figure shows estimates of the impact of the reforms on exploration expenses from our within-firm estimation for each country. Time 0 indicates the year of implementation of the reform. Dashed lines represent 95% confidence interval. Standard errors are clustered at the firm level.

Figure B.3: Substitution Effect: Local vs. Foreign Expenditures, Including Late Stage Exploration



Note: This figure plots the event-study coefficients for the impact of tax reforms on exploration expenses, including late-stage expenses
. The estimation uses the between-firm strategy. "Local Expenses" refers to exploration expenditures incurred in the treating jurisdiction. "Foreign Expenses" refers to expenditures incurred by the same firms in non-treating jurisdictions. Time 0 indicates the reform implementation year. Dashed lines represent 95% confidence intervals, clustered at the firm level.

Figure B.4: Heterogeneity: Late Stage Exploration



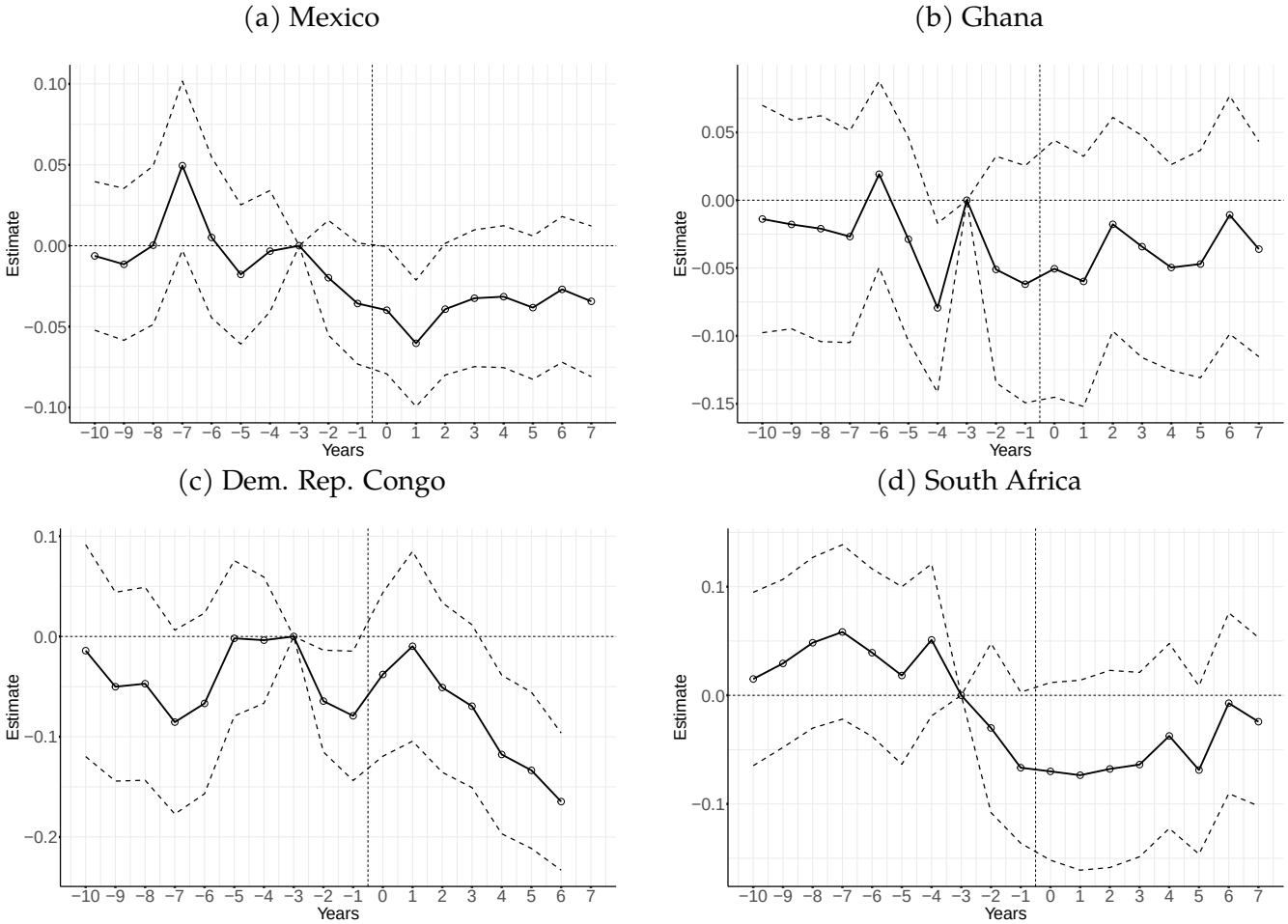
Notes: This figure shows estimates for "Late Stage" exploration expenses only. Time 0 indicates the year of implementation. Dashed lines represent 95% confidence intervals. Standard errors are clustered at the firm level.

Table B.2: Extensive Margin - Pre-Post

	Explore=1 (1)	Number of firms (log) (2)
Treated X Post = 1	-0.053***	-0.389***
	(0.008)	(0.078)
Standard-Errors	Firm	Country
Observations	263,004	1,863
R^2	0.20017	0.87543
Within R^2	0.00058	0.00551
Firm-Country fixed effects	✓	
Year fixed effects	✓	✓
Country fixed effects		✓

Notes: This table summarizes our results on the effects of the reforms on the extensive margin. The outcome variable for column (1) is a dummy equal to one when a given firm makes any exploration expenditures in the country, while in column (2), the outcome variable is the log of the number of firms in the country. Time 0 indicates the year of implementation of the reform. Standard errors are clustered at the firm level for column (1), and at the country level for column (2).

Figure B.5: Probability to Explore



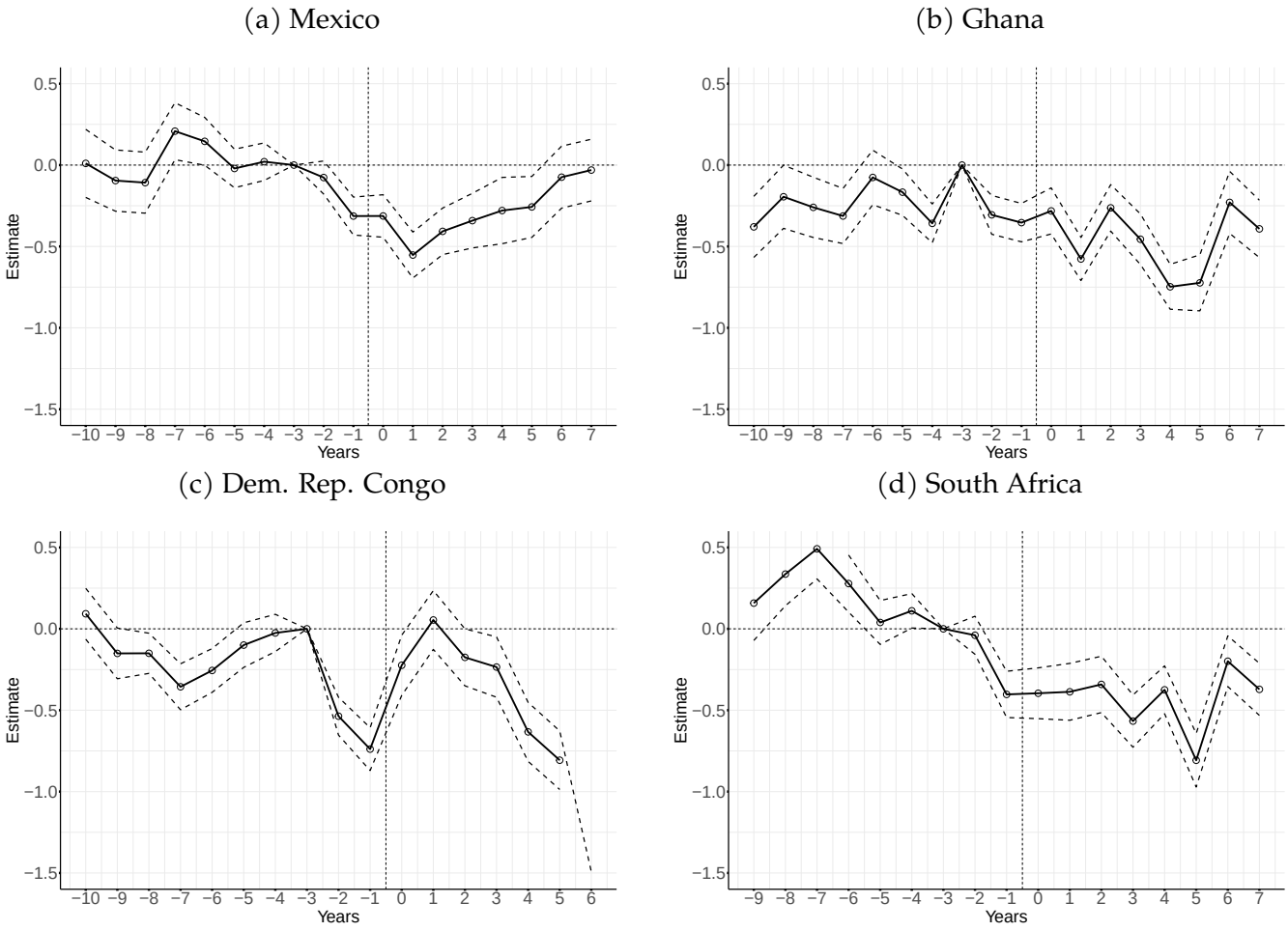
Notes: These figures show estimates of the impact of the reforms on the probability to explore in treated countries from our OLS estimation. Time 0 indicates the year of implementation of the reform. Dashed lines represent 95% confidence interval. Standard errors are clustered at the firm level.

Table B.3: Extensive Margin - Event Study

	Explore=1 (1)	Number of firms (log) (2)
Treated X Time = -10	-0.004	-0.058
	(0.018)	(0.139)
Treated X Time = -9	-0.010	-0.078
	(0.017)	(0.081)
Treated X Time = -8	0.0003	-0.048
	(0.018)	(0.116)
Treated X Time = -7	0.024	0.010
	(0.019)	(0.179)
Treated X Time = -6	0.004	0.025
	(0.018)	(0.106)
Treated X Time = -5	-0.010	-0.059
	(0.016)	(0.045)
Treated X Time = -4	-0.003	-0.061
	(0.014)	(0.093)
Treated X Time = -2	-0.031**	-0.239**
	(0.014)	(0.103)
Treated X Time = -1	-0.050***	-0.452***
	(0.014)	(0.087)
Treated X Time = 0	-0.047***	-0.306***
	(0.016)	(0.046)
Treated X Time = 1	-0.057***	-0.372***
	(0.016)	(0.129)
Treated X Time = 2	-0.044***	-0.307***
	(0.016)	(0.056)
Treated X Time = 3	-0.045***	-0.413***
	(0.016)	(0.073)
Treated X Time = 4	-0.048***	-0.525***
	(0.016)	(0.109)
Treated X Time = 5	-0.060***	-0.666***
	(0.016)	(0.129)
Treated X Time = 6	-0.043***	-0.568*
	(0.016)	(0.339)
Treated X Time = 7	-0.041**	-0.328***
	(0.018)	(0.116)
Standard-Errors	Firm	Country
Observations	253,847	1,606
R^2	0.20465	0.88821
Within R^2	0.00036	0.00859
Firm-Country fixed effects	✓	
Year fixed effects	✓	✓
Country fixed effects		✓

Notes: This table summarizes our results on the effects of the reforms on the extensive margin. The outcome variable for column (1) is a dummy equal to one when a given firm makes any exploration expenditures in the country, while in column (2), the outcome variable is the log of the number of firms in the country. Time 0 indicates the year of implementation of the reform. Standard errors are clustered at the firm level for column (1), and at the country level for column (2).

Figure B.6: Number of Firms



Notes: These figures show estimates of the impact of the reforms on the number of firms exploring in implementing countries. Time 0 indicates the year of implementation of the reform. Dashed lines represent 95% confidence interval. Standard errors are clustered at the firm level.

Table B.4: Production - Pre-Post

	Specialized Commodities	Common Commodities	All Commodities
		Production(log)	
	(1)	(2)	(3)
Post = 1 × Treated = 1	-0.074	-0.143*	-0.074
	(0.069)	(0.074)	(0.069)
Price (log)	-0.003	-0.005	-0.003
	(0.029)	(0.034)	(0.029)
Observations	55,582	44,803	55,582
R^2	0.91894	0.90298	0.91894
Within R^2	0.00023	0.00076	0.00023
Mine-Commodity fixed effects	✓	✓	✓
Year fixed effects	✓	✓	✓

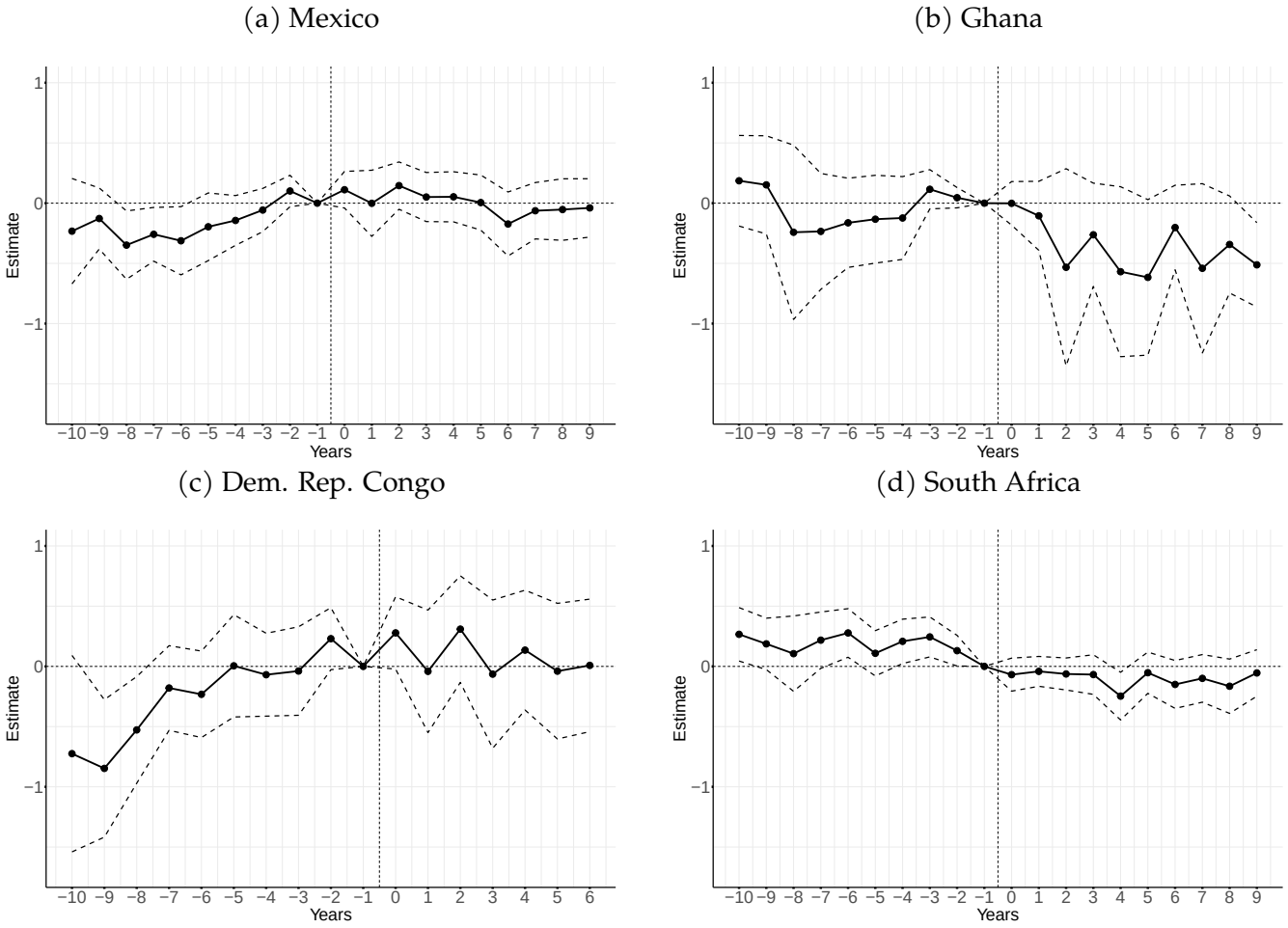
Notes: This table summarizes our estimates of the effects of the reforms on production. The outcome variable is the log of production volumes in metric ton for each mine. Column (1) shows the result restricting to minerals that are highly concentrated in our countries of interest, column (2) shows the results for other minerals produced more elsewhere, and column (3) shows the results for all minerals. Years covered are -10 to 9. Standard Errors are clustered at the mine level.

Table B.5: Production - Event Study Results

	Specialized Commodities	Common Commodities	All Commodities
		Production(log)	
	(1)	(2)	(3)
Treated Time = -10	-0.537**	0.099	0.036
	(0.262)	(0.108)	(0.104)
Treated Time = -9	-0.556**	0.069	0.002
	(0.228)	(0.080)	(0.079)
Treated Time = -8	-0.399	-0.069	-0.113
	(0.279)	(0.093)	(0.101)
Treated Time = -7	-0.187	0.020	0.0006
	(0.205)	(0.077)	(0.078)
Treated Time = -6	-0.164	0.014	-0.003
	(0.199)	(0.086)	(0.082)
Treated Time = -5	-0.453**	0.006	-0.032
	(0.211)	(0.082)	(0.079)
Treated Time = -4	-0.120	0.024	0.025
	(0.192)	(0.068)	(0.067)
Treated Time = -3	-0.040	0.074	0.085
	(0.157)	(0.061)	(0.059)
Treated Time = -2	0.006	0.117***	0.120***
	(0.136)	(0.044)	(0.043)
Treated Time = 0	-0.055	0.019	0.022
	(0.143)	(0.050)	(0.048)
Treated Time = 1	-0.124	-0.037	-0.038
	(0.147)	(0.073)	(0.067)
Treated Time = 2	-0.037	0.017	0.011
	(0.147)	(0.061)	(0.058)
Treated Time = 3	-0.212	-0.024	-0.038
	(0.171)	(0.065)	(0.063)
Treated Time = 4	-0.257	-0.096	-0.113
	(0.185)	(0.071)	(0.070)
Treated Time = 5	-0.167	-0.050	-0.058
	(0.177)	(0.073)	(0.070)
Treated Time = 6	-0.207	-0.157*	-0.154**
	(0.186)	(0.083)	(0.078)
Treated Time = 7	-0.154	-0.112	-0.105
	(0.203)	(0.080)	(0.076)
Treated Time = 8	-0.262	-0.107	-0.106
	(0.222)	(0.088)	(0.085)
Treated Time = 9	-0.104	-0.053	-0.045
	(0.211)	(0.085)	(0.080)
Price (log)	-0.016	-0.011	-0.014
	(0.058)	(0.026)	(0.024)
Observations	2,870	86,129	88,999
R^2	0.95103	0.93206	0.93420
Within R^2	0.01630	0.00065	0.00073
Mine-Commodity fixed effects	✓	✓	✓
Year fixed effects	✓	✓	✓

Notes: This table summarizes our estimates of the effects of the reforms on production. The outcome variable is the log of production volumes in metric ton for each mine. Column (1) shows the result restricting to minerals that are highly concentrated in our countries of interest, column (2) shows the results for other minerals produced more elsewhere, and column (3) shows the results for all minerals. Years covered are -10 to 9. Standard Errors are clustered at the mine level.

Figure B.7: Mine Production Volumes



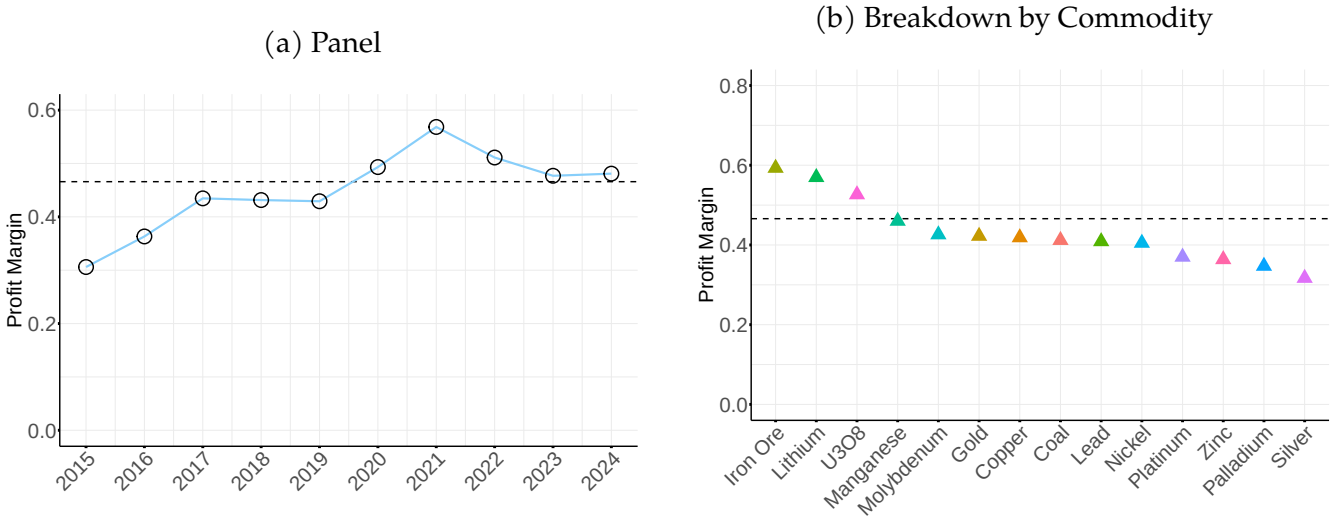
Notes: These figures show estimates of the impact of the reforms on production volumes at the mine level, controlling for the level of prices. Time 0 indicates the year of implementation of the reform. Dashed lines represent 95% confidence interval. Standard errors are clustered at the mine level.

Table B.6: Effects of Exploration Expenses on New Reserves

	Reserves Addition (log)	
	(1)	(2)
Exploration (log)	0.571***	0.576**
	(0.205)	(0.262)
Minerals Price (log)	0.821	
	(0.540)	
Observations	355	355
R^2	0.78259	0.82560
Within R^2	0.07275	0.03464
Commodity-Country fixed effects	✓	✓
Year fixed effects	✓	
Year-Commodity fixed effects		✓

Notes: This table summarizes my estimates of the effects of an increase in exploration expenditures on new reserves. The outcome variable is the log of the amount of reserves found in a given year. Standard errors are clustered at the country level.

Figure B.8: Profit Margins in the Mining Sector



Notes: This graph shows the weighted ratio between pretax profits and gross revenues. It is the sum of all pretax profits over the sum of all gross revenues, broken down by year in Figure B.8a and by commodity in Figure B.8b.