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Abstract

What are the effects of supply-side climate policies? We use global firm-level data to estimate the impact of 130 oil-tax reforms between 2000 and 2019 on oil production, exploration and discoveries. Higher taxes are found to reduce firms' exploration expenditures and oil discoveries. We quantify the oil market implications and show that the existing production-based taxes, averaging at 21%, reduce the long-term emissions by 1.3-2.7 $GtCO_2$ annually. Increasing the global tax rate would reduce emissions almost linearly, by 0.16 $GtCO_2$ per percentage point, while further shifting the distribution of rents from consumers to producers and governments.

Keywords: oil taxation, climate change, supply-side climate policies

JEL codes: E22; H23; L71

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1 Introduction

"*A carbon tax on fossil fuel consumption*" is economists' traditional response to climate change. Amid insufficient implementation, however, theoretical research has started to make the case for limiting fossil fuel *production* (Harstad, 2012; Asheim *et al.*, 2019). Policy initiatives in the United States and around the world show that this idea is gaining traction also among policy makers.[1] The purpose of this paper is to empirically estimate the impacts of supply-side climate policies. In particular, we seek to answer three questions. First, how do oil firms respond to supply-side taxes? Second, what is the effect of this supply side policy on global CO_2-emissions, given our estimates of individual firm responses? Third, how are the costs and benefits of this policy distributed across consumers, producers and governments?

We address these questions using a comprehensive global data set, where we observe oil production, production costs, exploration and discoveries at the firm- and asset-level over the period 2000-2019.[2] Our starting point is the observation that policies limiting oil production are already widely in place, as more than sixty countries tax their oil activities by production-based taxes (or royalties). By using data on historical petroleum tax reforms across essentially all oil producing countries, we can study the effects of supply-side taxes on production, exploration and discoveries. We employ a difference-in-differences research design, leveraging that we observe the same companies operating in multiple countries and hence receiving different tax treatments. To quantify the effects on a market-level, we combine our estimated supply elasticities with field-level data on extraction costs and a range of demand elasticities from the literature. Specifically, we consider the impact of taxes on CO_2-emissions, tax revenue, producer surplus and consumer surplus.

Our main finding is that companies respond to taxes by reducing oil exploration. A one-percentage point increase in the royalty rate decreases exploration by 3.0% and the amount of oil discovered by 4.4%. These effects are found only for production-based taxes. The effects of profit-based taxes are small and only weakly statistically significant, in line with the optimal tax theory that suggests such taxes to be neutral (e.g., Garnaut and Ross 1979; Daniel *et al.* 2010). We do not find any effects of either type of taxes on short-term production, consistent with the insight from Anderson *et al.* (2018) that oil producing firms flexibly choose when to drill, but that

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[1] For instance, Senate Finance Committee Democrats have floated the idea of a tax on the carbon content of coal, oil and gas (The Hill, 2021). In 2021, Greenland, Spain, Denmark and Ireland joined the earlier decisions of Costa Rica, France, Belize and New Zealand in unilaterally limiting oil exploration. In April 2021, the Biden administration initiated the net-zero producers forum (NZPF) consisting of energy ministries of Canada, Norway, Qatar, Saudi Arabia, and the United States (U.S. Department of Energy, 2021). In the future, the NZPF could follow up of the idea of an "inverse OPEC" put forward by Kamala Harris' campaign team in 2020, a supply-side climate coalition to help mitigate climate change (Climate change news, September 2020). Collier and Venables (2014) and Asheim *et al.* (2019) discuss such climate coalitions and supply side policies.

[2] An asset refers to an active license, a field or a discovery and the data covers 99.5% of oil reserves and more than 98.4% of oil production.

production from existing wells is governed by production constraints. When restricting the sample to unconventional deposits, we find similar effects of taxes on exploration and also find an effect on production. Finally, we find no evidence that the extraction cost (the breakeven price at which fields become profitable) of new discoveries are affected by taxes, implying little empirical support for the typical assumption that the reservoirs with the lowest extraction costs are discovered first (e.g. Livernois and Uhler 1987).

Our estimates of firm behaviour imply that the existing fiscal taxes constitute *implicit* CO_2-prices on oil production that already limit the amount of oil discovered through their effects on exploration. This implicit policy corresponds to an average of \$24 per ton of CO_2 (tCO_2) at an oil price of \$50 per barrel.[3] Notably, this figure is an order of magnitude larger than the typical demand-side carbon prices.[4] Our quantification suggests that the current production-based taxes translate into saved long-term emissions of 1.3-2.7 gigatons of CO_2 ($GtCO_2$) per year (4-7% relative to today's annual emissions). Correspondingly, we find that the taxes increase the oil price. The higher oil price has distributional impacts in the long-term oil market, as it moves surplus from *consumers* (-\$620 to -\$770 bn/year) to *producers* (\$250 to \$340 bn/year) and *governments* (\$320 to \$410 bn/year) as compared to a situation where all production-based taxes are removed. These numbers indicate that the current taxes create a *deadweight loss* of \$20 to \$60 bn/year, which corresponds to about \$18-\$20 per ton CO_2 emissions these taxes eliminate.

Our quantification further allows us to analyze a hypothetical supply-side policy: a *climate royalty surcharge* levied on new discoveries. Our results suggest that the effect of a surcharge adopted unilaterally by a price-taking country is 9%-20% of the intended emission reduction due to leakage resulting from increased supply by other countries as the oil price rises. Leakage is avoided if the surcharge is uniform and adopted globally. We find that a global climate royalty surcharge beyond today's tax-level reduces emissions almost linearly, by around 0.16 $GtCO_2$ per percentage-point increase in the rate. Such coordinated action implicitly allows producers to exert market power, increasing the oil price.

Our paper contributes to the literature on supply-side climate policies. This predominantly theoretical literature has emphasized that unilateral supply-side policies lead to a higher oil price and increased production abroad, and more so the more inelastic demand is relative to supply (Bohm, 1993; Hoel, 1994; Harstad, 2012; Harstad and Liski, 2012). The empirical papers in the

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[3] As Prest and Stock (2021) note, given a base oil price, an ad valorem royalty can be recast as an implicit CO_2 tax and vice versa. The average production-weighted royalty in our sample is 21%. Assuming an oil price of \$50/bbl and a CO_2 content of $0.43tCO_2$/bbl (EPA, 2021), we arrive at the CO_2 price as follows: $0.21 \times (\$50/\text{bbl})/(0.43\text{tCO}_2/\text{bbl}) \approx \$24/\text{tCO}_2$. These figures only incorporate emissions from oil combustion and not from the oil production itself (well-to-refinery GHG emissions).

[4] The average demand-side carbon price is currently at \$3.1/tCO_2. This number is a weighted average from the World Bank Carbon Pricing Dashboard, viewed at January 18, 2022 (World Bank, 2022). The existing demand side tax initiatives vary between \$0.1-\$137/tCO_2 and 78.5% of global emissions are not under any CO_2 pricing.

literature have employed numerical modelling to quantify the effects (Fæhn *et al.*, 2017; Erickson and Lazarus, 2018; Leroux and Spiro, 2018; Gerarden *et al.*, 2020; Prest and Stock, 2021; Prest, 2021). To the best of our knowledge, our article is the first to use quasi-experimental variation to empirically identify the impacts of supply-side climate policies.

We provide estimates of the short- and long-run supply elasticities. We find that the average oil supply is very inelastic in the short run, consistent with the findings of Güntner (2014) and Anderson *et al.* (2018). However, limiting climate change depends on cumulative emissions (Rogelj *et al.*, 2018), and the relevant elasticity is thus the long-run elasticity which we capture by the elasticities of exploration. In magnitudes, our estimates are higher than typical elasticities estimated in the literature (Ringlund *et al.*, 2008; Mohn and Osmundsen, 2008; Rao, 2018; Anderson *et al.*, 2018; Newell and Prest, 2019; Brown *et al.*, 2020).[5] This is plausible for two reasons. First, our approach measures elasticity by changes in oil exploration, not production or development of fields. Second, markets may respond more strongly to changes in taxes than prices, for example if a tax decrease is seen as more permanent or less risky in the long run.

Our paper also contributes to the small but growing literature on *unintended* climate policies, which affect the relative price of CO_2-emissions although they have another primary objective. Gerlagh *et al.* (2018) and Sen and Vollebergh (2018) study taxes levied for fiscal purposes, Shapiro (2020) study trade tariffs and Hahn and Metcalfe (2021) study an energy subsidy to low-income consumers. A central finding is that implicit CO_2 price due to such policies can be sizeable, which is consistent with the effects we document of fiscally motivated oil production taxes.

2 Methods and data

Tax data. We use a global data set on oil-related tax changes for 2000-2019. This data is collected from primary sources, Ernst & Young (EY) Corporate Tax guides (2000-2009), EY Oil and Tax Guides (2010-2019) and the Rystad Energy UCube tax database. We classify existing taxes as either production-based taxes (royalties) or profit-based taxes (resource rent taxes). Production-based taxes include those levied on gross production or gross income and windfall taxes levied on production if the oil price exceeds a certain threshold. In this tax category, costs are neither deductible nor refunded. Profit-based taxes include oil rent taxes, as well as windfall taxes and other taxes levied on profits from oil extraction. In this category, costs are either deductible or directly refunded.[6]

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[5] Our finding that investments in oil exploration are sensitive to royalties is in line with research showing that oil exploration is sensitive to the local business climate (Bohn and Deacon, 2000; Cust and Harding, 2020; Arezki *et al.*, 2019).

[6] Deduction rules of profit based taxes, such as the time profile of deductions, interest or uplifts paid on delayed deductions vary between tax regimes. In what follows, we bunch all profit-based taxes into one category and thereby

The theory on resource taxation has acknowledged that production-based taxes create an incentive to curb exploration and production, while profit-based taxes do not (Lund, 2009; Daniel *et al.*, 2010). Likewise, the ultimate aim of CO_2 -based taxes is to reduce emissions embedded in production. As noted by Prest and Stock (2021), it is possible to link production-based taxes (r) and CO_2-based corrective taxes (τ) by using the carbon content of the fuel (e_{oil}) and a base oil price (P_{oil}) as: $\tau = rP_{oil}/e_{oil}$. This observation is important for our identification strategy as it allows us to use changes in production-based taxes to quantify the effects of supply-side climate policies. This observation does not hold for profit-based taxes, at least not theoretically, because they do not distort exploration and production decisions. Our setting allows us to test this prediction empirically.

Figure 1A shows the global coverage of our data including all onshore and offshore assets, and Figure 1B shows royalties in our sample in 2019. The average production-weighted royalty over all countries was 21.0%. Assuming a reference oil price of $P_{oil} = \$50/\text{bbl}$ and a carbon content of oil at $0.43\text{t}CO_2/\text{bbl}$ we arrive at a global implicit CO_2 price of $\$24/\text{t}CO_2$. This average number, however, masks substantial heterogeneity across countries. Moreover, these figures do not include production subsidies (\$15bn/year, Jewell *et al.* 2018), which are small compared to consumption subsidies (\$324bn/year, Jewell *et al.* 2018) and production-taxes (\$320-\$410bn/year, this study). In Appendix A we show that high royalty rates are associated with high GDP, low institutional quality, high annual production and low demand-side carbon pricing, but there is no correlation between royalty rates and GDP.

Our unit of observation is *tax-regime* by *year*. As countries commonly set different taxes for onshore and offshore areas, we define a *tax regime* to be a unique combination of a country and an onshore or offshore area. When tax reforms change a range of taxes, our main specification uses the median change in production- or profit-based taxes. Section 5 explores the robustness of our results by analyzing the changes in lower and higher bounds.

We identify altogether 130 tax changes in 52 oil-producing countries. There were in total 54 royalty increases and 30 decreases; the average increase was 5.2 percentage points and the average decrease was 5.3 percentage points. There were 27 profit tax increases and 19 decreases. An average profit tax increase was 13.5 percentage points and decrease was 14.1 percentage points. In total, 35 countries had no tax changes over the study period.

Exploration, production and discoveries. Our analysis uses data on oil production, exploration investments and oil discoveries for the years 2000-2019. We use proprietary economic and production data from the UCube database of Rystad Energy, an oil industry consulting and data

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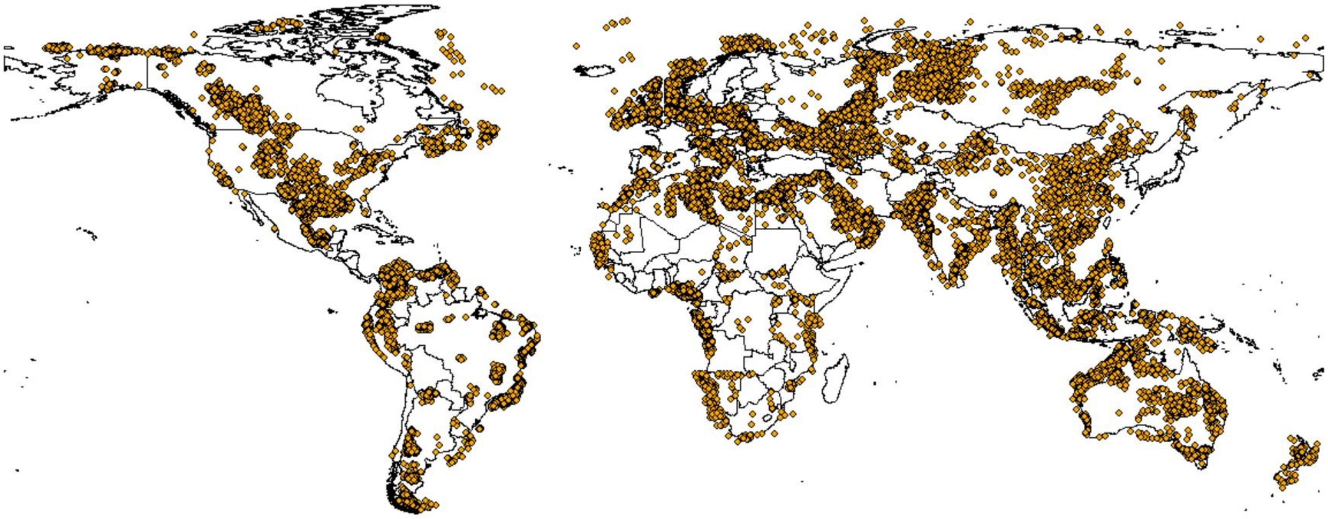
quantify the effect of *average* profit taxes. Our classification excludes changes in regular corporate income taxes, pricing of CO_2-emissions at the source and expenses related to achieving exploration or drilling rights (auctions or license fees). We do not include local (land owner, municipality- or state-level) contracts or taxes.

Panel A: Location of assets in our data



Panel B: Production-based tax rates

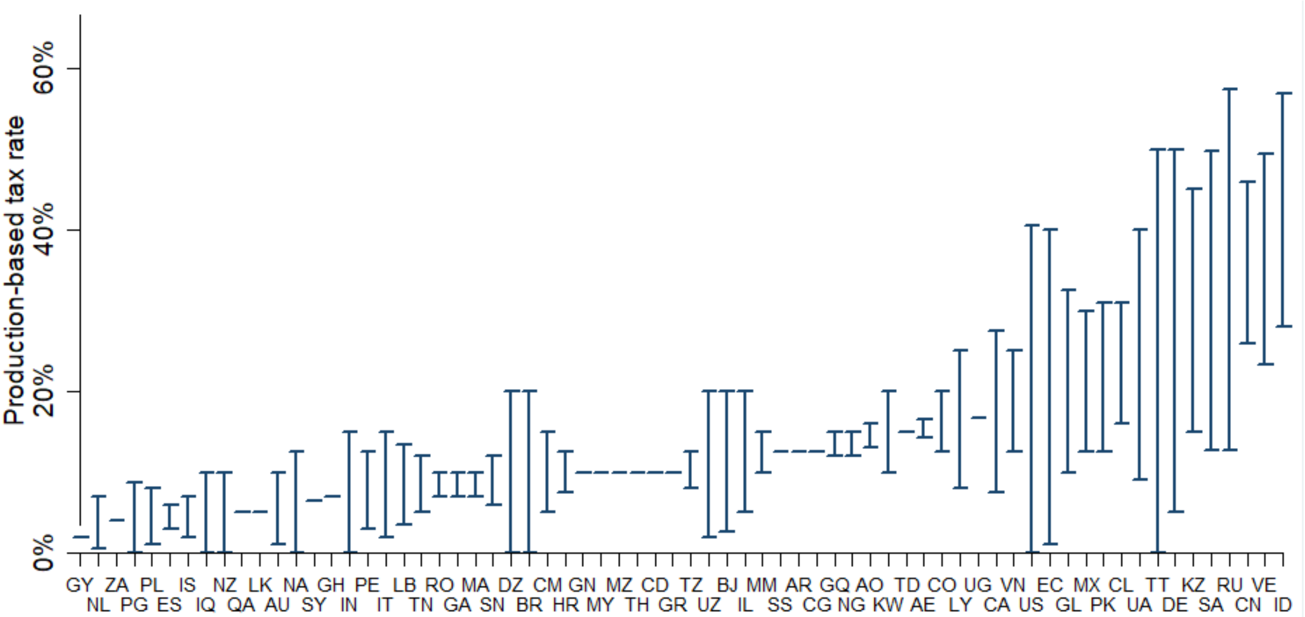


Figure 1: Location of oil producing fields and present royalty levels.

Notes: Panel A shows the geocoded locations of all assets in our data. Panel B shows the production-based tax rates on new discoveries in 2019. AZ, BH, KH, CY, DK, EG, IR, IE, KE, LA, MR, NO, OM, PE, GB, UY: No taxes (not shown in the figure); AR, AU, BR, CD, CM, CO, CH, DE, DZ, EC, GA, GH, GL, GN, GQ, GR, GY, HR, IL, IN, IQ, IT, KW, LB, LK, LY, MA, MM, MY, MX, NA, NG, NP, PE, PK, PL, QA, RO, SA, SN, SS, TD, TH, TJ, TN, TT, TV, UA, UG, US, ZA: Royalty; BJ, NZ: Royalty ad-valorem; IT: Fondo idrocarburi; MX: Over-royalty; EC: Sovereignty margin; TT: Supplemental oil tax; oil production levy; PK: Windfall levy; CL Special operating agreements; UZ:Subsurface user tax; MY: oil income tax; MZ:Oil production tax; AO:oil production tax; IS: Production levy; VN, CN: Resource tax; CN: Special oil gain levy; AZ: Default PSC regime; ES: Direct tax on the value of the extraction; CA, GL: Gross royalty; ID: Gross-split mechanism; RO, KZ: Mineral extraction tax; RO, NA:Export levy, KZ: Rent tax on exports; CG: Mineral fee.

company. The data set includes data on company-year specific oil and gas production, exploration CAPEX and OPEX for all assets (i.e., active licenses, fields or discoveries) between 2000 and 2019. The data has practically full global coverage, as it includes 84 oil-producing countries around the globe that, together, have 99.5% of the global oil reserves and 98.4% of the global oil production

(EIA, 2020). Fields are classified as either conventional or unconventional, where unconventional hydrocarbons include oil sands, extra heavy oil and tar sand, shale gas and shale oil, very tight reservoirs and coalbed methane.

We observe the amount of oil exploration per company, asset and year. For discoveries, we observe a cross section of the total discovered amount of oil per field, but not the time variation in when these discoveries are added to existing fields. To capture the time dimension, we assume that, for each field discovered within our study period, discoveries over time take place in proportion to the exploration capex in different years.[7] For each field with discovered oil reserves we observe the discovery year and the break-even price, that is, the oil price at which development of an already discovered field is estimated to have a net present value of zero after taxes. We interpret breakeven prices as proxies for extraction costs.[8] Oil companies are classified based on the historical operator at the time of drilling. In the main specification, small companies that operate in three or fewer countries are indexed based on their company-segment.[9]

3 Empirical approach

Empirical strategy. Our difference-in-differences strategy compares a firm's operations in a country before and after a royalty tax change to the same firm's activities in other countries over the same period. We estimate variations of the following linear regression model:

$$Y_{ijt} = \beta_R Royalty_{jt} + \beta_{PT} ProfitTax_{jt} + \gamma_{ij} + \gamma_{it} + \gamma_{rt} + \epsilon_{ijt} \tag{1}$$

The main dependent variable, Y_{ijt}, is the natural logarithm of exploration investment, oil production, discovered oil reserves or discovery-weighted breakeven prices by company i in tax regime j and year t. $Royalty_{jt}$ and $ProfitTax_{jt}$ denote production- and profit-tax rates in tax regime j at year t, where taxes vary by the location of the asset (onshore or offshore), the country and the year. Our coefficient of interest is β_R, the effect of the royalty rate on different outcome variables. The variable $ProfitTax_{jt}$ controls for changes in other taxes.

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[7] The timing of exploration expenditure relative to the year of discoveries is shown in Appendix Figure A.4, where we show that roughly 30% per cent of the exploration capex is spent at the year of discovery, around 5% before and the rest after.

[8] Appendix Figure A.2 shows that the distribution of breakeven prices has been relatively stable throughout our study period. Appendix Table A.2 we discuss the internal validity of this variable.

[9] Company-segments are: E&P company, exploration company, INOC, Independent, Industrial, Integrated, Investor, Major, NOC, Operating company, Supplier and Other. Our main specification with company-year and company-tax regime fixed effects only uses variation from companies that drill at least in two countries in a given year. By indexing the small companies we are able to use more data and thereby get more statistical power in the main analysis. The implicit assumption we make is that small companies within a given a company-segment respond similarly to year-specific shocks. In Appendix Table A.6 we show that results are robust to alternative company classifications.

Equation (1) includes a set of fixed effects. Company × tax regime-dummies (γ_{ij}) capture any time-invariant unobserved factors, such as a company's home bias or other preferences for a certain country or geographic area. Company × year fixed effects (γ_{it}) control for unobservable time-varying characteristics at the company-level, such as firm-specific technology, geological competence or expectations regarding the future oil price. Region × year fixed effects (γ_{rt}) control for region-specific shocks, such as changing economic conditions, where the regions are Europe, Africa, Asia and Oceania, North American and South America.

4 Results

Event study. Figure 2 presents the impact of royalty changes on exploration (Figure 2a), production (Figure 2b), discoveries (Figure 2c) and breakeven prices (Figure 2d). These event study graphs are based on estimation of equation (1), using an indicator for tax increases (=1) or tax decreases (=-1) and allowing the coefficients on the indicator variable to vary with event time. The graphs plot the associated β_R coefficients together with their 90 percent confidence intervals. Zero denotes the year the tax change comes into effect.

The lack of statistically significant pre-treatment effects lend support to the parallel trends assumption in our difference-in-differences strategy.[10] Moreover, we see no evidence of anticipation effects before the tax changes. Figures 2a and 2c show that both exploration and discoveries respond to changes in production taxes with a time lag of about two to five years. The delayed responses are consistent with the time lags related to licensing, seismic data acquisition, analyses and drilling preparations, which are typical in the exploration industry.[11] Figures 2b and 2d show null-results on both oil production and breakeven prices; the coefficients are close to zero and statistically indistinguishable from zero throughout.

Effects on exploration. Table 1 presents our main estimates, which are based on equation 1 using actual tax rates. We show results for different sets of fixed effects in columns 1-3 and control for profit taxes in column 4.[12]

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[10] Our approach, relying on two-way fixed effects and staggered implementation of reforms, may be biased if treatment effects are heterogeneous or dynamic. In Section 5 we show that the event study patterns are robust to using a stacked regression, which does not rely on previously treated units as controls for later treatments.

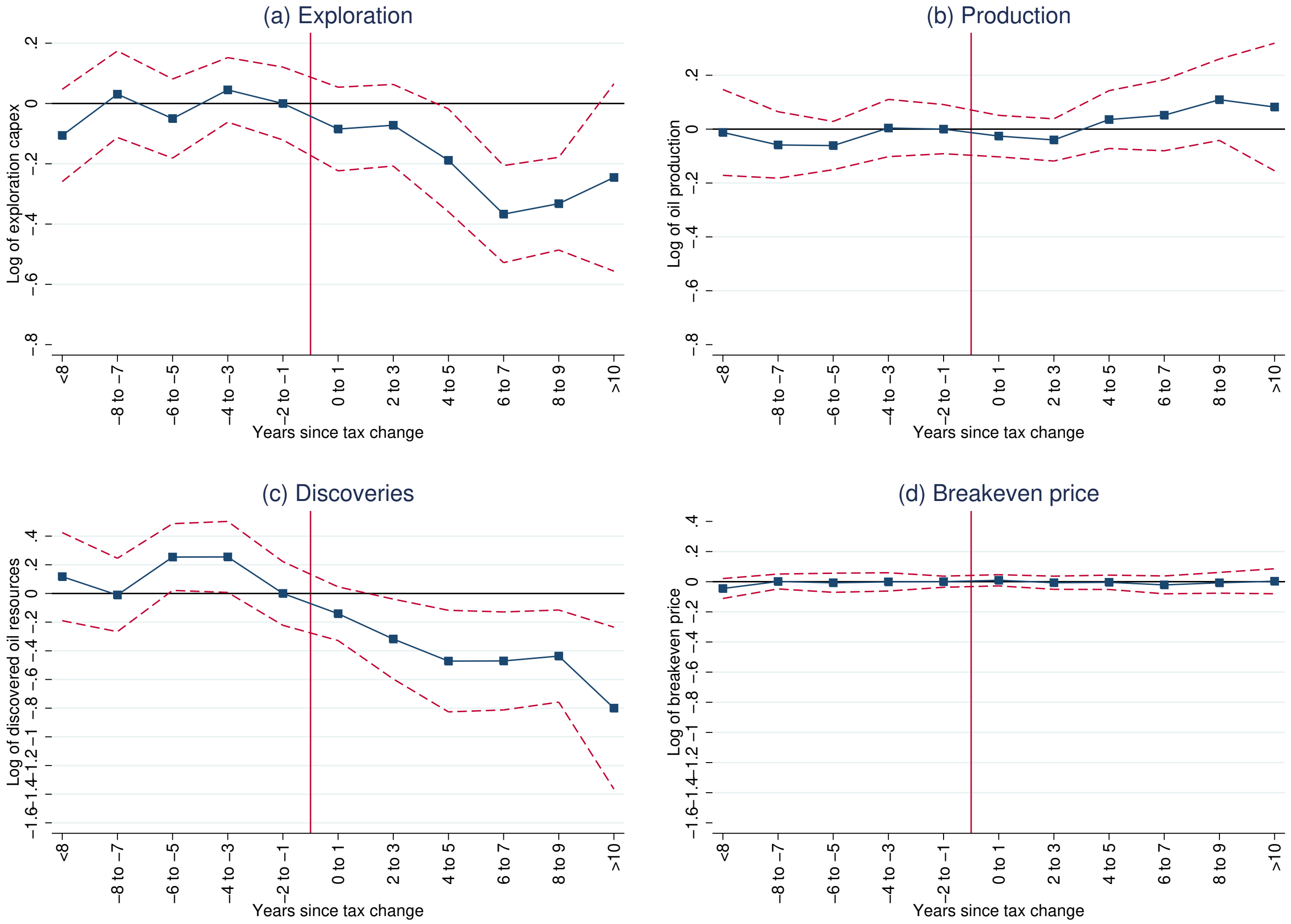
[11] For example, Łucki and Szkutnik (1990) report an average time lag of 1.2-5.4 years between seismic prospecting and exploration drilling and Hendricks and Porter (1996) report an average time lag of 1.6 years between license acquisition and exploration drilling in the U.S. These reported time lags are consistent with our event study, where the effect of tax changes kicks in with a delay.

[12] Note that the results of Table 1 are based on logarithmic transformation and they drop zero-values for a company in a given tax regime in a given year. In Appendix Table A.4 we show the results are robust if we use a balanced sample, that is, only company-regime-year that have non-zero values for all dependent variables: exploration capex, production, discoveries and breakeven prices.

Table 1: Effects of taxes on exploration, production and discoveries.

	(1)	(2)	(3)	(4)
Panel A: Impact on exploration				
Royalty rate	-.0262	-.0289	-.0268	-.0301
	(.0055)	(.0060)	(.0067)	(.0063)
Profit tax rate				-.0094
				(.0045)
N	41737	41737	41539	41539
Panel B: Impact on production				
Royalty rate	-.0009	-.0003	-.0012	-.0007
	(.0052)	(.0075)	(.0061)	(.0059)
Profit tax rate				.0019
				(.0048)
N	23823	23823	23045	23045
Panel C: Impact on discoveries				
Royalty rate	-.0413	-.0556	-.0440	-.0438
	(.0125)	(.0153)	(.0197)	(.0202)
Profit tax rate				.0014
				(.0064)
N	19657	19657	18868	18868
Panel D: Impact on breakeven prices				
Royalty rate	-.0001	-.0003	-.0018	-.0024
	(.0052)	(.0052)	(.0057)	(.0051)
Profit tax rate				-.0039
				(.0018)
N	14041	14041	13136	13136
Year FEs	x			
Region-year FEs		x	x	x
Company-year FEs			x	x

Notes: This table reports regression coefficients from 16 separate regressions, 4 per panel. The dependent variable was: log of exploration capex in Panel A, log of oil production in Panel B, log of discovered oil resources in Panel C, log of breakeven prices for oil in Panel D. Variable Royalty rate is the production-based tax rate and variable Profit tax rate is the profit-based tax rate in levels. Standard errors two-way clustered by firm and tax regime are in parentheses.


(a) Exploration

(b) Production

(c) Discoveries

(d) Breakeven price

Figure 2: Estimated impact of profit-tax changes on (a) exploration, (b) production, (c) discoveries and (d) breakeven prices

Notes: Graphs show coefficients on year-since-royalty-change indicators from regressions corresponding to the specification of eq. (1), where royalty increases are given value 1 and decreases value -1. For regimes that undergo multiple tax reforms, observations may have several event indicators equal to 1 or -1. Such an event study does not require a reference category; see for example Keiser and Shapiro (2019). The graph is readjusted such that the coefficient for year -1 equals zero and other coefficients can be interpreted as changes relative to that year. Connected dots show yearly values, dashed lines show 90% confidence interval. Standard errors are two-way clustered by country and company. Data covers years 2000-2019.

Increased royalty rates have a negative effect on exploration (panel A), consistent across all columns. Our preferred estimate in column 4 shows that a one percentage point increase in royalty rates decreases exploration investment by 3.0%. The result for profit taxes shows a small and only weakly significant effect. A one percentage point increase in profit taxes decrease investments by, on average, 0.9%. While theoretical arguments state that profit taxes should be nondistortionary (see e.g. Garnaut and Ross 1979; Daniel *et al.* 2010), our results provide some evidence that the real-life profit taxes may not fully adhere to this theoretical prediction. This may be due to costs that are not deductible or delays in deductions in combination with financial constraints (Ahlvik and Harding, 2021).[13]

Effects on production. We find small and statistically insignificant coefficients on both royalties and profit taxes for production (Panel B). The results are likely to reflect the (lack of) response by existing, older wells, because the time lags from seismic studies to production are more than ten years globally (Łucki and Szkutnik, 1990). This null-result echoes earlier papers' estimated elasticities (Anderson *et al.*, 2018; Güntner, 2014) finding that short-term oil production tends to be unresponsive to prices and, as we find, also to taxes.

Effects on discoveries. To get at the question of long-run oil supply effects, we move on to estimating the effects of tax changes on discoveries of oil resources (Panel C). We estimate consistent and significant effects for all specifications. A one-percentage point increase in royalty rates decreases discovered oil amounts by about 4.4%. Note that this estimated discovery effect is the intensive margin, that is, it is based on variation within non-zero discoveries only. Although we find a larger effect on discovered oil reserves than on exploration CAPEX, the 95 percent confidence intervals of column 4 in Panels A and C overlap. The effect of profit taxes is not statistically significant and the point estimate also changes sign.

Effects on extraction costs. We find that tax changes have no impact on the extraction cost of newly discovered deposits (Panel D). This suggests that a higher tax neither make companies search for deposits with low production cost (a statistically significant negative coefficient), nor that firms respond to a tax increase by finding smaller high-cost deposits (a statistically significant positive coefficient).

5 Robustness and additional analyses

Table 2 examines the robustness of the baseline estimates and presents additional analyses as explicated below. All specifications include region-year, company-year and company-regime fixed effects, corresponding to column (4) of Table 1. Details and robustness results are found in Online Appendix B.

Staggered difference-in-differences. Recent econometric literature on staggered difference-in-difference design has identified a potential bias in two-way fixed effects models when treatment effects are heterogeneous or dynamic (Sun and Abraham, 2020; Callaway and Sant'Anna, 2020;

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[13] In Appendix Table A.3 we compare our results to estimates from the previous literature. Our estimated effects are somewhat larger than other papers focusing on the long-run elasticity (exploration), and they are significantly bigger effects than in papers that focus on either short-run (production) or medium-run (field development).

Goodman-Bacon, 2021). Column 1 of Table 2 follows Cengiz *et al.* (2019) and runs a stacked regression where we create 18 cohort-specific data sets, one for every treatment-year, which include tax changes in that cohort and uses never-treated countries as controls (see also Baker *et al.* 2021 and Cunningham 2021). The results in Table 1 remain robust: We find significant effects on exploration and discoveries, and no impact on production or breakeven prices. The stacked event study graph in Appendix Figure A.5 shows no signs of pre-trends.

Endogenous tax changes. Our main identification strategy relies on the assumption that tax changes are exogenous. This assumption would be violated if the tax change itself is caused by increased exploration (reverse causality) or an unobserved factor (omitted variable). Our event study in Figure 2 shows no indication of reverse causation, and in Appendix Figure A.3 we find no significant correlation between tax reforms and oil prices. We further explore the possibility that tax reforms and our effects may be driven by large companies with the power to influence the government's decision. Table 2 splits the sample along three dimensions that proxy for companies'

Table 2: Effects of taxes on exploration, production and discoveries, robustness

	(1) Stacked regression	(2) Private ownership	(3) Small company	(4) No existing production	(5) Small countries	(6) Non-OPEC	(7) Conventional	(8) Unconventional	(9) Reform, low-end	(10) Reform, high-end
Panel A: Impact on exploration										
Royalty	-.0291	-.0229	-.0359	-.0235	-.0274	-.0257	-.0224	-.0530	-.0261	-.0220
	(.0095)	(.0066)	(.0074)	(.0108)	(.0076)	(.0058)	(.0094)	(.0162)	(.0079)	(.0042)
N	288532	17387	10726	28991	30734	34886	25830	2628	41539	41539
Panel B: Impact on production										
Royalty	-.0031	-.0018	-.0009	.0328	.0022	.0042	.0008	-.1735	.0027	-.0024
	(.0071)	(.0073)	(.0070)	(0.1035)	(.0049)	(.0068)	(.0057)	(.0484)	(.0070)	(.0037)
N	163003	6525	6057	11351	14995	18787	22678	1280	23045	23045
Panel C: Impact on discoveries										
Royalty	-.0465	-.0346	-0.774	-.0185	-.0274	-.0282	-.0393	-.0765	-.0522	-.0214
	(.0148)	(.0150)	(.0249)	(.0394)	(.0200)	(.0196)	(.0188)	(.0278)	(.0203)	(.0149)
N	88386	3670	4388	7554	8285	11050	12814	1616	13981	13981
Panel D: Impact on breakeven prices										
Royalty	-.0032	.0036	.0011	-.0063	-.0083	-.0039	-.0030	-.0031	.0015	-.0022
	(.0048)	(.0044)	(.0036)	(.0032)	(.0063)	(.0054)	(.0051)	(.0050)	(.0043)	(.0031)
N	87460	3468	4238	7581	7409	10326	12227	1188	13136	13136

Notes: The table reports coefficients from 40 separate regressions, 10 per panel. All specifications use company-region FEs and control for profit taxes. Column (1) uses region-year-indicator and company-year-indicator FEs, (2)-(8) use region-year and company-year FEs. Column (2) uses private companies only, (3) uses companies drilling in one country only, (4) uses firms with existing oil or gas production in the country, (5) uses all except the fifteen largest producers in our sample, (6) uses non-OPEC members only, (7) uses only conventional fields, (8) uses only unconventional fields. Variable Royalty is the median production-based tax rate in columns (1)-(8), low-end in (9) and high-end in (10). Standard errors two-way clustered by firm and tax regime are in parentheses.

lobbying power. Even when restricting the sample to only cover private companies that have less ties to the government (column 2), small companies that arguably have less lobbying power than the large ones (column 3) and companies without existing production in the country and, hence, that have a weaker incentive to lobby (column 4), we find effects that are similar to those presented in Table 1.

Spillovers. We explore whether our estimation violates the Stable Unit Treatment Value Assumption (SUTVA). First, one may worry that companies shift activity from one regime to another in response to tax reforms, for example if firms were credit constrained and a tax change in one regime made more funds available to do exploration in other areas. This would lead to an upward bias in our estimates. To address this possibility, Table 2 shows results using only companies that drill in one country only (column 3). We find that the results are similar, and point estimates even somewhat larger, for these firms that are not exposed to cross-border spillovers.

A second violation of SUTVA would be if a tax change in one country affects production and exploration elsewhere through changes in the global oil price. We do not think this is a major concern within our study period.[14] As we find no effect on the short-term production, there should be no effect on the short-term oil price (see Panel B of Table 1). If spillovers through the oil price is a worry, we expect this to be a smaller concern for small or unorganized oil producing countries that have less impact on the market. Table 2 shows that results are robust when using only small countries (column 5) or countries that are not OPEC members (column 6).

Conventional vs unconventional oil. Table 2 runs a split-sample analysis for conventional (column 7) and unconventional (column 8) fields. While we find expected effects for both types of hydrocarbons, unconventional deposits turn out to be somewhat more tax-sensitive. Notably, also production from unconventional fields responds to tax changes. These results are consistent with recent findings in the literature that production from unconventional reservoirs is more price sensitive than production from conventional reservoirs (Bjørnland *et al.*, 2021).

Ranges of tax changes. As Figure 1B shows, tax systems sometimes include a range of tax rates. In the main analysis, we approximate the magnitude of tax reforms by the change in the median tax rate. Table 2 (columns 9-10) repeats the analysis using instead the lower- and higher-ends of the tax changes. We find statistically significant effects for exploration, but for the high-end reforms the effect on discoveries turns insignificant at the 10 percent level.

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[14] In Section 6 we aim to quantify leakage in the long-term by numerical modelling. Long-term leakage takes into account that new discoveries eventually increase production and thereby oil prices. As long as the time lag between discoveries and production is long enough, this should not violate SUTVA for our estimation period 2000-2019.

6 Quantification

In this section, we use our estimates to carry out a partial equilibrium analysis in order to analyze the impact of supply-side climate policies on global CO_2-emissions as well as on producer surplus, consumer surplus and tax revenue. We consider a hypothetical policy coined *climate royalty surcharge*, a tax levied on oil production, adopted either unilaterally or globally. We assume that, first, the surcharge is levied on only new discoveries and not on existing assets, and second, that it replaces the existing production-based taxes.

We further make the following assumptions. First, observing extraction costs (per field) and taxes (per tax regime) allows us to map out the residual long-term supply curve of the global oil market. As we find no impact on breakeven prices (Panel D of Table 1), we assume that the distribution of new deposits follows from the historical distribution for each tax regime over the study period. Second, we use the estimated semi-elasticities to shift the supply when taxes change. Here we make a structural assumption that the estimated coefficients for exploration and discoveries (Panels A and C of Table 1) are constant across the range of taxes we consider. Third, based on the null-effect on short-term production (Panel B of Table 1), we assume that production from existing fields is insensitive to tax changes. Fourth, the residual long-term demand elasticity is based on parameters from the literature. In order to provide a range of results, we focus on two cases: For an upper bound we use elasticity -0.5, for a lower-bound we use elasticity -0.2.[15] The level of the demand is set to be consistent with long-run oil price of \$50/bbl. Online Appendix C presents the details on how the analysis is conducted.

Unilateral policies. We begin by using our estimates to analyze the effects of a climate royalty surcharge adopted unilaterally by a small, price-taking country. When a country restricts its oil production, marginally higher prices increase production in other countries (Hoel, 1994; Harstad, 2012). Using the formula for leakage rate from the earlier studies, our estimates suggest that the resulting global emission reduction amounts to 9%-20% of the single country's reduction, depending on the demand elasticity.[16]

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[15] Our intention is not to take a stance on what the long-term price elasticity of oil demand is, but rather study the implications of our results using a wide range of demand elasticities. Our choice of baseline demand elasticity range follows Prest and Stock (2021). Consistent with this range, Hamilton (2009), for example, points to a long-term demand elasticity for crude oil of -0.31 found by Dahl (1993) and -0.21 found by Cooper (2003). At the higher end of demand elasticities in the literature, Balke and Brown (2018) find a mean long-term demand elasticity of -0.51 and Uria Martinez *et al.* (2018) report an average long-term demand elasticity from -0.61 for new oil price maxima (where we disregard end-use price elasticities which are mechanically and systematically biased relative to the crude oil elasticity, as explained in Hamilton (2009).) At the lower end, IMF (2011) and Arezki *et al.* (2017) suggest estimates between -0.07 and -0.09. To account for these estimates, in Figure 3 we also show results for a wider range of demand elasticities, ranging from -0.1 to -0.6.

[16] The effect of reducing supply by one unit is $-e_D/(-e_D + e_S)$, where e_D is the demand elasticity, -0.2 or -0.5, and e_S is the long-term supply elasticity, 1.96 (from Table A.3). See Hoel (1994), Harstad (2012), Erickson and

It is ex-ante unclear whether a climate royalty surcharge levied on top of the existing royalties can raise revenue, as tax revenues follow a Laffer curve: there is a direct positive effect from a higher royalty rate but tax revenues eventually fall as the tax base narrows. For a price taking country, we find that the revenue maximizing royalty level is at 22.8%.[17] This is close to the average existing royalty levels (see Figure 1), which may explain why we observe these royalties, although this average figure conceals substantial heterogeneity across countries.

Global policy. Figure 3 shows results for adopting a global climate royalty surcharge ranging from 0% to 40%. Panel A shows the *change* in emissions, Panel B the *changes* in the consumer and producer surpluses and Panel C the *change* in tax revenue. All changes are relative to today's tax system. Thus, the left-end of the figure, i.e. 0% climate royalty surcharge, is a scenario where all current taxes are dropped. The right-end of the figure is a scenario where a global 40% climate royalty surcharge is adopted. Dark shaded areas show the bounds for high (-0.5, dashed line) and low (-0.2, solid line) demand elasticities. Light-shaded areas show a wider elasticity range (from -0.1 to -0.6).

A climate royalty surcharge shifts the long-run supply, which affects both equilibrium production, CO_2-emissions and the oil price. The more elastic the demand is relative to supply, the larger is the effect of a given supply shift on CO_2-emissions. Figure 3A shows these effects for varying levels of the climate royalty surcharge for the high- and low-end elasticities.[18] Removing the current royalties (0% royalty, Fig.3A) would increase emissions by 1.3-2.7 $GtCO_2$ annually. This substantial increase amounts to 4-7% relative to today's annual emissions from all sources. Increasing the royalty rate from today's level, reduces emissions almost linearly by around 0.16 $GtCO_2$ per percentage point increase.

To illuminate the tax incidence, Figure 3B shows the impact on consumer and producer surplus.[19] A higher climate royalty surcharge has two effects. First, it removes exploration of dis-

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Lazarus (2014) and Borenstein (2018) for versions of the formula. Our numbers only take into account the direct leakage through the oil market, for an analysis of other effects (e.g., via OPEC's response, other fossil fuels, or production emissions), see Fæhn *et al.* (2017).

[17] The long-term tax revenue is $prQ(r)$, where p is the oil price, r is the royalty rate and $Q(r)$ discoveries as a function of this rate. This function is maximized at $r = -Q(r)/Q'(r)$; that is, when the royalty rate equals minus one over the semi-elasticity of discoveries. Using column 4 of Panel C in Table 1: $-1/(-.0438) \approx 22.8$.

[18] Our results are conservative, because they only focus on emissions embedded in oil production (using emission factor of $0.43tCO_2/bbl$; EPA, 2021). We do not include emissions in natural gas and emissions from production. Direct emissions from oil production are considered to be covered by the "demand-side" policies, such as local carbon taxes and emissions trading schemes, and not considered in this paper. The direct emissions vary substantially, from 3.3 g CO_2eq./MJ in Denmark to 20.3 g CO_2eq./MJ in Algeria, see Masnadi *et al.* (2018). Moreover, we do not take into account that oil may displace other fossil fuels.

[19] Note that the global oil demand is affected by (1) non-uniform demand-side climate policies (Ramstein *et al.*, 2019) and (2) subsidies on oil consumption that remain large (Coady *et al.*, 2017, 2019). Demand therefore deviates from the consumers' pre-tax willingness to pay and our definition of consumer surplus should be interpreted with caution.

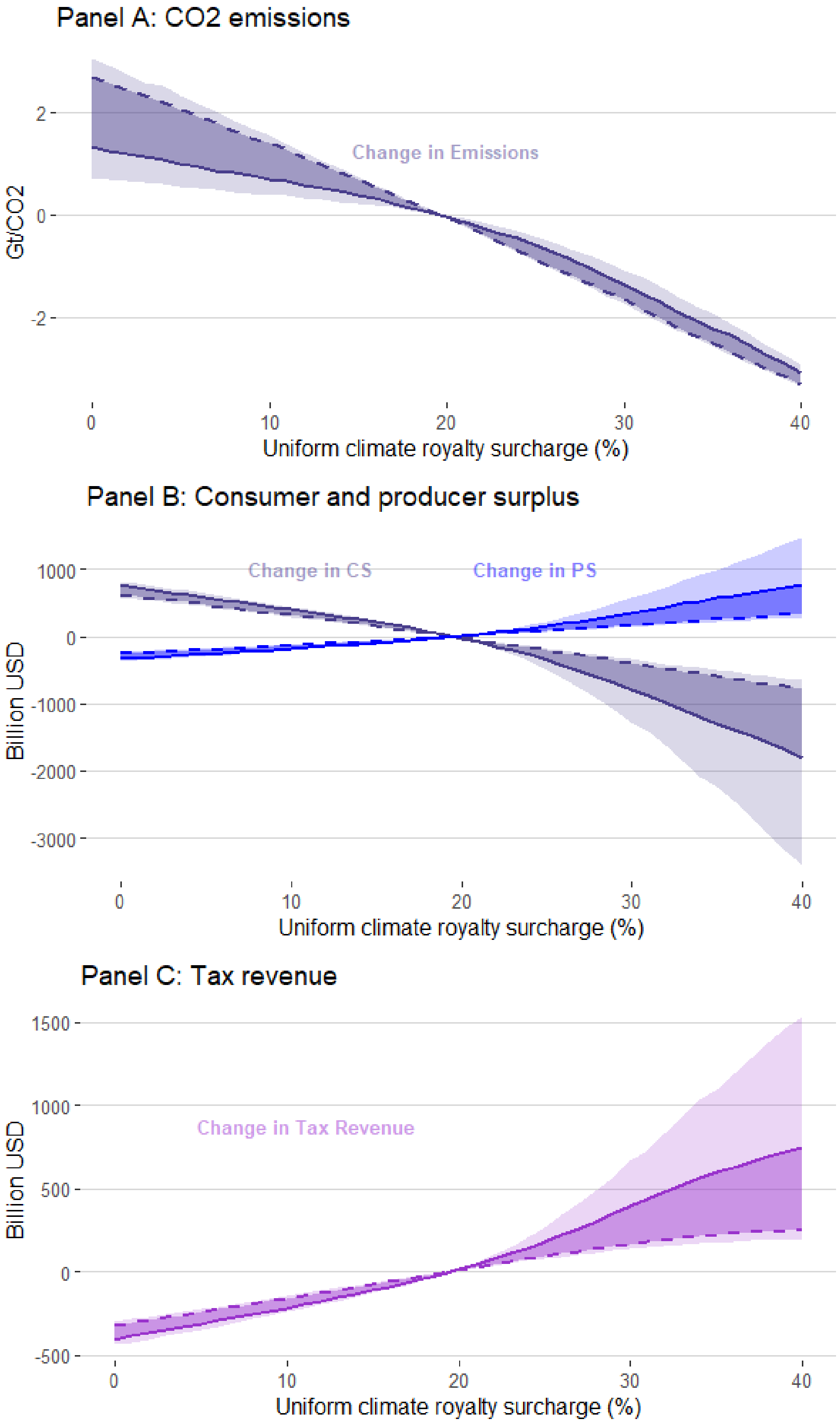

Figure 3: Effects of varying climate royalty surcharge on (a) emissions, (b) consumer and producer surplus and (c) tax revenue

Notes: The figure shows effects relative to today's levels (with the non-uniform taxes presented in Fig. 1) of varying the uniform global climate royalty surcharge rate. Note that the point where y-axis is zero represents a *uniform* global tax that produces the same emissions, CS, PS or Tax revenue as today's *non-uniform* taxes. Dark shaded areas show higher and lower bounds for elasticities; -0.2 (solid line) and -0.5 (dashed line). Light shaded areas show a wider range from -0.1 to -0.6. Panel A: Emissions are the embedded CO_2-emissions in oil production annually; Panel B: Consumer surplus (CS) is the difference between demand and the oil price, Producer surplus (PS) is the difference between oil price on the on hand and extraction cost plus taxes (royalties and profit-taxes) plus exploration capex expenditure on the other hand; Panel C: tax revenue from royalties and profit taxes.

coveries for which consumers have positive willingness to pay and producers find it profitable to operate. Second, a royalty increases the oil price both for new discoveries and existing production, redistributing rents from consumers to producers. In total, removing all taxes would increase consumer surplus by \$620-\$770 bn per year and decrease producer surplus by \$250-\$340 bn per year. Consumer surplus is monotonically decreasing and producer surplus monotonically increasing in the royalty. A climate royalty surcharge would hence move surplus from consumers to producing companies.

Figure 3C shows that a higher global climate royalty surcharge is able to increase tax revenue. The coordinated supply-side policy allows producers to exert market power and, like producers, also governments benefit from the higher oil price. Removing production-based oil taxes for new discoveries (0% royalty, Fig.3C) would reduce tax revenue globally by \$320-\$410 bn per year. A higher climate royalty surcharge has potential to further increase the tax revenue, though at a decreasing rate.

Last, taxes also create a deadweight loss, equal to \$20-60 bn per year. Combining this with the estimated emission reduction, we find that the average cost of the current, implicit, climate policy is \$18-20/tCO_2. This number is below the typical values for the social cost of carbon (e.g. Nordhaus 2017), which implies that the current taxes are welfare-improving.

7 Conclusions

For the Paris Agreement to successfully reduce emissions and limit global warming, large amounts of oil need to be left in the ground (McGlade and Ekins, 2015; Welsby *et al.*, 2021). Corrective prices on oil production offer a promising theoretical opportunity to achieve this objective. We study the effectiveness and incidence of supply-side policies by the use of historical reforms of production-based oil taxes.

We emphasize three findings. First, oil firms respond to higher production-based taxes by reducing exploration, which leads to fewer new reserves and hence lower future production capacity. We find no effect on oil production from operating fields. Second, the production-based taxes currently in place around the world reduce global emissions by 1.3-2.7 GtCO_2 per year. Moreover, the deadweight loss associated with these taxes is below typical values for the social cost of carbon. Third, the cost of production-based taxes is borne by consumers, while governments and producing companies increase their revenues. Supply-side climate policies may therefore meet resistance from consumers and gain support from producers, but we leave the geopolitical feasibility of a global supply-side treaty for future research.

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APPENDIX FOR ONLINE PUBLICATION

A Descriptive statistics

Existing royalties. What kind of countries are using production-based oil taxes? We correlate the existing taxes for new discoveries with observable outcomes in Figure A.1 below. Panel (a) shows correlations between royalty rates and the log of GDP per capita, showing evidence for a weak correlation between the two variables. When we correlate royalty rates with institutional quality in Panel (b), measured by the World Bank rule of law index, we find a weak negative correlation. Countries with worse institutions are more likely to use high royalties. One reason for why countries use production-taxes instead of profit taxes, that are supposedly non-distortionary, is the required institutions and administration needed to handle cost deductions (Daniel *et al.*, 2010). Panel (c) correlates royalties with production from all fields discovered in our study period, and shows that countries with high production are more likely to set high royalties. Panel (d) explores the correlation between demand- and supply-side policies. It shows that countries that have ambitious climate policies tend to have lower implicit supply-side policies.

Oil exploration and production data. Figure A.2a plots the oil price (dashed black line), exploration expenditure (red line) and oil production (blue line). Oil production does not seem to correlate with oil prices, but exploration expenditure is associated with the oil price: Both the gradual increase between 2005 and 2014 and the drop in 2014 are mirrored in the exploration data with a delay. Figure A.2b shows a kernel plot of breakeven prices for fields discovered in our study period, 2000-2019, separately for 5-year periods. The mode breakeven price is at $35-50/bbl and there are no substantial differences in breakeven prices between years.

Table A.1 shows the summary statistics of the data. Columns (1) and (2) show data for all countries. Columns (3) and (4) shows data for countries that undergo at least one reform in the study period. Columns (5) and (6) are countries that have no reforms in the period.

Exploration capex and discovery year. We observe the cross-section of final discovery sizes per field (backlogged value), but not the times when these discoveries are added. For example, if 100 MMbbl are discovered in the first year of discovery of a field, and the next years additional 50 MMbbl are discovered at the same field, Rystad Energy reports the final discovery size to be 150 MMbbl. In the analysis, we use the timing of exploration capex to create time variation in discovery sizes. The assumption is that exploration investments give a direct mapping to the discovered reserves. Figure A.4 shows the average field's exploration investments profile relative to discovery year. About 30% exploration investments happen at the year of discovery. Before a discovery, wildcat exploration wells are drilled to explore whether there are oil deposits in a given location. Around 5% of the total exploration expenditure takes place before the discovery is made, which include hydrocarbon shows that motivate further exploration. After a discovery is made, appraisal wells are typically drilled to obtain more data about the size and extent of the discovery. A discovery may also trigger new drilling in the neighborhood, which will later be added to the same field.

Internal validity of the breakeven price data. The breakeven prices from Rystad Energy AS are calculated by using revenue and cost life-cycle profiles. The revenue and cost data are either sourced from company reports or modelled. In our sample, the predominant method used is the latter, as most discoveries are predicted to operate beyond last sample year (2019), therefore making it impossible to rely solely on company reports covering the whole life-cycle. To check the internal validity of the breakeven price data, we perform a simple analysis by regressing a set of variables on the breakeven price. We are interested in knowing if the data behaves as we would expect, showing that production costs are higher for fields that are (1) smaller, (2) located offshore, and (3) located in deeper sea areas. More specifically we run the following model for fields discovered after 2000:

$$BE_{icd} = \beta_1 TotR_{icd} + \beta_2 WaterDepth_{icd} + \beta_3 Offshore + \gamma_c + \gamma_d + \epsilon_{icd} \tag{A.1}$$

The i-index denotes fields, the c-index notes countries, and the d-index notes discovery years. BE is the natural logarithm of the breakeven price; $TotR$ is the natural logarithm of the total discovered reserves; $WaterDepth$ is the water depth for offshore fields (equal to zero if the field is located onshore); $Offshore$ is a dummy that takes value 1 if the field is located offshore; γ_c is the fixed effect for country c; and γ_d is the fixed effect for discovery year d. Results of this regression are shown in Table A.2. We find that coefficients have expected signs: Breakeven prices are lower for large fields, and higher for offshore fields that are located deeper. The simple model in equation (A.1) has a modest coefficient of determination of 0.36.

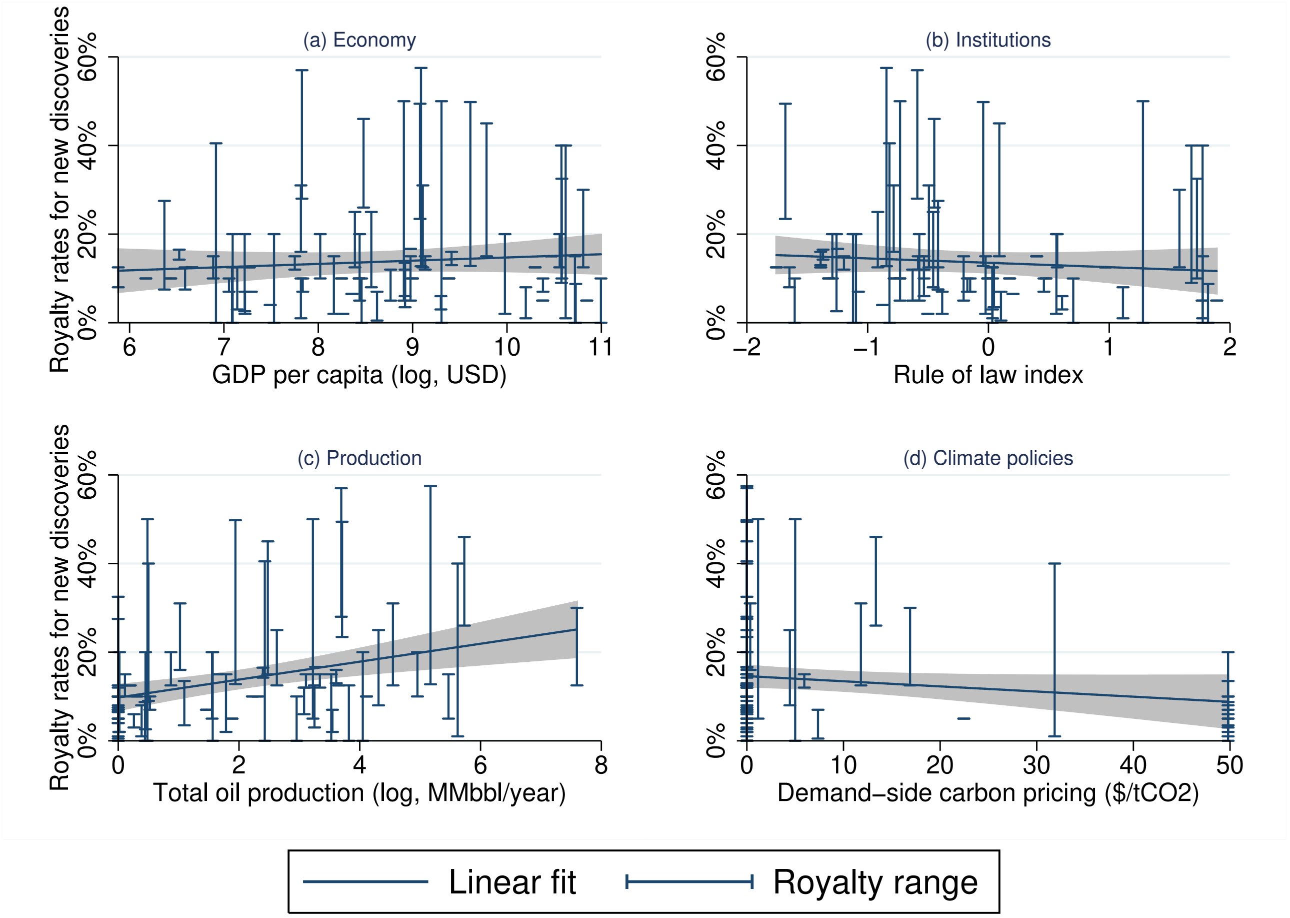
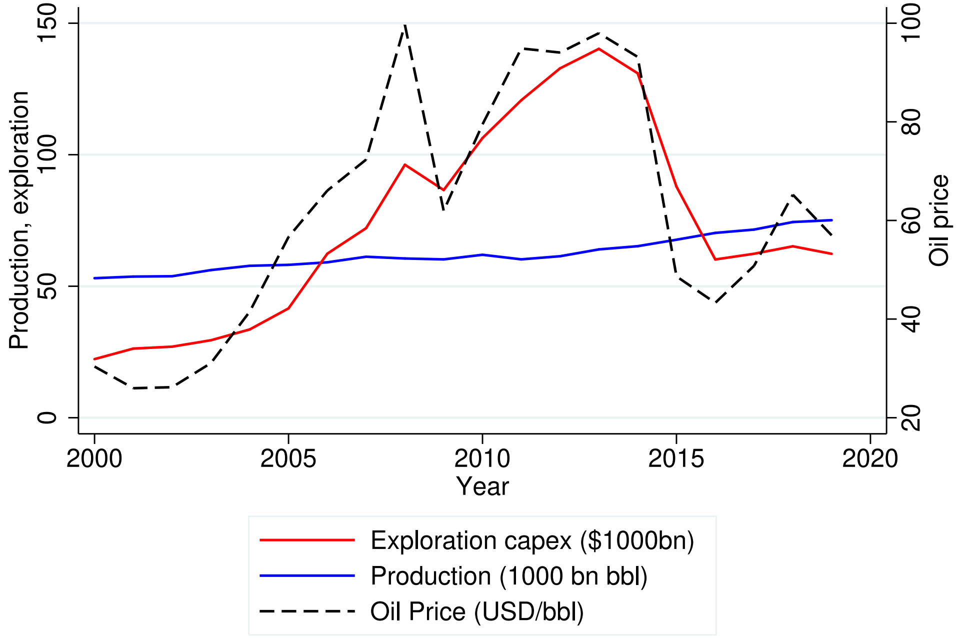


Figure A.1: The association between present-day production-based taxes and (a) the economy, (b) institutions, (c) production and (d) climate policies.

Notes: This figure shows the correlation with royalties and the mean of the following variables over our study period (2000-2019): Panel A: Log of GDP per capita in USD; Panel B: World Bank's rule of law index; Panel C: Log of 1+Oil production; Panel D: Carbon pricing. Data from data.worldbank.org/ (Panels A-C) and https://carbonpricingdashboard.worldbank.org/ (Panel D), viewed January 18 2022.

(a) Exploration and production



(b) Breakeven prices

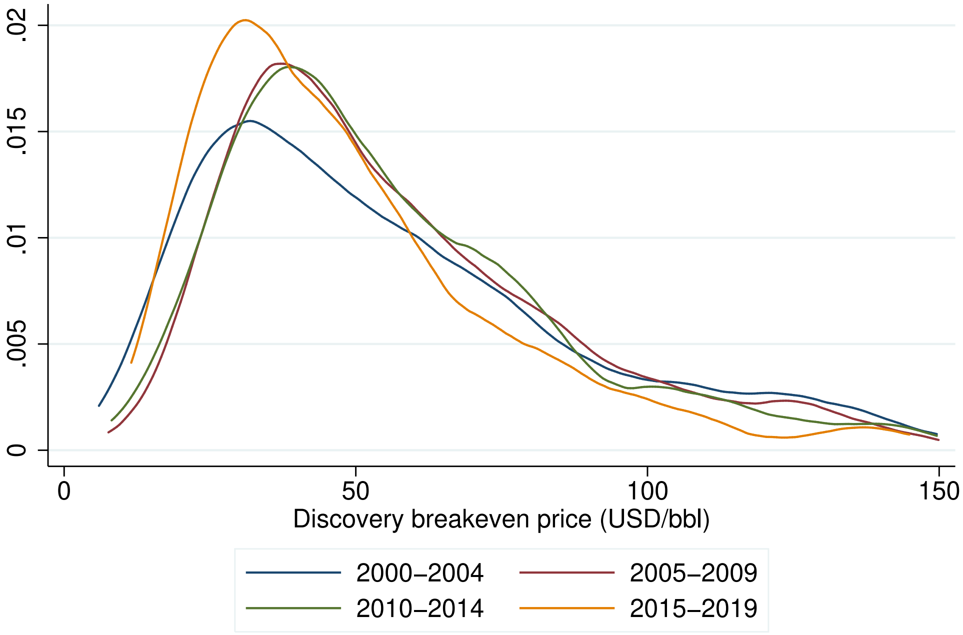


Figure A.2: Development of exploration expenditure, production and oil price for 2000-2019

Notes: Panel A shows the annual development of aggregate exploration capex (solid red line), production (solid blue line) and the oil price (dashed black line). Correlation between aggregate exploration capex and oil price: 0.9130; correlation between aggregate oil production and oil price: 0.2615. Correlation between aggregate exploration capex and aggregate oil production: 0.4862. Panel B shows the distribution of discovery breakeven prices (USD/bbl) in our study period for three periods: 2000-2004 (blue), 2005-2009 (brown), 2010-2014 (green) and 2015-2019 (yellow).

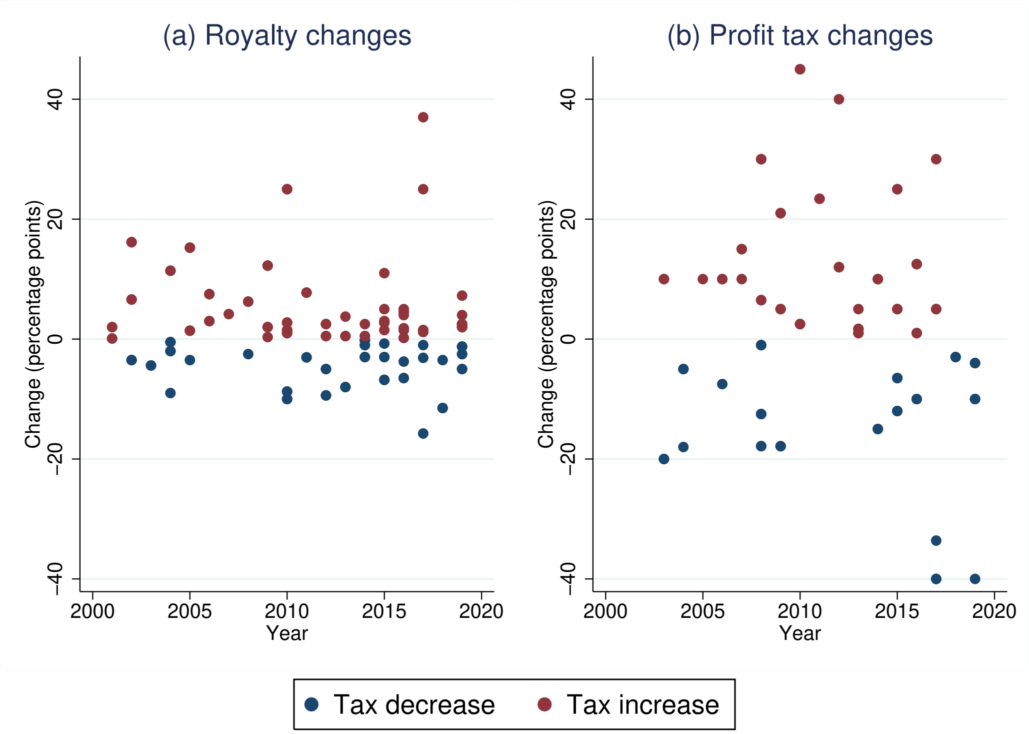


Figure A.3: Changes in (a) royalties and (b) profit taxes in our study period.

Notes: This figure plots tax changes in our study period. Each plot represents one tax increase (red dot) or decrease (blue dot) of a production-based tax or royalty (Panel A) or profit-based tax (Panel B). Zero values mean no tax change and are not plotted. Correlation between royalty increase and profit tax increase: 0.0714, correlation between royalty decrease and profit tax decrease: 0.0422. Correlation between royalty increase and oil price: -0.0377; royalty decrease and oil price: 0.0043; profit tax increase and oil price: 0.0461 and profit tax decrease and oil price: -0.0183.

Table A.1: Summary statistics

	All		Royalty change between 2000-2020		No royalty change between 2000-2020	
	(1)	(2)	(3)	(4)	(5)	(6)
	Mean	Std	Mean	Std	Mean	Std
ExCapex (Million USD)	30.80	203.1	33.7	227.1	24.4	135.5
Oil production (MMbbl/year)	26.2	113.4	22.1	110.1	35.2	119.7
Oil discovery size (MMbbl)	1642.5	8604.3	1485.0	9110.4	1990.8	7350.7
Breakeven price ($/bbl)	57.9	30.8	60.4	30.9	52.3	29.8
Number of assets	47,612		32,786		14,826	

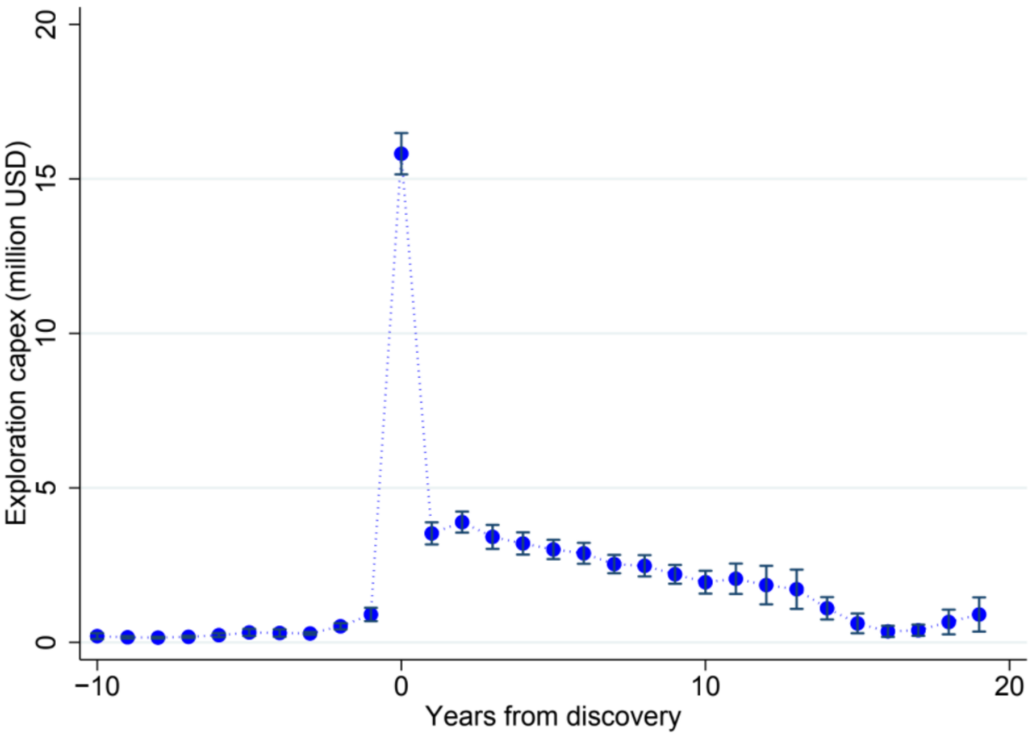


Figure A.4: Timing of exploration capex relative to discovery year in the data

Notes: The graph shows the average exploration capex per asset discovered after 2000. Y-axis is the exploration cost in million US Dollars per year. X-axis is the year relative to the year when the discovery is made; negative values are pre-discovery periods and positive values post-discovery periods.

Table A.2: Correlation between breakeven prices and fixed field characteristics

	(1)	(2)	(3)
Deposit size	-.1811	-.1840	-0.1874
	(.0030)	(.0032)	(0.0032)
Offshore	-.0054	.0550	0.078
	(.0154)	(.0183)	(.0183)
Water depth	.000126	.000090	0.000098
	(.000013)	(.000015)	(.000016)
Fixed effect	No	Country	Country + year
Observations	8,732	8,732	8,732
R2	0.2766	0.3451	0.3603

Notes: This table reports correlations between observable asset characteristics and the breakeven prices. Deposit size is the natural logarithm of the size. Offshore is a dummy that takes value one for offshore assets. Water depth denotes depth of the asset in meters, and takes value zero for onshore assets.

B Additional robustness checks and analyses

Price-elasticity of supply and comparison to previous literature. Our main results in Table 1 provides *semi-elasticities*, that is, the effects of production-based taxes in levels on petroleum production and exploration in logarithms. This gives directly a percentage-change in variables of interest (production, exploration) on changes in tax levels. In order to facilitate comparison with previous studies, we also solve (after-tax) price elasticities:

$$Y_{ijt} = \beta AfterTaxPrice_{jt} + \gamma_{ij} + \gamma_t + \epsilon_{ijt} \tag{B.1}$$

where Y_{ijt} is the natural logarithm of either production, giving the short-run price elasticity, or exploration, giving the long-run price elasticity. After-tax price is defined as natural logarithm of: $AfterTaxPrice_{jt} = (1 - Royalty_{jt}/100) \times OilPrice_t$. In this model, all the variation comes from royalty changes as $\beta \times log(Oilprice_t)$ will be absorbed by year fixed-effects γ_t.

Table A.3 summarizes our elasticity results along with several notable papers that perform similar estimations. The table divides studies into those estimating the elasticity of production (short-run elasticity, Panel A), drilling of development wells (medium-run elasticity, Panel B) and exploration (long-run elasticity, Panel C). The results paint a consistent picture. In the short run oil production is insensitive to price fluctuations in most presented estimates, including ours. We find elasticity 0.063 using equation (B.1). Elasticities reported in the literature vary between 0-0.08. An exception is Rao (2018) who finds a statistically significant elasticity (0.371) for Californian firms responding to oil taxes. One explanation is that most Californian wells lacks sufficient subsurface reservoir pressure and oil is produced by pumping, making production more sensitive to prices; the effect disappears for flowing wells. In the medium-run oil companies respond to oil prices by increasing drilling activity, which the medium-run elasticities take into account. These tend to be around 0.5-0.75, an order of a magnitude larger than the short-term elasticities. The long-run elasticities also capture how oil and gas exploration changes when prices change. Our long-run elasticity is 1.960 using equation (B.1), somewhat higher than the reported numbers in the literature. One explanation may be that, unlike previous studies, we estimate the effects using tax changes. If the markets perceive tax changes as more permanent or less risky than price spikes, the exploration investment is expected to respond more strongly.

Balanced sample. Our main results in Table 1 show results for four dependent variables: Exploration capex, oil production, discovered reserves and breakeven price. Due to the log transformation, that specification drops all companies where that variable gets value zero, which leads to unbalanced number of observations between panels. Table A.4 presents same results for a limited balanced sample, where we only take into account fields that have non-zero variables for all variables. In practice, this specification only includes companies that have production, exploration and make discoveries with reported breakeven prices in a given year. Table A.4 show that the main results in Table 1 are robust to limiting the sample this way.

Stacked regression. Recent advances in econometric theory have recognized potential problems in difference-in-differences models with staggered treatment timing (Sun and Abraham, 2020; Goodman-Bacon, 2021; Baker *et al.*, 2021; Cunningham, 2021). Problems may arise in models using two-way fixed effects, like in our equation (1), where earlier treated units act as controls for later reforms if the treatment effect is heterogenous or dynamic. To study the robustness of our main result we follow Cengiz *et al.* (2019) and run a stacked regression. We create 18 event-specific datasets $k = 2001, 2002, ..., 2019$, including regimes experiencing a tax reform in that given year k, and "clean controls", that is, regimes without any tax reforms in 2000-2019. The stacked regression takes the form:

$$y_{ijkt} = \beta_R Royalty_{jt} + \beta_{PT} ProfitTax_{jt} + \gamma_{ijk} + \gamma_{ikt} + \gamma_{rkt} + \epsilon_{ijkt} \tag{B.2}$$

where y_{ijkt} is the dependent variable (exploration capex, discoveries) on a company i, tax regime j, year t and indicator k. As Cengiz *et al.* (2019) and Baker *et al.* (2021) note, this approach is equivalent to a setting where the events happen contemporaneously (for each events k), and therefore avoids possible problems with using earlier tax reforms as controls.

Figure A.5 presents and event-study for a stacked difference-in-differences analysis which shows no signs of pre-trends. The results of model (B.2) are shown in Table A.5. The main result, effect of taxes on exploration effort, is similar in size but, as the stacked regression uses less data, has somewhat larger standard errors (Panel A). The effect on production is still small and statistically significant in all the specifications (Panel B). The effect on discoveries is still negative and is almost unchanged (Panel C). The impact on breakeven oil prices is statistically indistinguishable from zero in all specifications (Panel D).

Different company classifications. Table A.6 shows the main results for different company classifications. The main results in Table 1 indexes small companies that operate in three or fewer countries based on their company-segment. We explore whether this assumption causes a bias in the results by exploring two other ways to classify companies. Columns (1)-(4) shows the result when each international company operating in two or more countries has its own unique index i. In this case, we have less statistical power because observations where a company is not operating in two or more countries in a given year are absorbed by company-year fixed-effects. The results are qualitatively robust. In columns (5)-(8) we use a stricter indexing, where all companies are indexed by their company-segment. We have fewer companies in total, resulting in fewer observations and less statistical power than in Table 1. The coefficients, however, are robust when compared columns (1)-(4) or Table 1.

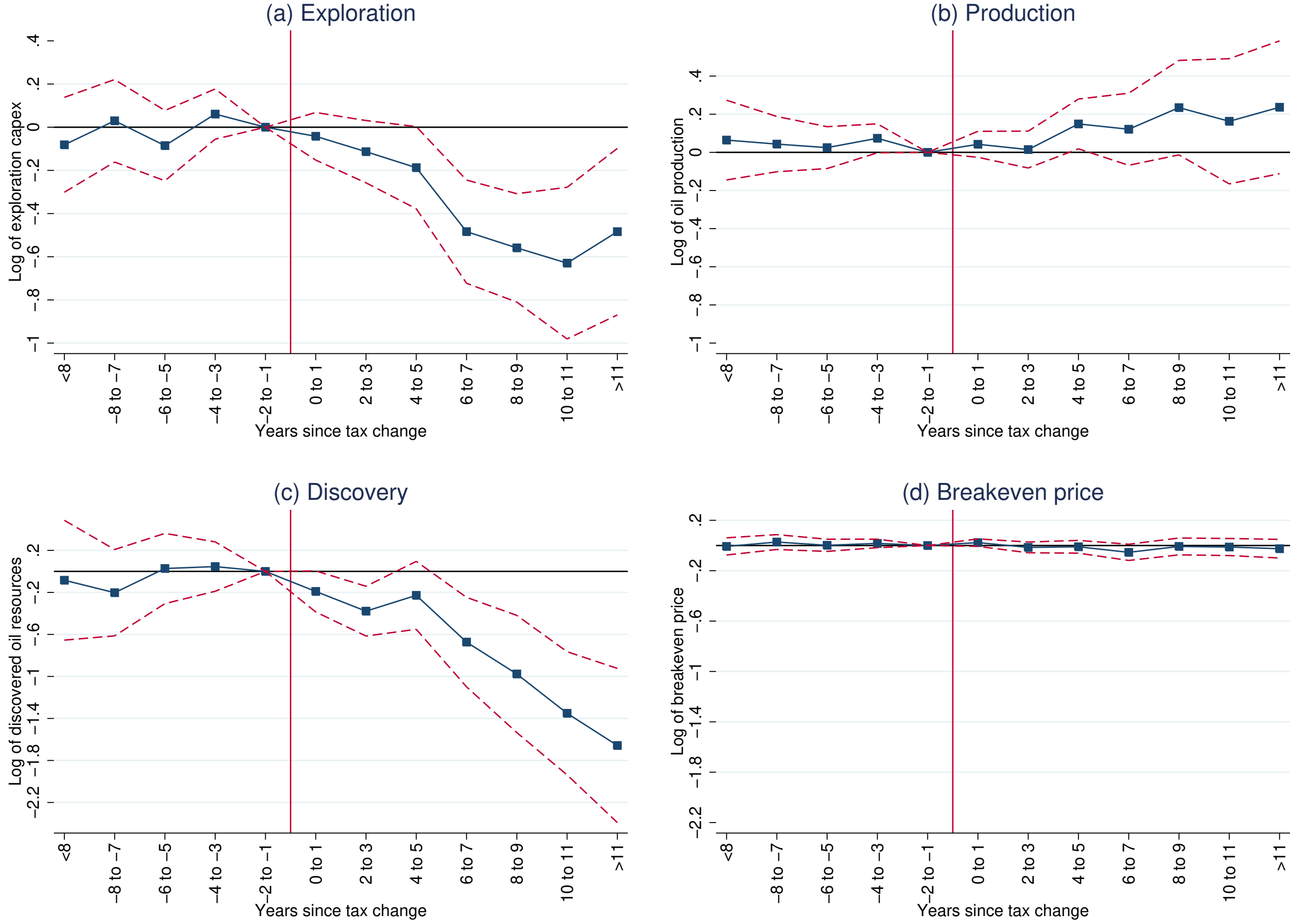


Figure A.5: Estimated impact of profit-tax changes on (a) exploration, (b) production, (c) discoveries and (d) breakeven prices in a stacked regression

Notes: Graphs show coefficients on year-since-royalty-change indicators from regressions corresponding to our stacked-by-event specification (B.2), where royalty increases are given value 1 and decreases given value -1. Connected dots show yearly values, dashed lines show 90% confidence interval. Standard errors are clustered by country and company. Data covers years 2000-2019.

Table A.3: Comparison of price elasticities with other studies

	Elasticity	Variable of interest	Identifying variation	Geographical coverage
Panel A: Short-run elasticity				
This study	0.063 (0.406)	Production	Tax changes	Global
Anderson et al. (2018)	0.001 (0.003)	Production	Price changes	Texas
Rao (2018)	0.371 (.025)	Production	Tax changes	California
Güntner (2014)	0.075	Production	Demand shocks	Non-OPEC
Panel B: Medium-run elasticity				
Anderson et al. (2018)	0.732 (0.201)	Development	Price changes	Texas
Newell et al. (2019)	0.56 (0.33)	Development	Price changes	Texas
Brown et al. (2020)	0.517 (0.139)	Development	Tax changes	United States
Panel C: Long-run elasticity				
This study	1.960 (0.410)	Exploration	Tax changes	Global
Ringlund et al. (2008)	0.99	Exploration and development	Price changes	Non-OPEC
Dahl and Duggan (1998)	1.231	Exploration	Survey article	United States
Mohn and Osmundsen (2008)	0.41 (0.07)	Exploration	Price changes	Norway

Table A.4: Effects of taxes on exploration, production and discoveries, for a balanced sample.

	(1)	(2)	(3)	(4)
Panel A: Impact on exploration				
Royalty rate	-.0199	-.0287	-.0280	-.0307
	(.0094)	(.0086)	(.0089)	(.0086)
Profit tax rate				-.0113
				(.0040)
N	9488	9488	8579	8579
Panel B: Impact on production				
Royalty rate	-.0033	.0001	-.0090	-.0103
	(.0085)	(.0125)	(.0144)	(.0143)
Profit tax rate				-.0051
				(.0041)
N	9488	9488	8579	8579
Panel C: Impact on discoveries				
Royalty rate	-.0392	-.0530	-.0473	-.0460
	(.0125)	(.0165)	(.0234)	(.0247)
Profit tax rate				.0054
				(.0053)
N	9488	9488	8579	8579
Panel D: Impact on breakeven prices				
Royalty rate	.0051	.0047	.0035	.0034
	(.0026)	(.0024)	(.0025)	(.0025)
Profit tax rate				-.0017
				(.0015)
N	9488	9488	8579	8579
Year-indicator FEs	x			
Region-year-indicator FEs		x	x	x
Company-year-indicator FEs			x	x

Notes: This table reports regression coefficients from 16 separate regressions, 4 per panel. The dependent variable was: log of exploration capex in Panel A, log of oil production in Panel B, log of discovered oil resources in Panel C, log of breakeven prices in Panel D. Variable Royalty rate is the production-based tax rate and variable Profit tax rate is the profit-based tax rate relative to the initial year, 2000. Standard errors two-way clustered by firm and tax regime are in parentheses.

Table A.5: Effect of taxation on exploration, production, discoveries and prices, stacked regression

	(1)	(2)	(3)	(4)
Panel A: Impact on exploration				
Royalty rate	-.0269	-.0294	-.0261	-.0270
	(.0079)	(.0092)	(.0095)	(.0087)
Profit tax rate				-.0108
				(.0050)
N	354920	354920	337505	337505
Panel B: Impact on production				
Royalty rate	-.0021	.0006	-.0024	-.0020
	(.0054)	(.0075)	(.0069)	(.0069)
Profit tax rate				.0045
				(.0038)
N	198935	198935	181275	181275
Panel C: Impact on discoveries				
Royalty rate	-.0332	-.0405	-.0423	-.0424
	(.0107)	(.0138)	(.0139)	(.0137)
Profit tax rate				-.0032
				(.0101)
N	161956	161956	137245	137245
Panel D: Impact on breakeven prices				
Royalty rate	-.0016	-.0019	-.0039	-.0032
	(.0058)	(.0056)	(.0060)	(.0049)
Profit tax rate				-.0041
				(.0018)
N	121855	121855	101458	101458
Year-indicator FEs	x			
Region-year-indicator FEs		x	x	x
Company-year-indicator FEs			x	x

Notes: This table reports regression coefficients for the stacked-by-event analysis; see equation (B.2), which includes indicators for every tax-reform-year as shown in the three bottom rows. The table presents 16 separate regressions, 4 per panel. The dependent variable was: log of exploration capex in Panel A, log of oil production in Panel B, log of discovered resources in Panel C, log of breakeven prices in Panel D. Variable Royalty rate is the production-based tax rate and variable Profit tax rate is the profit-based tax rate relative to the initial year, 2000. Standard errors two-way clustered by firm and tax regime are in parentheses.

Table A.6: Main results for different company classifications

	All international companies				Company-segment			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Panel A: Impact on exploration								
Royalty	-.0242	-.0253	-.0252	-.0284	-.0252	-.0286	-.0279	-.0286
	(.0047)	(.0053)	(.0060)	(.0058)	(.0077)	(.0092)	(.0094)	(.0094)
Profit tax				-.0088				-.0031
				(.0039)				(.0046)
N	51935	51935	49307	49307	16058	16058	16051	16051
Panel B: Impact on production								
Royalty	-.0035	-.0021	-.0030	-.0022	-.0013	-.0020	-.0013	-.0018
	(.0057)	(.0082)	(.0062)	(.0059)	(.0055)	(.0073)	(.0075)	(.0079)
Profit tax				.0029				-.0016
				(.0053)				(.0061)
N	28209	28209	25004	25004	10655	10655	10652	10652
Panel C: Impact on discoveries								
Royalty	-.0451	-.0574	-.0457	-.0450	-.0508	-.0665	-.0650	-.0643
	(.0115)	(.0149)	(.0209)	(.0222)	(.0127)	(.0174)	(.0170)	(.0182)
Profit tax				.0042				.0044
				(.0081)				(.0094)
N	17237	17237	14044	14044	7488	7488	7459	7459
Panel D: Impact on breakeven prices								
Royalty	-.0001	-.0005	-.0008	-.0017	-.0012	-.0008	-.0003	-.0008
	(.0049)	(.0048)	(.0059)	(.0052)	(.0063)	(.0061)	(.0058)	(.0055)
Profit tax				-.0042				-.0030
				(.0020)				(.0025)
N	16200	16200	13089	13089	7187	7187	7158	7158
Year FEs	x				x			
Region-year FEs		x	x	x		x	x	x
Company-year FEs			x	x			x	x

Notes: This table reports regression coefficients from 32 separate regressions, 8 per panel. Columns (1)-(4) define companies such that all companies that are active in two or three countries are treated as independent companies and companies that only drill in one country are indexed by their company-segment. Columns (5)-(8) define companies by their company-segment: E&P, Exploration, INOC, Independent, Industrial, Integrated, Investor, Major, NOC, Operating, Supplier or Other/Unspecific. The dependent variable was: log of exploration capex in Panel A, log of oil production in Panel B, log of discovered resources in Panel C, log of breakeven prices in Panel D. Variable Royalty rate is the production-based tax rate and variable Profit tax rate is the profit-based tax rate relative to the initial year, 2000. Standard errors two-way clustered by firm and tax regime are in parentheses.

C Quantification of distributional impacts

Our quantification takes oil demand curves as given, characterized by the range of demand elasticities documented in the literature. We then use our estimates for the oil tax effects and combine these with detailed information from Rystad Energy on essentially all oil fields, to derive and shift the oil supply curve. Note that our analysis focuses on supply and demand associated with counterfactual annual *new* discoveries and, hence, the demand curve is the residual of total oil demand, net of the part that is covered by existing producing oil fields. We assume that the expected annual flow of new discoveries is equal to the expected expansion of annual production capacity.

For each field in the oil supply curve, we observe the size (discovered oil resources) and the associated post-tax breakeven price (the oil price at which the field becomes profitable). Using information on the taxes levied on each field allows us to calculate their respective pre-tax breakeven prices. Those values depict the oil price at which development of an already discovered field would have become privately profitable without taxes, which may be interpreted as the field's privately accrued extraction costs.

Figure A.6 conceptually illustrates how we deconstruct the effects of tax changes on oil supply into a development effect and an exploration effect. In Panel (a), light gray bars are the pre-tax breakeven prices, dark gray areas are the production-based tax components, and the width denotes the size of each discovered field. When a discovered field is treated with a tax reform while others are not, this changes the field's post-tax extraction costs. As a result, the order of fields in the supply curve may change. We dub the sum of these effects as the *development effect* of a tax reform (Panel (a)). In addition comes the *exploration effect* of a tax reform (Panel (b)), which follows from our discovery estimate: An increase in the tax rate decreases firms' exploration efforts and contracts the volume of new discoveries according to our estimated semi-elasticity on discoveries. Regarding extraction costs, our empirical estimates suggest that tax changes on average do not affect pre-tax extraction costs. Hence, we assume that the expansion resulting from a tax decrease is as if the size of each existing discovered field increases, as indicated by the dark grey shifts in Panel (b). Finally, the boxes at the bottom of Figure A6 illustrate that embedded in the exploration effects, there will also be an increase in firms' exploration costs (associated with the new discoveries).

Figure A.7 illustrates how these two effects play out when simulating annual new discoveries across two different scenarios: in Panel (A), we remove all existing taxes; in Panel (B), we assume a uniform, global climate royalty surcharge of 30%.

When analyzing the oil market equilibrium and distributional effects, we rely on a definition of the equilibrium price of oil. In our quantification, this market price of oil is defined by the

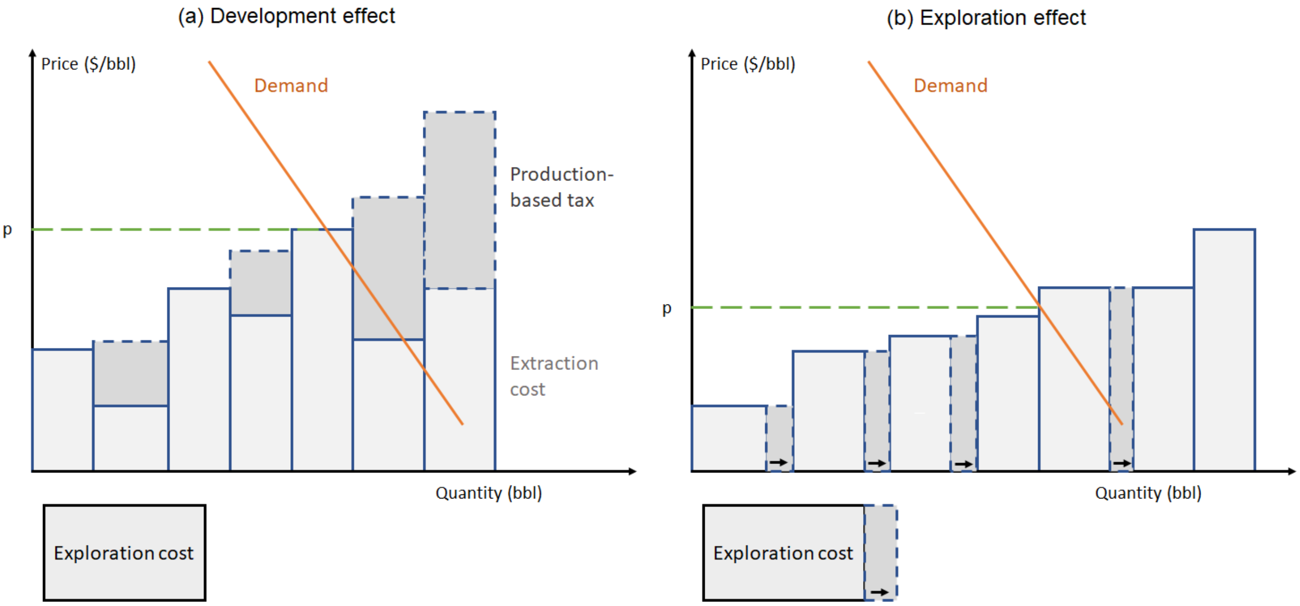


Figure A.6: Illustration of our quantification: Long-term supply and demand.

intersection between expected annual flows of demand and supply, which in effect is determined in our marginal market of new discoveries and residual demand.

In our analysis of the distributional incidence of a globally uniform climate royalty surcharge, as well as the effects on global CO_2 emissions, we start by defining consumer surplus (CS) in the marginal market as the area between the residual demand curve and the oil price (in Figure A.7). Producer surplus (PS) is defined as the area between the oil price and post-tax extraction costs (the supply curve in the figure), minus the sum of profit-based taxes and exploration costs. Total oil tax revenue is then the sum of production-based and profit-based taxes.

In addition to the annual new discoveries shown in Figure A.7 (with an initial equilibrium at around 10 billion barrels per year/27 million barrels per day),[20] the market also includes production from existing deposits (approximately 35 billion barrels per year/96 million barrels per day; not shown in the figure). Based on our estimation results on production effects in Section 4, we assume that tax reforms do not change production from existing fields. However, the already producing fields matter because price changes transfer rents across consumers, producers and governments also in that part of the market. For these fields we define change in CS as the change in oil price times their total production level. An increase in CS results in an equivalent decrease in PS and tax revenue. Finally, CO_2 emissions follows directly from production. We always use a CO_2 content of $0.43tCO_2/bbl$ (EPA, 2021).

Figure 3 simulates the effects of different levels of the climate royalty surcharge on CS, PS,

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[20] According to Rystad energy and QZ.com, annual global discoveries of gas and oil deposits varied between 5 and 20 billion barrels in the period 2015 and 2021.

total government tax revenue, and CO_2 emissions, respectively. In practice, we run a loop where the model is solved for a uniform global royalty rate from 0%,1%...,40%. Each loop creates a new market equilibrium such as the one shown in Figure A.7 and solves for a new equilibrium oil price, production, emissions, consumer surplus, producer surplus and tax revenue. All calculations are carried out numerically in R.

Finally, note that we limit our quantification to accounting for the first-order effect of a tax reform on price and quantity. In reality, one may expect an additional second-order effect whereby firms respond to the resulting price change. Capturing this second-order effect is, however, not trivial. Most importantly, it requires information on how and when firms may be expected to respond to the (expected) change in the equilibrium price. While one might speculate that firms' responses to price changes may be comparable to our estimates for how they respond to tax changes, one could also argue that firms' expectations over taxes and prices are different (e.g., depending on the statistical properties of prices relative to taxes). As we lack reliable information on relevant firm-responses to price changes, we abstract from the second-order effect. Yet, note that (i) the second-order effect (on price and quantity) will go in the opposite direction of the first-order effect (gradually dampening the first-order effect) and (ii) the second-order effect will be smaller than the first-order effect. The intuition for the latter is that, at any given price, a higher tax makes exploration and discoveries less profitable, decreasing the quantity and increasing the price (relative to the pre-tax levels). Hence, the equilibrium level of discoveries can never converge back to the that given by the initial equilibrium price. In addition, note also that (iii) the magnitude of the second-order effect will generally depend on the demand elasticity: a lower demand elasticity will give a higher post tax-reform price, which will result in a larger shift in the supply curve due to the second-order effect.

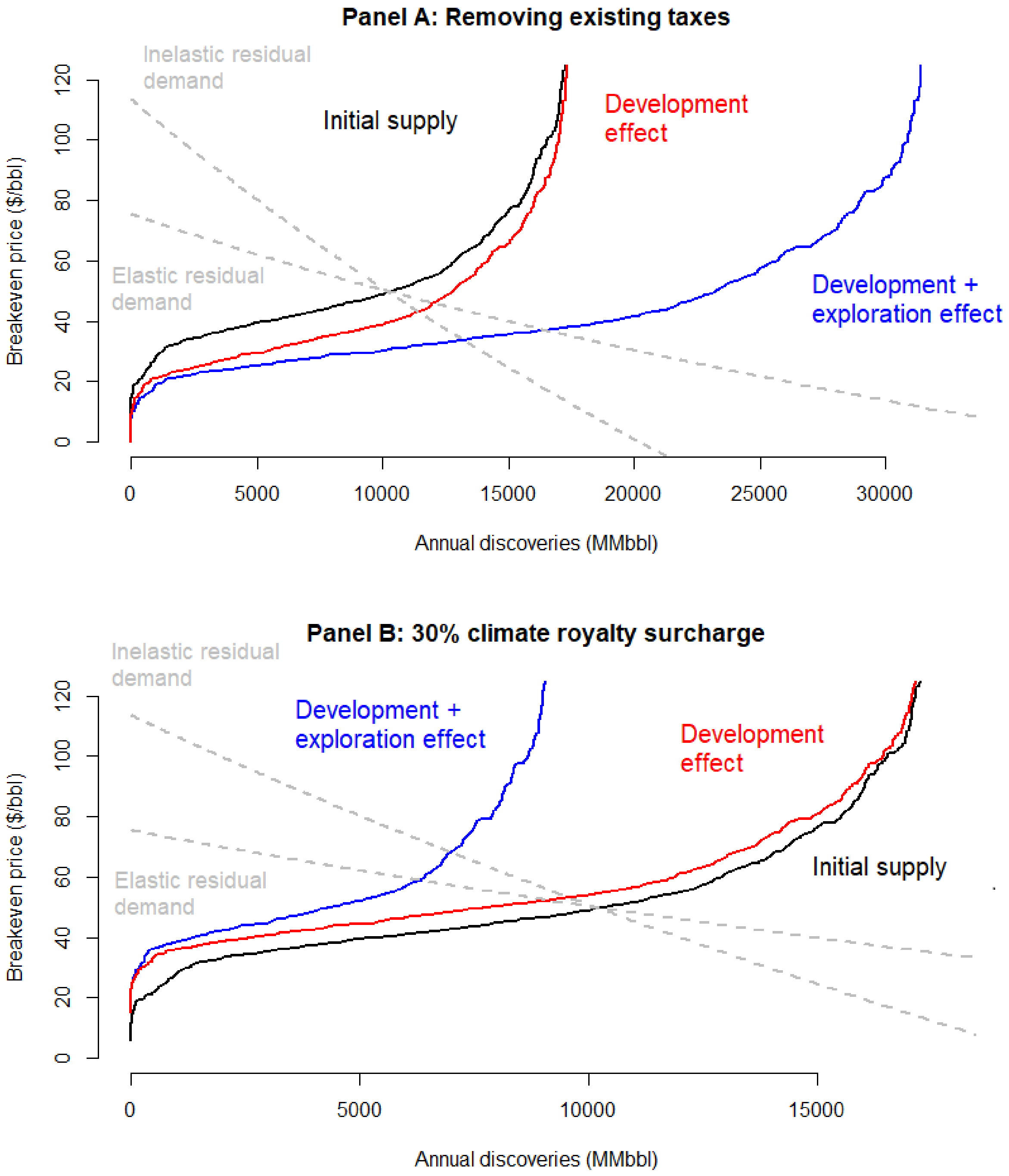

Figure A.7: Two illustrations of the long-term oil market: (a) existing production-based taxes are removed and (b) implementation of a minimum 30% climate royalty surcharge

Notes: In (a) the black line denotes the original oil supply curve, the red line is the post tax change oil supply (development effect) the blue line the new supply curve with exploration when all production-based are set to zero (exploration effect). The effect is calculated based on our preferred estimate in Panel B of Table 1. In (b) The black line denotes the original supply, red line the post-tax supply (development effect) and the blue line is the new supply when all countries set a 30% climate royalty surcharge (exploration effect).

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