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FINDERS, KEEPERS?

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ABSTRACT

Natural resource taxation and investment often exhibit cyclical behavior, associated with shifts in political power. Why do finders get to keep more of their discoveries in some periods than others? We show such cycles result from the inability of governments to commit to future taxes and firms to commit to credibly exiting a country for good. In a cycle, large resource revenues induce a high tax which lowers exploration investment and thereby future findings, which in turn leads governments to reduce tax rates again. Tax oscillations are more pronounced for resources which take longer to develop, or following temporary resource price shocks. Our tractable model provides the first rational-expectations explanation of resource tax cycles under endogenous exploration investment and threat of expropriation. We document evidence of cyclical behavior in several countries with both strong and weak institutions, and provide detailed case studies of two Latin American countries.

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1 Introduction

Taxation of natural resources is a dominant source of government revenue in many countries. More than twenty resource-rich countries obtain three-quarters of their export revenues or half of their government revenues from oil and gas related activities (Venables, 2016). The quest for obtaining the associated profits is consequently often the single most important public policy issue in these countries (Boadway and Keen, 2010; Hogan and Sturzenegger, 2010). These matters are often sufficiently salient to shift political sentiments in the population, to drive political platforms, to determine election outcomes, and to even cause coups or civil wars (Manzano and Monaldi, 2008; Venables, 2016).

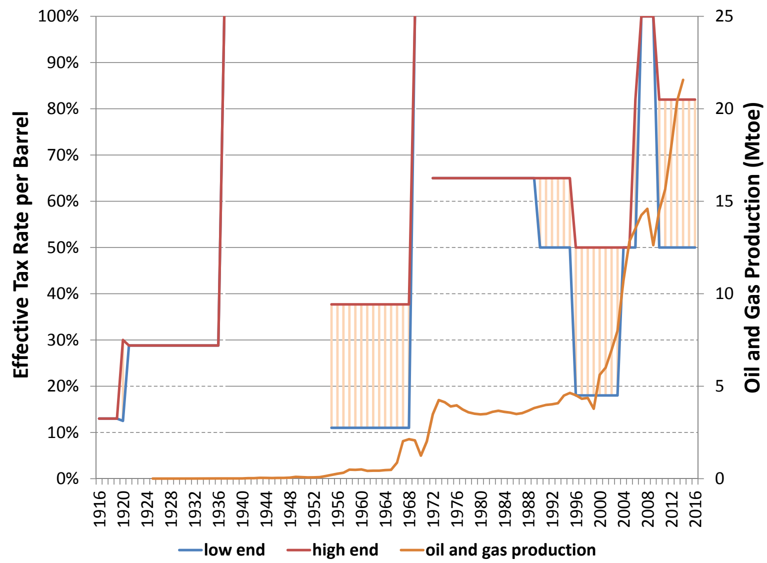
This paper aims to explain a commonly observed feature of resource markets: cyclicality in resource taxation. These cycles take the form of reoccurring policy shifts from tax breaks to tax hikes (or expropriations) and back to tax breaks, and are naturally accompanied by cyclicality in new investments. In an extreme, yet common, consequence these cycles are also associated with shifts in political power. To explain such behavior, we extend the resource-taxation literature by developing the first model with fully forward-looking agents and limited ability of governments to commit to tax rates and firms to commit to exiting. Thus, apart from explaining the empirically prevalent taxation cycles, our model also fills an important gap in the resource-economics literature.

A clear illustration of recurring resource-taxation cycles is given by the history of oil and other hydrocarbons in Bolivia. Figure 1 (either panel) plots Bolivia's effective net resource-income tax rate over the past century. Periods of low tax rates that stimulate investment and production are followed by extremely high taxes and expropriations, which subsequently required the government to offer a favorable fiscal regime to lure back investors. Bolivia has experienced three such cycles, with expropriations in 1937 (Standard Oil), 1969 (Gulf Oil) and 2004-2009 (several foreign companies) and low tax rates in between. Other examples abound. Venezuela expropriated its foreign investors in 1975 and 2007, in both cases following decades of relatively favorable fiscal terms. Israel offered a low tax rate of 28% to gas exploration firms before the discovery of the large Leviathan gas field in 2010. In anticipation of surging production levels, the Israeli government increased taxes to 42% in 2014 (The Jerusalem Post, 2014). This led to investment decreases (Sachs and Boersma, 2015) and then, very recently, to the government promising new, favorable conditions to gas companies (Times of Israel, 2015). The conflict between a government's desire to tax resources yet not to scare away investors has also been apparent in the British government's to-ing and fro-ing over the taxation of North Sea oil firms (Financial Times, 2014).[1] Many other countries such as Argentina, Ecuador, Iran, Uganda and Yemen have gone through similar cycles (Hajzler, 2012). Section 2 describes Bolivia's and Venezuela's history of taxation cycles in more detail.

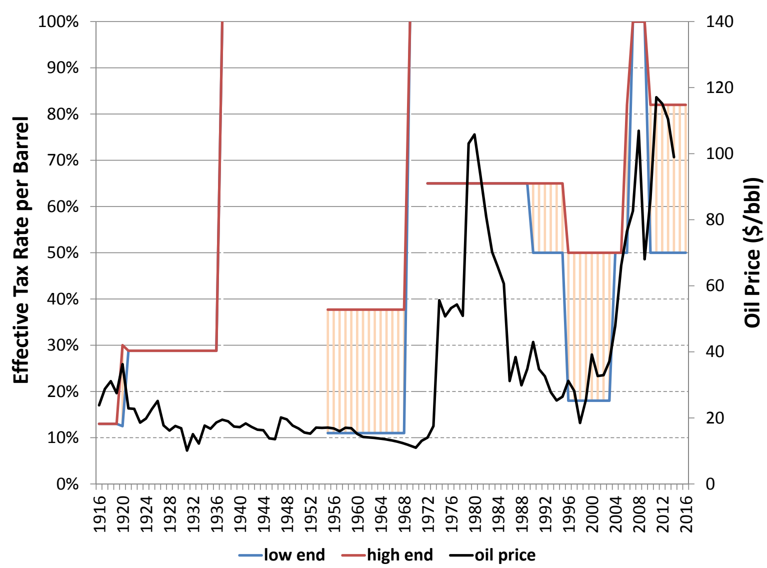
To explain such cycles we develop a rich yet tractable model with four key assumptions.

[1] The Financial Times reported that "[t]he UK chancellor in his Autumn Statement went some way towards meeting industry calls to reverse his tax raid on North Sea oil and gas producers in 2011 by cutting the supplementary charge on profits from 32 to 30 percent, with a hint of more to come."

Figure 1: Tax Cycles in Bolivia and (Panel a) Oil and Gas Production or (Panel b) Oil Price



(a) Relationship Between Effective Tax Rate and Oil and Gas Production



(b) Relationship Between Effective Tax Rate and Oil Price

Notes: Tax rate refers to the effective net resource-income tax rate per barrel of oil equivalent. Sources: Jemio (2008), Manzano and Monaldi (2008), WoodMackenzie (2012), Klein and Peres-Cajías (2014), BP (2015), International Energy Agency (2015). Years in which assets are expropriated are coded as a 100% tax rate (though effectively tax rates could be *higher than* 100% in those years). Gaps in tax rates represent periods in which no foreign firms were producing. In some years, tax rates are plotted as a range instead of a single value, as different rates applied to different projects. Low end and high end ranges indicate the minimum and maximum tax rates (when available), which can differ depending on project characteristics.

The first is that governments cannot commit to tax rates for more than a few years.[2] This realistic assumption can be motivated by political-economy considerations (Persson and Tabellini, 1994) or by basic principles of law. As William Blackstone commented on English law: "Statutes against the power of subsequent Parliaments are not binding" (Blackstone, 1765).[3] The second assumption is that firms cannot commit to leaving a country for good following a change in the agreed fiscal terms. This describes large oil majors such as ConocoPhillips and Exxon who, for instance, reinvested in Venezuela after being expropriated in the 1970s. It also describes situations where, if one firm leaves, another firm takes its place as observed in, for instance, Bolivia in the 1950s. The third assumption is that mines are long-lived, relative to the government's period of commitment. It usually takes several decades from the time a firm starts exploring for resources until it makes a successful discovery, starts a full-scale mining operation, and finally exhausts the resource. This has the implication that old mines, discovered earlier, exist in parallel with newer mines. The fourth assumption is that governments cannot, or do not, differentiate tax rates between different mine vintages that exist in parallel (or, at least, not perfectly). While certain governments have resorted to some form of differentiated taxes, this seems to be an exception rather than the rule.[4]

These assumptions imply that each government faces a trade-off: high taxes maximize profits from old mines but harm new investments and hence profits from new mines. Since mines are long-lived, firms naturally choose investment based both on current and expected future taxes. As a result, a rational government that is unable to commit, when choosing its current tax rate, has to consider the impact of today's tax rate on all future taxes and on all future investment decisions by the firms.

The model predicts that, following an earlier large discovery, the government will set a high tax to ensure getting a large share of the bonanza. This in turn will inhibit new investments which lowers the future tax base. Hence, in the next period the government refocuses to encouraging new investment and therefore lowers the tax. These high new investments imply a large inelastic tax base in the period after and hence an increase in the tax and so on.[5] The model thus predicts cycles in resource taxation and investment in line with the observations described earlier. While not modeled explicitly, the shifts in tax

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[2] If governments could fully commit to future tax rates, the problem has an elegant theoretical solution: the first-best outcome would be achieved by auctioning off the exploration rights. This would induce firms to pay the total expected profits and explore efficiently thereafter. Limited commitment is a likely reason for the rare occurrence of pure auction systems for exploration and extraction rights.

[3] In the context of natural resources, this principle has been applied in a recent ruling by the Supreme Court of Israel, denying the government the right to tie its own hands with respect to future tax changes for gas companies. The motivation was that a commitment "that binds the government to [...] no changes in legislation and opposing legislative initiatives for 10 years – cannot stand"(Reuters Africa, 2016).

[4] Cycles remain even under some form of tax differentiation, but it is important that governments cannot *perfectly* differentiate between old and new mines. In the extreme case of full differentiation, governments would always tax existing production at 100% while taxing new mines at a lower rate. The result is an unattractive equilibrium with limited investment. Perfect tax differentiation is rare if non-existent, potentially due to the reputation cost of permanently sky-high taxes on older mines and other costs of expropriation such as international arbitration.

[5] An inelastic tax base is consistent with recent evidence that oil production from existing wells is almost completely unresponsive to oil price shocks (and, thus, tax rates) (Anderson, Kellogg and Salant, 2014).

policy can be expected to take the form of either incumbent politicians changing their policy or by new politicians taking over. That is, political sentiments in society change along with the cycles.[6]

The model yields a number of additional predictions. A backloaded mining profile – i.e., most of the mining profits coming with a lag – means firms mainly care about the tax tomorrow. Hence, mining investment is insensitive to today's taxes, implying they are set high. This of course happens in all periods, which implies a high tax level and limited investment throughout. This scenario would apply to projects with large lead times, such as drilling for oil and gas at deep offshore fields or in the Arctic.

Further, both high production and high spot prices are predicted to increase the tax rate as the government then focuses on getting a large share of the extraordinary resource profits. Both these factors can explain expropriations in practice. Take the Bolivian example (Figure 1, panel b). The expropriations in 1937 and 1969 did not coincide with high prices. Conversely, the price spike in the early 1980s did *not* lead to expropriations. The resource nationalism in the early 2000s started during a period of sharply increasing production before the oil price spike, but was later fueled by increasing oil prices as well. In Venezuela, the high oil prices seem to have been the immediate cause for the wave of expropriations in the mid 2000s. Our model incorporates both channels for tax increases and does not rely on high prices as their sole driver.

This paper is by no means the first to analyze resource taxation (for overviews see Lund, 2009; Boadway and Keen, 2010) but, as stated above, we are the first to present a model of an endogenous "natural resources trap" (as Hogan and Sturzenegger (2010) dub the difficult dynamic hold-up problem associated with resource investment) with fully rational, forward-looking behavior and limited commitment on part of governments and firms. The papers most related to ours include a number of important contributions analyzing dynamic commitment problems such as Thomas and Worrall (1994) and Bohn and Deacon (2000). These and other papers yield important insights about optimal resource contracts and taxation when governments cannot commit. We build on this literature by relaxing two unsatisfactory features of existing models: exogenous expropriations and the assumption that individual firms can effectively punish an expropriating host government (e.g., by the threat of autarky). Thereby we take the standard approach in dynamic public finance and macroeconomics.[7]

[6] As we are agnostic as to the uses of government revenue, the model is consistent with tax collection for corrupt purposes. Besides stealing "official" tax revenues, corrupt politicians may request bribes and other illegal payments. Such side payments are unobserved, but likely to be very small compared to transfers through official taxes or expropriations, and unlikely to interact with the official tax rates and the main channels for cycling in our model (high production and unexpected, temporary price increases).

[7] Our setup is similar to Klein, Krusell and Rios-Rull (2008) who describe the lack of commitment as a "game between successive governments." See also, for instance, Benhabib and Rustichini (1997) and Ortigueira (2006) for similar setups. Since the seminal paper of Kydland and Prescott (1977), a large part of the dynamic public finance literature has been analyzing various forms of commitment problems (e.g., Persson and Tabellini, 1994; Reis, 2013). The main approach in this literature is to focus on capital as a generator of output. Since resource extraction creates few jobs and is, in many countries, performed by non-domestically owned firms, we treat the resource sector primarily as a source of government income implying a dynamic Laffer trade-off under limited commitment. Related to our focus on taxation cycles, Hassler, Krusell, Storesletten and Zilibotti (2008) analyze circumstances under which oscillatory human-

Many resource-taxation models study the effect of expropriation risk on private investment.[8] For example, Bohn and Deacon (2000) and Wernerfelt and Zeckhauser (2010) analyze how the risk of expropriation affects the speed of extraction and optimal contracts. However, being mainly interested in the reaction of firms, the risk of expropriation in their models is exogenous. Aghion and Quesada (2010), Engel and Fischer (2010) and Rigobon (2010) also assume exogenous expropriations. In contrast, our paper explicitly models the interaction between successive governments that, like firms, hold rational expectations. We therefore endogenize the tax (in the extreme case, expropriation) and the reactions of future governments. We also extend earlier analyses to include different mining profiles and price changes, factors obviously important for resource markets.

Endogenous expropriation has been considered in the seminal paper by Thomas and Worrall (1994), which analyzes foreign direct investment in a setting where a single firm and the government are forward-looking but unable to commit even in the short run. They consider how an incentive-compatible contract in a repeated game between a host government and a single firm would be structured, with reneging deterred by trigger-strategy punishments. In their model, the investment rate ratchets up over time until a steady state is reached. Thus, in equilibrium, investment cycles are not observed while taxes, too, tend to increase. Hence, the model cannot explain the presence of repeated cycles in taxation and investment. The same problem arises if contracts are sustained by the threat of autarky in the case of permanent withdrawal by firms. This applies to Stroebel and van Benthem (2013), in which expropriations occur with positive probability after which the country remains in autarky forever. In both papers, the punishment strategies imply there is only one resource firm which the host country can invite in. We dispense with contracts, considering instead a situation with minimal (one-period) commitment by the government and with many resource firms unable to credibly exit the market for good. This is a better description of the investment conditions and firm behavior in many politically unstable, resource-holding countries.

The paper proceeds as follows. Section 2 documents repeated cycles of taxes and investment in Bolivia and Venezuela that are consistent with our model's dynamics. In Section 3, we present the basic model along with comparative statics with respect to the mining profile, resource price and the firms' discount rate. Here, we assume the government does not care about future revenues. Section 4 extends the model to a case in which the government cares about tax revenues in the more distant future, showing tax cycles appear here too. In Section 5, we illustrate how stochastic resource discoveries initiate new cycles of taxation. Section 6 concludes.

capital taxes are optimal from a normative perspective. Our analysis is positive and the tax cycles in our setting are not optimal.

[8]Other papers focus on the question of how to make resource taxes neutral (e.g., Campbell and Lindner, 1985; Fane, 1987), which is less related to our work. Yet other papers study optimal contracts (e.g., Baldursson and Von der Fehr, 2015) and optimal taxation (e.g., Daubanes and Lasserre, 2011).

2 Episodes of repeated tax and investment cycles

We now describe in more detail Bolivia's and Venezuela's history of long-run cycles in taxation and investment. These countries' dealings with foreign resource firms provide instructive case studies and motivation for our model. We emphasize that many other countries – such as Argentina, Ecuador, Israel, Iran, Uganda and Yemen – have gone through similar cycles (Hajzler, 2012).

2.1 Bolivia

Low taxes spur initial investments. Bolivia opened up its hydrocarbons sector to foreign investors in 1916 and the first foreign oil company (Standard Oil; a predecessor of ExxonMobil) entered in 1921. In that year, the Organic Law on Petroleum set the fiscal terms for the decades to come, mainly consisting of an 11% royalty plus an obligation to return 20 percent of the licensed area back to the state once production began (Jemio, 2008).

Expropriation and low subsequent investment. The relationship between the government and Standard Oil turned sour around the 1932-1935 Chaco War, in which the oil-rich Gran Chaco region was claimed by both Bolivia and Paraguay. Standard Oil started shutting down equipment and moving it out of the country and was generally seen by the public as betraying the Bolivian government. After the war ended, the David Toro government created state-owned company Yacimientos Petrolíferos Fiscales Bolivianos (YPFB) in late 1936 and expropriated Standard Oil's assets in 1937 (Klein and Peres-Cajías, 2014).[9] This marked the beginning of almost two decades without foreign oil investment; the legislation provided that YPFB could be associated with foreign business, but either for fear of expropriation or lack of interest, no foreign company invested.

Low taxes, high investment. Production by YPFB grew in the 1940s and early 1950s, but Bolivia concluded that it could not provide the capital investment needed for a significant expansion of the oil industry. The government therefore offered a favorable fiscal regime to foreign investors (the "New Petroleum Code" of 1955). Standard Oil did not return, but Gulf Oil seized the opportunity. As a result, production grew fast, especially in the mid and late 1960s. Revenues grew fast despite falling oil prices.

Resource nationalism: Expropriation and low subsequent investment. This sparked another episode of resource nationalism. Supported by popular resentment against Gulf Oil's increasing profits, the military government of general Alfredo Ovando Candía expropriated the company in 1969 and transferred its properties to YPFB (Peres-Cajías, 2015). Oil production fell drastically right after the expropriation of Gulf Oil.

Low taxes, high investment. Soon afterwards, Bolivia once again realized the need for stable investment conditions to boost production, especially since natural gas production and exports to Argentina were about to take off. Decree Law No. 10170 provided stable

[9] Neither high production nor high oil prices characterize this expropriation. In fact, Standard Oil had not been producing much due to the chaos surrounding the Chaco War, so when YPFB took over it could increase production without much investment.

fiscal terms that were gradually made more favorable over a period of more than three decades. Bolivia resisted the temptation to expropriate when oil prices soared in the mid and late 1970s. In 1990, the government reduced the tax rates for certain fields somewhat in a further effort to attract private investment. When oil and gas production stagnated and even started to decline in the mid 1990s, the Hydrocarbon Tax Law of 1996 substantially reduced the fiscal take for new fields. In 1996-1997, president Gonzalo Sánchez de Losada even privatized YPFB. All this led to a successful wave of foreign investment in the natural gas sector. International oil and gas companies such as BG Group, BP, Petrobras, Repsol and Total entered the country (Valera, 2007).

Resource nationalism: Tax increases and low subsequent investment. Resource nationalism started yet again by the early 2000s. Even before oil and gas prices were on the rise in the mid 2000s, there was growing public discontent about the profits made by foreign resource firms as their production had increased rapidly. President Sánchez de Losada had to resign during the Bolivian gas conflict in 2003, in which the protesters demanded full nationalization of the hydrocarbons sector. His successor, president Carlos Mesa, held a national referendum – which passed in 2004 – to repeal the existing hydrocarbon law and to increase tax rates on oil and gas companies.[10] This ended the significant wave of foreign investment.

As Manzano and Monaldi (2008) put it, private investors in Bolivia and other Latin American oil producing countries were "partially the victims of their own success". Fifteen years of large private investments had resulted in new resource discoveries which, from the year 2000 onwards, translated to a strong growth in production. This created strong incentives to increase government take, as illustrated by the gas conflict in 2003 and the referendum in 2004. In 2005, the referendum was signed into law as the new Hydrocarbon Law No. 3058 which revoked the tax breaks from 1996. The 2005 law also established state ownership of oil and gas at the wellhead and made it mandatory for operators with existing contracts to transfer to the new terms (WoodMackenzie, 2012).

This more punitive taxation system still did not satisfy many people who believed that full nationalization was preferable. Following protests in La Paz in May 2005, president Mesa was forced to resign. The sharply increasing gas production had created strong incentives for newly elected president Evo Morales to increase taxes further even at constant oil and gas prices, but the resource price increases of the mid 2000s gave him the perfect opportunity to increase taxes to very high levels in response to popular demand. In 2006, tax rates for some fields increased to as much as 82%. Morales then nationalized certain foreign assets in 2007 as per his election pledge.

Lowering of taxes to spur investment. As Morales realized that Bolivia needed three billion dollars in investment to meet its gas export obligations to Argentina and

[10]In this case, the changes in the tax rates were forced on the government by political unrest and public pressure. In other cases, a government or president can independently initiate fiscal changes, either upon (re-)election or in the middle of an existing term. These various channels are consistent with our model, which does not need to explicitly specify the exact conditions under which a government can change the rules of the game.

Brazil, the government quickly softened investment conditions after the nationalizations. In 2010, fiscal terms mostly reverted to those in the 2005 Hydrocarbon Law. The government started offering tax breaks as it feared that hydrocarbon production would stall. By June 2011, fifteen foreign companies had signed contracts for oil and gas exploration; not a single company pulled out of Bolivia this time (Chávez, 2012).

The Bolivian history illustrates a sequence of long-run cycles in taxation and investment, with expropriations in 1937, 1969 and 2004-2009, and low tax rates in between, in line with our model predictions. It also illustrates how production levels are an important driver of cycles, in addition to resource prices.

2.2 Venezuela

Low taxes and a stable tax regime spur initial investment. Oil was first discovered in Venezuela in 1878, but the first well was not drilled until 1912. Royal Dutch Shell and Standard Oil soon became major oil producers as Venezuela became the second-largest oil producing country in the world. Oil made up more than 90 percent of exports by 1935 (Venezuela Analysis, 2003). The First Petroleum Law went into effect in 1922. When production grew between 1922 and 1943, the government realized the need for a stable long-term investment climate. In 1943, Venezuela passed the Hydrocarbons Law, which aimed to ensure that foreign companies could not make greater profits from oil than they paid to the Venezuelan state yet also allowed the world's largest oil companies access to Venezuela's vast reserves at reasonable tax rates for the decades to come (Figure 2, either panel). This created stable investment conditions that firmly established the industry and allowed the oil sector to expand rapidly. Between 1944 and 1958, production more than tripled and the annual growth rate of the net capital stock of the oil industry was on average 14.3% (Monaldi, 2001) (Figure 2, panel a).

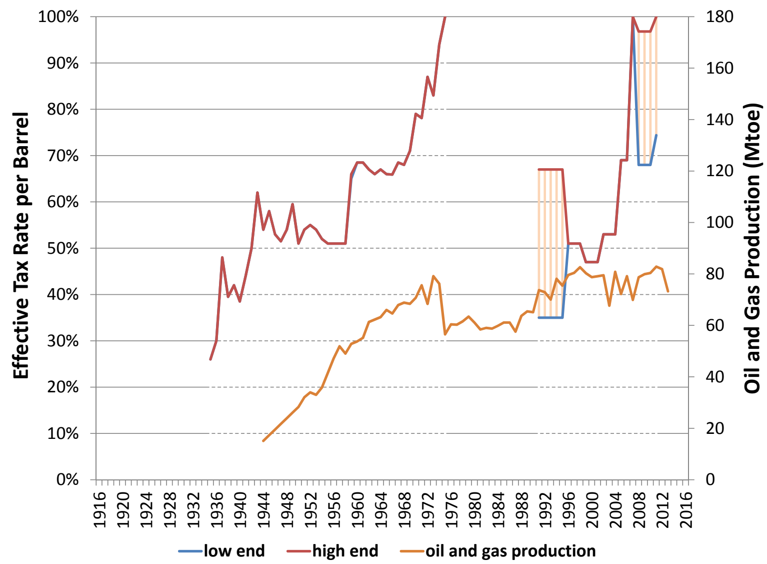
Resource nationalism, tax increases and subsequent low investment. This spectacular growth in oil production tempted the government to capture a larger share of the profits. Taxes increased dramatically in the period 1959-1972.[11] As a result of the increased taxes, oil investment declined in the period 1959-1976, but oil production continued to rise until the early 1970s. It then fell abruptly, though with a significant lag to the reduced investment levels.[12]

In 1973, the oil embargo in the Middle East led to a dramatic increase in oil prices. In 1974, the newly elected president, Carlos Andrés Perez, used this to promise the population that Venezuela would become a first-world country in just a couple of years. He started nationalizing the oil industry, a process that finished with the creation of Petroleos de

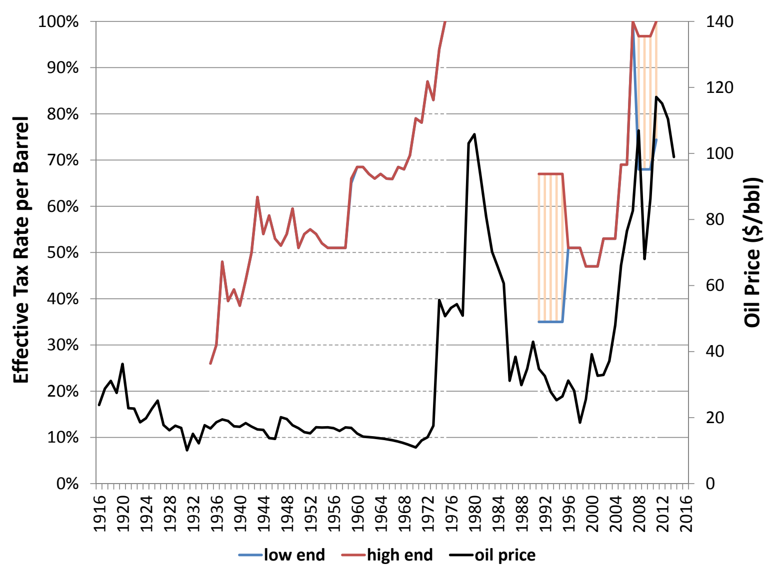
[11] In 1959, the government share rose from 51% to 65%; a radical break with the 50-50 rule from the 1943 Hydrocarbons Law. In the late 1960s, oil taxes increased further to levels around 71% in 1969. Yet another law increased tax rates to over 78% in 1970. By 1972, tax rates had creeped up to levels around as high as 90%. Up to that point, oil prices had been low and decreasing from $16 per barrel in 1943 to $14 per barrel in 1972. In an attempt to raise global oil prices, Venezuela was instrumental in the formation of the Organization of Petroleum Exporting Countries (OPEC) in 1960.

[12] This is again consistent with Anderson et al. (2014) who find that investment, not production, is the main margin of adjustment to changing oil prices or tax rates.

Figure 2: Tax Cycles in Venezuela and (Panel a) Oil and Gas Production or (Panel b) Oil Price



(a) Relationship Between Effective Tax Rate and Oil and Gas Production



(b) Relationship Between Effective Tax Rate and Oil Price

Notes: Tax rate refers to the effective net resource-income tax rate per barrel of oil equivalent. Sources: Monaldi (2001), Manzano and Monaldi (2008), WoodMackenzie (2012), BP (2015), International Energy Agency (2015). Years in which assets are expropriated are coded as a 100% tax rate (though effectively tax rates could be *higher than* 100% in those years). Gaps in tax rates represent periods in which no foreign firms were producing. Low end and high end ranges indicate the minimum and maximum tax rates (when available), which can differ depending on project characteristics.

Venezuela (PDVSA) in 1976 (Venezuela Analysis, 2003). In the process, Venezuela paid Conoco, Exxon, Gulf Oil, Mobil and Shell only 20 percent of the market value of their assets (Wirth, 2001). Conoco left the country, but other firms stayed and signed contracts for training local staff and technological support.

Tax breaks to spur foreign investment. After the expropriation, PDVSA controlled all oil production. PDVSA increased investments dramatically, taking advantage of the prevailing high oil prices. Despite the fast growth, the government realized in the 1980s that foreign investment and expertise was needed to develop the massive heavy oil resources in the Orinoco Belt. Against that background, Venezuela opened up the oil sector to foreign investment again in 1990. Foreign investors were offered tax rates well below the rates of around 80% that PDVSA had been paying during the late 1970s and early 1980s. By 1996, four joint ventures had entered Venezuela and Conoco came back after leaving the country following the expropriations of 1976.[13] By the mid 1990s, private investment had increased substantially and Venezuela was top on the list for foreign investment in petroleum exploration and production (Manzano and Monaldi, 2008; Hajzler, 2012).

Resource nationalism, nationalization and production decreases. In the early 2000s, resource nationalism was on the rise again. When Hugo Chávez first came to power in 1998, he did not announce any plans for PDVSA. But in 2001, Chávez introduced a new Hydrocarbons Law that increased royalties and forced private investors to sign agreements in which they could only operate in joint ventures with at least 51% PDVSA ownership. Also, when his initial popular support had faded by 2002, Chávez responded to public protests by announcing a re-nationalization of the oil industry. He took control over PDVSA, which was to be managed "by the people and for the people" (Energy Tribune, 2007). In the resulting chaos, oil production fell and Venezuela had to renege on oil deliveries.

While this resource nationalism started in a period of high production and sunk investment (and low oil prices), the sharp increase in oil prices in the mid 2000s added to the government's desire to impose higher taxes and more restrictions on foreign investors. By 2007 the government had nationalized the oil industry, taking a majority control of all privately operated projects without providing market compensation. ConocoPhillips and ExxonMobil subsequently decided to abandon their assets in the Orinoco basin and exit the country. BP, Chevron, Statoil and Total accepted that PDVSA increased its share from 40% to 78% (Guriev, Kolotilin and Sonin, 2011; Hajzler, 2012). Tax rates have remained high since then. In 2008, Venezuela imposed a first windfall tax on incremental revenues when the oil price exceeds $70 per barrel. In 2011, the government increased this tax further and introduced a second windfall tax for oil prices between $40 and $70 per barrel (WoodMackenzie, 2012).

Altogether, the history of Venezuela presents another clear example of long-run cycles of taxation and investment, with expropriations in 1975 and 2007 following long periods of

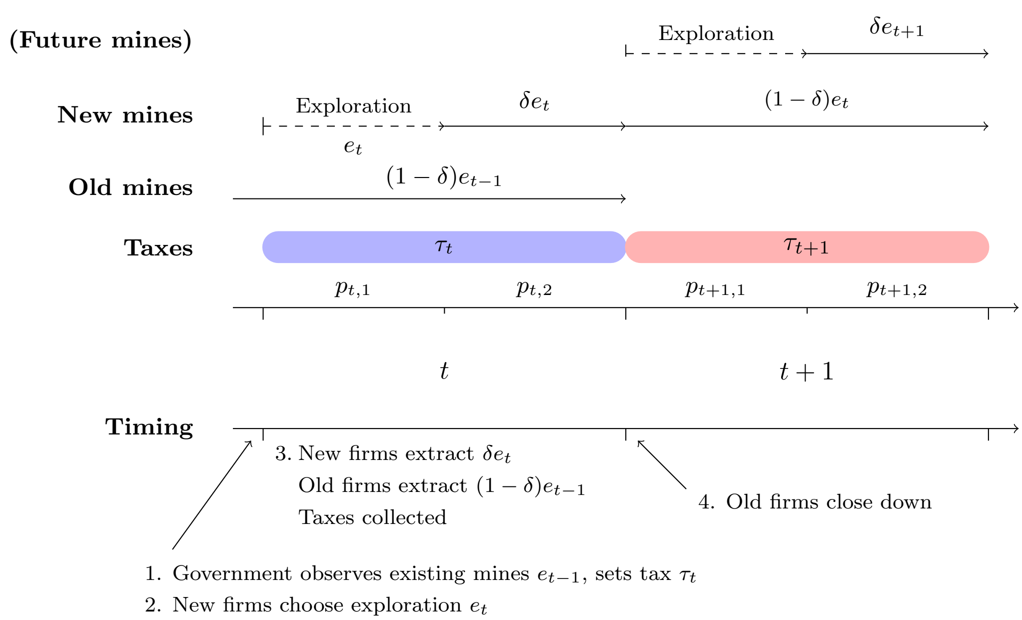
[13] Miguel Espinosa from Conoco's treasury department explained the decision to come back as follows: "In spite of our previous experience, we were eager to participate in the Venezuelan oil sector once again. We had long-standing commercial relationships with PDVSA – buying their crude to supply our refineries – and strong personal relationships. When the door opened, we took the opportunity" (Esty, 2002).

more favorable fiscal regimes. Foreign investment dissipates and foreign investors leave the country when taxes are high but come back later when tax rates are low again.

3 Model of resource taxation with limited commitment

In this section we outline a simple model of resource exploration and solve for the equilibrium policies. The overall purpose of our setup is to capture three main aspects: firstly, that old mines and new mines exist in parallel, with taxes not differentiating between the two; secondly, that mines exist beyond the time a government can commit to; thirdly, that mine development takes time, so that there is a delay between the investment decision and the first revenues.

Figure 3: The Sequence of Events in Period t



There are two types of agents in the economy: a government wanting to maximize tax revenue and a large pool of candidate resource-prospecting firms. The sequence of decisions is depicted in Figure 3. The government commits to a tax for a certain time interval with the objective of maximizing its own revenues from the resource during this time. After the interval has elapsed, the government can freely change the tax. This lack of long-term commitment implies there is in essence a sequence of governments each facing a different optimization problem. The time intervals, which we call periods, are indexed by t. The timing of decisions within each period is as follows. The government observes the existing stock of mines and then announces a tax rate which it commits to for only period t. After this announcement, new firms determine their exploration effort and their mines open with a lag. This means that within each period t there are two subperiods $s \in \{1, 2\}$. In the first subperiod only the old mines are being extracted from and in the second subperiod extraction is taking place both from the old and the new mines. Finally, when the current period t ends, the old mines close down while the new stay open for the entire next period $t+1$ (i.e., the new mines in period t become the old mines in $t+1$).

There is an infinite quantity of land available. A small plot of land can be explored for natural resources by using appropriate factors (e.g., petroleum geologists and drilling rigs, or dynamite and diggers). There is a linear supply curve for these factors, so that factor cost w as a function of aggregate exploration $\overline{e}$, after a normalization of the price level, is

$$w_t = \overline{e}_t$$

implying that aggregate costs are quadratic.[14] We work with a linear-quadratic model for analytical tractability.

Aggregate exploration effort (i.e., investment) in period t is denoted by e_t. Since the model is deterministic e_t is also equivalent to discoveries. Exploration takes place in the first subperiod and every unit of exploration yields a known quantity of resources α. For simplicity, we assume α to be constant, but it could easily be made time-varying, reflecting for instance exogenously changing land quality or advances in mining technologies.[15]

Any discoveries made in period t can be exploited in periods t and $t+1$, after which the firm in question closes down. Denote the exogenous (world market) resource price in period t, subperiod s by $p_{t,s}$. Assume that the exploration costs are inclusive of the costs of developing the deposit, so that extraction itself is costless. Firms extract during the two periods. In the first period a share $\delta < 1$ of the mine's content is extracted and in the second period $1-\delta$ is extracted. This way, a small δ captures a backloaded mining profile and vice versa. For example, if $\delta < \frac{1}{2}$ then most of the extraction from a new mine takes place beyond the commitment period of the current government.

Define the average resource price in period t as $\tilde{p}_t \equiv \frac{p_{t,1}+p_{t,2}}{2}$. The representative firm's problem is given by

$$\max_{e_t} \left((1-\tau_t)\delta p_{t,2} + \beta(1-\tau^e_{t+1})(1-\delta)\tilde{p}^e_{t+1}\right)\alpha e_t - \overline{e}_t e_t$$

in which the firm takes the current and expected taxes (τ_t, τ^e_{t+1}) as given. The discount factor used for future revenues is $\beta \in [0, 1]$.

As the objective function is linear in the choice variable, an equilibrium requires that profits equal zero and that aggregate exploration equals the choice of the representative firm $\overline{e}_t = e^*_t$, hence

$$e^*_t = \left((1-\tau_t)\delta p_{t,2} + \beta(1-\tau^e_{t+1})(1-\delta)\tilde{p}^e_{t+1}\right)\alpha. \tag{1}$$

[14] Upward sloping supply implies scarcity of production factors, such as drilling rigs and crews in the oil sector. Alternatively we could consider atomistic firms with internal diseconomies of scale; e.g., an increasing cost of time spent on exploration.

[15] In Appendix A.1, we derive the formulae in Lemma 1 for a time-varying path α_t.

Prices are assumed to be strictly positive and $\delta \in [0,1]$, so that exploration effort can be zero only if $1-\tau_t = \beta(1-\tau^e_{t+1}) = 0$, i.e., only if there would be full expropriation (100% taxes) both this period and the next. This means that, since firms are forward-looking, they will choose to explore today despite a very high current tax if they foresee a low tax tomorrow.

We assume the government is unconcerned with the revenues obtained in future periods and only wants to maximize the revenues obtained today (this is relaxed in Section 4). The government recognizes the firms' reaction function and solves

$$\max_{\tau_t} \tau_t \alpha \left[(1-\delta)\tilde{p}_t e_{t-1} + \delta p_{t,2} e^*_t(\tau_t)\right] \tag{2}$$

with the corresponding first-order condition

$$\tilde{p}_t(1-\delta)e_{t-1} + p_{t,2}\delta e^*_t(\tau^*_t) + \tau_t p_{t,2}\delta e'(\tau^*_t) = 0. \tag{3}$$

In words, the government trades off the extra revenue, given the existing tax base, against the new tax base that becomes smaller. The existing tax base – the pre-existing mines – are fully inelastic. Since each firm reacts to taxes over multiple periods, the government needs to consider how its tax affects investment and hence taxes tomorrow which again feeds back on today's investment. Thus, a succession of short-termist governments are linked by long-lived firms. With no pre-existing mines ($e_{t-1} = 0$), the government would simply choose to sit at the top of its one-period Laffer curve (where it still needs to take into account how the current tax affects firms' expectations of future taxes). With a positive pre-existing stock of developed mines, the government prefers to set a higher tax rate.

To solve for the Markov-perfect equilibrium we guess and verify that the government in the next period uses a linear tax policy

$$\tau^e_{t+1} = A_{t+1}e_t + B_{t+1} \tag{4}$$

(so that taxes tomorrow are a linear function of the discoveries made today). To emphasize, the coefficients A_{t+1}, B_{t+1} may depend on time. The linear policy is an equilibrium only as long as corner solutions are avoided, i.e. if $\tau_{t+1} \leq 1$, $\forall t$. We will impose parametric conditions which ensure this below. With the supposed linear policy function, the firms' zero-profit condition can be turned into a fixed-point problem (by substituting (4) into (1)):

$$e^*_t = \left((1-\tau_t)\delta p_{t,2} + \beta(1-(A_{t+1}e^*_t + B_{t+1}))(1-\delta)\tilde{p}^e_{t+1}\right)\alpha$$

with the equilibrium resource exploration effort given by

$$e^*_t = \frac{\left(\delta p_{t,2} + \beta\tilde{p}^e_{t+1}(1-\delta)(1-B_{t+1})\right)\alpha}{1+\beta\tilde{p}^e_{t+1}(1-\delta)\alpha A_{t+1}} - \frac{\alpha p_{t,2}\delta}{1+\beta\tilde{p}^e_{t+1}(1-\delta)\alpha A_{t+1}}\tau_t. \tag{5}$$

This is a linear function of the current period tax τ_t, and also a function of the expected short-run (within-period) resource price $p_{t,2}$ and the expected average prices in the next period $\tilde{p}^e_{t+1}$. Thus our conjectured linear tax policy rule yields linearity of $e^*_t(\tau_t)$:

$$e^*_t = C_t \tau_t + D_t, \tag{6}$$

with C_t and D_t expressed as functions of A_{t+1} and B_{t+1} in (5). Together with (3), this confirms that setting a linear tax policy is indeed optimal for the government. Imposing rational expectations implies $\tau^e_{t+1} = \tau^*_{t+1}$, and we can recursively solve for the coefficients of the policy rule:

Lemma 1. *The Markov-perfect equilibrium policies $\tau^*_t(e_{t-1})$ and $e^*_t(\tau_t)$ are given by* (4) *and* (5)*, with*

$$A_t = \frac{1}{2\delta\alpha\tilde{p}_t}\frac{1-\delta}{\delta}\sum_{i=0}^{\infty}\left(\frac{\beta}{2}\left(\frac{1-\delta}{\delta}\right)^2\right)^i \prod_{j=0}^{i}\left(\frac{\tilde{p}_{t+j}}{p_{t+j,2}}\right)^2$$

$$B_t = \frac{1}{2} - \frac{1}{2}\sum_{i=1}^{\infty}\left(-\frac{\beta}{2}\frac{1-\delta}{\delta}\right)^i \prod_{j=1}^{i}\frac{\tilde{p}^e_{t+j}}{p_{t+j-1,2}},$$

as long as the sums are bounded and always yield taxes $\tau^* \in [0,1]$.

Proof. In Appendix A.1. □

We will next make particular assumptions to simplify the general policy rules of Lemma 1, in order to conduct comparative statics on the equilibrium outcome and to highlight the key model dynamics.

3.1 Basic results

As our base case, we take the specification with a constant resource price ($p_t = p$, $\forall t$). As long as the geometric sums in Lemma 1 are bounded, which we ensure below, we obtain stationary coefficients $A_t = A, B_t = B$, with

$$A = \frac{1}{\alpha p\delta\left(2\frac{\delta}{1-\delta} - \beta\frac{1-\delta}{\delta}\right)}, \qquad B = \frac{1+\beta\frac{1-\delta}{\delta}}{2+\beta\frac{1-\delta}{\delta}} \equiv \underline{\tau} \tag{7}$$

and, using this with (5) and (6), $C_t = C, D_t = D$, with

$$C = -\frac{\alpha p\delta}{2}\left(2-\beta\left(\frac{1-\delta}{\delta}\right)^2\right), \qquad D = \alpha p\delta\left(2-\beta\left(\frac{1-\delta}{\delta}\right)^2\right)\frac{1+\beta\frac{1-\delta}{\delta}}{2+\beta\frac{1-\delta}{\delta}} \tag{8}$$

Thus the equilibrium policy rule for the government is

$$\tau^*_{t+1} = \begin{cases} \frac{1}{\alpha p\delta\left(2\frac{\delta}{1-\delta}-\beta\frac{1-\delta}{\delta}\right)}e_t + \frac{1+\beta\frac{1-\delta}{\delta}}{2+\beta\frac{1-\delta}{\delta}} & \text{if } e_t < \alpha p\delta\frac{2\frac{\delta}{1-\delta}-\beta\frac{1-\delta}{\delta}}{2+\beta\frac{1-\delta}{\delta}} \\ 1 & \text{otherwise.}\end{cases} \tag{9}$$

Combining (4) and (6) with the constant coefficients, we have the following tax transition for an interior solution:

$$\tau_{t+1}^{*} = AD + B + AC\tau_t = \frac{1}{\delta}\frac{1+\beta\frac{1-\delta}{\delta}}{2+\beta\frac{1-\delta}{\delta}} - \frac{1}{2}\frac{1-\delta}{\delta}\tau_t. \tag{10}$$

By letting $\tau_t = \tau_{t+1}^{*} = \tau_{ss}$, it follows immediately that there is a unique steady state at

$$\tau_{ss} = \frac{B+AD}{1-AC} = \frac{1}{1+\delta}\frac{2+2\beta\frac{1-\delta}{\delta}}{2+\beta\frac{1-\delta}{\delta}}. \tag{11}$$

Note that the tax transition rule has a slope of $-\frac{1}{2}\frac{1-\delta}{\delta}$. In other words, low taxes today, by inducing higher exploration, lead to high taxes in the next period.

We now impose a parametric restriction on δ which guarantees the above solution is an equilibrium:

$$\delta > \delta' \equiv \frac{1-2\beta+\sqrt{8\beta+1}}{6-2\beta}. \tag{12}$$

This restriction is sufficient to ensure that three conditions hold. First, we must have $\frac{\beta}{2}\left(\frac{1-\delta}{\delta}\right)^2 < 1$ for the policy rule coefficients in Lemma 1 to converge.[16] Second, we require $\delta \geq \frac{1}{3}$ to ensure the tax transition (10) does not diverge (i.e. it must have a slope between -1 and 0) so that the steady state is stable, with tax cycles diminishing in magnitude. Third, we require $\delta > \delta'$, where δ' is given by $\frac{\beta}{2}\left(\frac{1-\delta'}{\delta'}\right)^2 = \frac{3}{2} - \frac{1}{2\delta'}$, so that a very low stock of existing mines will not lead to taxes low enough for the next period's taxes to hit 100%. In fact, this last condition is sufficient to ensure the other two hold as well.[17]

The stable tax transition also guarantees that tax rates are never at 100% for two subsequent periods, so that exploration will always take place. This can also be seen from the decision rule. Evaluating the decision rule at $e_t = 0$ yields the lowest possible tax rate of $\frac{1+\beta\frac{1-\delta}{\delta}}{2+\beta\frac{1-\delta}{\delta}}$ for the next period. This implies that $\tau_t^{*} \in \left[\frac{1+\beta\frac{1-\delta}{\delta}}{2+\beta\frac{1-\delta}{\delta}}, 1\right] \forall t$. A few steps of algebra also yield that $\tau_{t+1}(\tau_t = 1) = \frac{1+\frac{1}{2}\beta\frac{1-\delta}{\delta}+\frac{1}{2\delta}\beta\frac{1-\delta}{\delta}}{2+\beta\frac{1-\delta}{\delta}} < 1$. In words, with the parametric restriction guaranteeing stability, 100% taxes can only occur if the initial stock is very high. As we have assumed that the tax transition is stable, any deviations from the steady-state tax rate will decay. Thus, 100% taxes will be followed by low taxes, and these in turn will be followed by taxes which are high – but below 100%. Full expropriation can occur in the initial period, if the economy starts with a very large existing stock of active mines; following this, taxes will always be strictly interior.[18]

[16] The condition ensures A_t converges. It is straightforward to verify that, as long as this holds, B_t also converges: the lower bound for δ to ensure convergence of B_t is $\beta/(2+\beta)$, which is less than $\sqrt{\beta/2}/\left(1+\sqrt{\beta/2}\right)$ (the lower bound for δ to ensure convergence of A_t), as $\beta \leq 1$.

[17] It is easy to confirm, by plotting the two sides of the equation defining δ', that $\delta' \in [\frac{1}{3}, \frac{1}{2}]$, and that the first condition also holds given $\delta > \delta'$. Solving the equation yields a quadratic, the positive root to which is given in equation (12).

[18] The case of an unstable tax transition would lead to an eventual cycle of repeated full expropriations, but this would make the equilibrium non-linear.

We summarize the dynamic properties of the benchmark case here:

Proposition 1. *With a constant resource price p, the taxes will cycle around the steady state τ_{SS}.*

Proof. In the preceding text. □

We will now discuss some implications of the proposition.

Corollary 1. *i) Within a time period there is a positive relationship between the tax rate and the value of the current mines. ii) Within a time period there is a negative relationship between the tax rate and mining investments (i.e., exploration and development of mines).*

To illustrate the implications of these corollaries consider a country which has just recently discovered that it has some resources but where these have not been explored yet. That is, the initial stock of mines is zero ($e_0 = 0$). For this country $\tau_0^* = \frac{1+\beta\frac{1-\delta}{\delta}}{2+\beta\frac{1-\delta}{\delta}}$ which is the lowest possible tax in any period. This means that countries with a newly discovered resource *potential* will offer a low tax to initiate exploration.

The proposition further implies:

Corollary 2. *i) The tax in period t is negatively related to the tax in period $t+1$. ii) The number of existing mines in period t is negatively related to the number of existing mines in period $t+1$.*

Prediction (i) in Corollary 2 implies that the country with zero initial mines will also be the one that raises taxes the most once discoveries have been made. So the cycles will be particularly strong in less mature resource-producing countries.

To illustrate the main mechanism of the model consider the case of a flat extraction profile $\delta = \frac{1}{2}$. Then the government will set a tax

$$\tau_{t+1}^* = \begin{cases} \frac{2}{\alpha p(2-\beta)} e_t + \frac{1+\beta}{2+\beta} & \text{if } e_t < \alpha p \frac{1}{2} \frac{2-\beta}{2+\beta} \\ 1 & \text{otherwise} \end{cases} .$$

This represents the government's Laffer-type trade-off between getting a large share of the revenues and incentivizing the development of a large tax base. The tax differs from a static Laffer tax in two ways. First, the term $\frac{2}{\alpha p(2-\beta)} e_t$ implies that the government will set a higher tax since part of the tax base consists of pre-existing, inelastic capital that is unaffected by the current tax. If no old mines exist, this term disappears. To highlight the second difference, suppose that $e_{t-1} = 0$. In a static model, but otherwise similar linear-quadratic specification, the tax would be $\tau_t^* = \frac{1}{2}$. In our dynamic model, $\tau_t^* = \frac{1+\beta}{2+\beta} > \frac{1}{2}$. That is, the tax is higher than the static Laffer tax even if there is no inelastic capital. The reason for this is that patient firms care about future revenues, which mitigates the negative effect of today's tax rate on investment. First, the firm still expects to obtain some future revenues; second, a higher tax today leads to lower exploration, which means taxes in the next period will be lower. Note that with perfectly impatient firms ($\beta = 0$) and no pre-existing revenues ($e_{t-1} = 0$), the tax would be $\tau_t^* = \frac{1}{2}$. For the same reasons, the steady-state tax $\tau_{ss} = \frac{2}{3}\frac{2+2\beta}{2+\beta} \in \left(\frac{2}{3}, \frac{8}{9}\right)$ also exceeds the static Laffer optimum of $\tau^* = \frac{1}{2}$.

3.2 Mining profile

We now consider how the mining profile, indexed by δ, affects the above results. Recall that a low δ implies resource revenues are more backloaded, with fraction $1-\delta$ of the revenues arriving beyond the government's commitment period.

Note that the steady-state tax τ_{ss} given in (11) is below unity and decreases in δ. The tax transition rule (10) becomes steeper with low δ, which implies that oscillations decay more slowly for backloaded mining profiles. Furthermore, as A and B are both decreasing in δ we get the following results:

Corollary 3. *i) For a given stock of existing mines, the more backloaded the mining profile is, the higher is the tax. ii) Given the stock of existing mines, the more backloaded the mining profile is, the lower is the exploration effort. iii) The more backloaded the mining profile is, the more slowly deviations from a steady-state tax decay:*[19]

$$\frac{\partial \frac{|\tau^*_{t+1}-\tau_{ss}|}{|\tau_t-\tau_{ss}|}}{\partial \delta} < 0.$$

These predictions are intuitive. When the mining profile is very backloaded, then the firm, when deciding on its exploration investment, mainly cares about future taxes as that is when the mine will produce most of its value. The government today knows this and therefore has an incentive to set a high tax to ensure getting a large share of the profits from the old mines. This of course happens in all periods implying that, in general, the tax rate will be higher. When the mining profile is sufficiently backloaded, the tax regime becomes so directed at getting at the current mines' profits that this completely strangles the industry (i.e. if $\frac{\beta}{2}\left(\frac{1-\delta}{\delta}\right)^2 \geq 1$). As an illustration, consider the polar case of a completely backloaded mining profile ($\delta \to 0$). Then the government, knowing that whatever it does will not have an effect on the current-period production from the new mines, only cares about taxing the old mines and sets the tax at an appropriation level $\tau^*_t = 1$. This of course means there will not be any exploration at all since the firms foresee this.

The opposite case is one where the mining profile is sufficiently frontloaded so that all the mining occurs in the current period ($\delta \to 1$). In this case the firm is fully responsive to any tax change and there is no linkage between the taxation of subsequent governments. In this case the model converges to the results of a static model, i.e., the Laffer tax of $\tau^*_t = \frac{1}{2}$. Thus, the high taxes we obtain in the model hinge on 1) mines existing beyond the commitment period of the government and on 2) firms that care about later profits.

The intuition for part (ii) of the corollary is similar. Given the existing stock of mines, more backloaded revenues will reduce the total value of any new discoveries (because of discounting) while making the government's tax schedule today more onerous. As a result, exploration falls with backloadedness.

For part (iii) of the corollary, note that the rate at which oscillations decay is simply the absolute value of the slope of the tax transition (10), which itself depends on how sensitively

[19] A bit of algebra shows that the decay rate in the inequality is given by $|AC| = \frac{1}{2}\frac{1-\delta}{\delta}$.

governments respond to pre-existing mines and firms respond to taxes. An impatient government overseeing a very backloaded resource cares much more about taxing the existing tax base than about encouraging new exploration, and thus responds more sensitively to the stock of pre-existing mines. Equilibrium exploration becomes less responsive to current taxes, as future revenues weigh more and as future taxes are expected to respond more. The government's increased sensitivity dominates, so that equilibrium taxes become more variable.

There are two ways to interpret the results on the mining profile δ. The first is that they pertain to geological constraints. Capital intensive and technologically challenging projects, such as offshore drilling, Arctic drilling and ultra-deep drilling, have long lead times between exploration and the start of commercial production. Corollary 3 implies that countries in which these projects represent a large share of hydrocarbon extraction set higher tax rates (and see lower exploration) than countries with frontloaded extraction profiles (e.g., conventional oil).

The second interpretation is that δ represents the government's commitment period. If a government is able to commit for many years, then the "current period" applies to a large share of the profits – δ is large. Corollary 3 then says that countries with stable governments, that is, ones which can be trusted not to change the tax very often, will have lower taxes and more exploration activity. A long commitment period may of course be the result of a stable autocratic regime or characterize a democratic country with sparse elections or low turnover.[20]

3.3 Price changes

We now turn to the effect of price changes on the tax policy. To highlight the mechanism we will consider a price change for one period ($p_{t,s}$) and assume that the price afterwards is constant at some level p.

Lemma 2. *Suppose $p_{t+i,s} = p$, $\forall i \geq 1$, $s \in \{1, 2\}$. Then, for $i \geq 0$,*

$$
\begin{aligned}
A_{t+i} &= \frac{1}{\alpha\delta} \frac{\tilde{p}_{t+i}}{p_{t+i,2}^2} \frac{1}{2\frac{\delta}{1-\delta} - \beta\frac{1-\delta}{\delta}}, \\
B_{t+i} &= \frac{1 + \frac{\beta}{2}\frac{1-\delta}{\delta}\left(1 + \frac{p}{p_{t+i,2}}\right)}{2 + \beta\frac{1-\delta}{\delta}}, \\
C_{t+i} &= -\frac{\alpha\delta p_{t+i,2}}{2}\left(2 - \beta\left(\frac{1-\delta}{\delta}\right)^2\right), \\
D_{t+i} &= \alpha\delta\left(2 - \beta\left(\frac{1-\delta}{\delta}\right)^2\right)\frac{p_{t+i,2} + \beta\frac{1-\delta}{\delta}\frac{p_{t+i,2}+p}{2}}{2 + \beta\frac{1-\delta}{\delta}}.
\end{aligned}
$$

[20]Strictly speaking, a longer commitment period also decreases β since it postpones the firms' second-period profits. The derivative $d\tau_{ss}/d\beta > 0$. Hence a long commitment period has two effects, both of which are lowering τ_{ss} – one through decreasing β and one through increasing δ.

Proof. The firm's problem is unchanged, given the expectation of a linear government policy function with arbitrary coefficients, so the equilibrium still satisfies (5), which yields C_{t+i} and D_{t+i} as a function of A_{t+i+1} and B_{t+i+1}. The latter are obtained from Lemma 1, substituting in the particular price path we consider. Observe that for $i \geq 1$, the given coefficients are constants and coincide with those in Section 3.1. The result then follows by substituting out A_{t+i+1} and B_{t+i+1}. □

Inspection of the coefficients A_{t+i}, B_{t+i}, C_{t+i} and D_{t+i} yields the following prediction:

Corollary 4. *An unexpected increase in the spot price $p_{t,1}$ raises the current tax.*

This is seen from the fact that an increase in $p_{t,1}$ raises the average price in period t, $\tilde{p}_t$, thus raising A_t. The prediction is intuitive. An unexpected, temporary, positive price shock increases the value of existing (old) mines vis-á-vis new mines (which appear only in subperiod 2). Hence, the government becomes more concerned about extracting tax revenues from the existing stock of mines.[21]

Persistent price shocks are more difficult to analyze for an arbitrary price path. However, if we only consider a path of constant prices, as in Section 3.1, we get the following prediction:

Corollary 5. *i) An unexpected and persistent positive price shock lowers the current tax, without altering the steady-state tax. ii) This amplifies the tax cycles if the current stock of pre-existing mines is below the steady state and, unless the shock is large, dampens them if the stock is above the steady state. iii) The entire path of equilibrium exploration increases.*

Proof. Note from (7) that A is decreasing in price while B is unchanged. From (11) note that a change in the (constant) price has no effect on the steady state $\tau_{ss} = (B + AD)/(1 - AC)$ (the p in A cancels out with the same p in C and D). Together with the government policy rule (9), these imply (i). Note further that the slope of the tax transition function $\tau^*_{t+1} = B + AD + AC\tau_t$ is then independent of p. As, given e_{t-1}, the current tax falls, and as the tax transition is unchanged, a cobweb diagram confirms that the cycle becomes more pronounced if $e_{t-1} < e^*(\tau_{ss})$ and, unless the shock is large (see footnote 22 below), less pronounced if $e_{t-1} > e^*(\tau_{ss})$, implying (ii). The exploration transition is $e^*_t = D + BC + ACe_{t-1}$, so that

$$e^*_{t+i} = (D + BC) \sum_{j=0}^{i} \left((AC)^j\right) + (AC)^{i+1} e_{t-1}.$$

$D + BC$ increases proportionally with p, and AC is unaffected, confirming (iii). □

Part i) of this corollary says that if the price shock is expected to persist, the initial tax will fall. This occurs since the price increase makes new firms more sensitive, on the margin, to the tax rate: a higher price translates a marginal change in the (proportional) tax rate τ into a higher change in the implied tax per unit of resource found (in dollars).

[21] This has been tested by Guriev et al. (2011) and Stroebel and van Benthem (2013), who use a panel data set on expropriation events to provide empirical evidence that a higher oil price is associated with an increased probability of expropriation.

It is the latter which firms balance against marginal cost when choosing their exploration efforts. The indirect effect – higher taxes lowering exploration effort – outweighs the direct effect of higher tax revenues, even taking into account the pre-existing stock of mines.

Current exploration increases, directly in response to a higher price and indirectly due to the lower tax. The net effect is for taxes in the subsequent period to rise, then fall, rise, and so on. As outlined in part ii) of the corollary, if the price increase occurs when the pre-existing stock of mines is low, so that the oscillation is in the "low tax" phase, the price increase amplifies the cycles. If the increase happens with a high pre-existing stock (with the oscillation in the "high tax" phase), the price increase counteracts the cycles.[22]

The steady-state tax is unchanged due to the assumption of linear exploration costs. While the government wants to lower the tax schedule, at the same time firms want to explore more, which of course implies the government wants to increase the tax rate. In the linear equilibrium these effects exactly offset each other.

4 Extension: Patient government

In the previous sections, we have assumed that the government is perfectly impatient: it does not care for future tax revenues at all. We will now study whether relaxing this assumption would alter our main results.

Suppose the government discounts future tax revenues by the discount factor β^G. Then, the government's value function, given an existing stock of reserves e_{t-1}, is

$$V(e_{t-1}) = \max_{\tau_t} \tau_t \left(\alpha(1-\delta)\tilde{p}_t e_{t-1} + \alpha\delta p_{t,2} e_t^*(\tau_t)\right) + \beta^G V(e_t^*(\tau_t)).$$

Note that, in contrast with (2), the government now also cares about all future tax revenues. The representative firm still uses the discount factor β. We can solve the model as before; details are in Appendix A.2. For tractability, we only consider the outcome with constant prices ($p_{t,s} = p$) and a flat extraction profile ($\delta = \frac{1}{2}$).

We guess and verify that, in the Markov-perfect equilibrium, the tax policy function and the equilibrium exploration are still linear, i.e. given by (4) and (6), and stationary (so that the coefficients A, B, C, D are constants). Hence, the structure of these functions is exactly as before. However, the equilibrium coefficients of course depend on the new parameter β^G.

[22]Strictly speaking, the second half of part (ii) holds for small price shocks only. Suppose that the price shock occurs after a period of low taxes, so that the stock of past investments e_{t-1} is high. Absent the price shock, the current tax would be above the steady state. A small shock will move the tax closer to the steady state, and cycling diminishes. A sufficiently large shock, however, could bring the tax to *below* the steady state and, if the shock is large enough, to a tax that deviates from the steady state (in absolute value) more than the tax without the price shock. If that happens, the cycling continues with an increased amplitude. Finally, note that starting from a steady state, a price shock will kick-start cycling, with taxes lowered once the shock hits.

Proposition 2. *i) Tax cycles exist for all $\beta^G \in [0,1]$. ii) Relative deviations from steady-state taxes decay more slowly, the more patient is the government:*

$$\frac{\partial \frac{|\tau^*_{t+1} - \tau_{ss}|}{|\tau_t - \tau_{ss}|}}{\partial \beta^G} > 0.$$

Proof. In Appendix A.2.[23] $\square$

Most importantly, this proposition says that tax cycles will exist also if the government is patient. In fact, as part ii) says, for a given period length, more patient countries should see more persistent tax cycles following an unexpected shock.

The reason for result (ii) is that the rate at which tax cycles disappear is decreasing in the reactivity of the government and the market: highly responsive taxes or investment will cause more persistent cycles. The government indeed becomes more responsive when β^G is high. To see why, take future governments' decision rules, and the firms' exploration function, as a given. A government today optimally equates the marginal benefit of increasing the tax rate – the total size of a period's tax base – with the marginal cost of lowering exploration, thus shrinking the tax base. For a patient government, shrinking the tax base is undesirable because it lowers the tax take today and in the next period. However, as the next period's government will lower the tax rate in response to a smaller tax base, this marginal cost is partially offset: higher taxes today mean lower taxes tomorrow, so that lower investment today hurts less. A more patient government perceives this offsetting effect on future revenues as more important, so that high government patience implies a relatively flat marginal cost curve, and thus a greater tax response to a shift of the marginal benefit curve. Such a shift would result from a change in the stock of pre-existing mines.

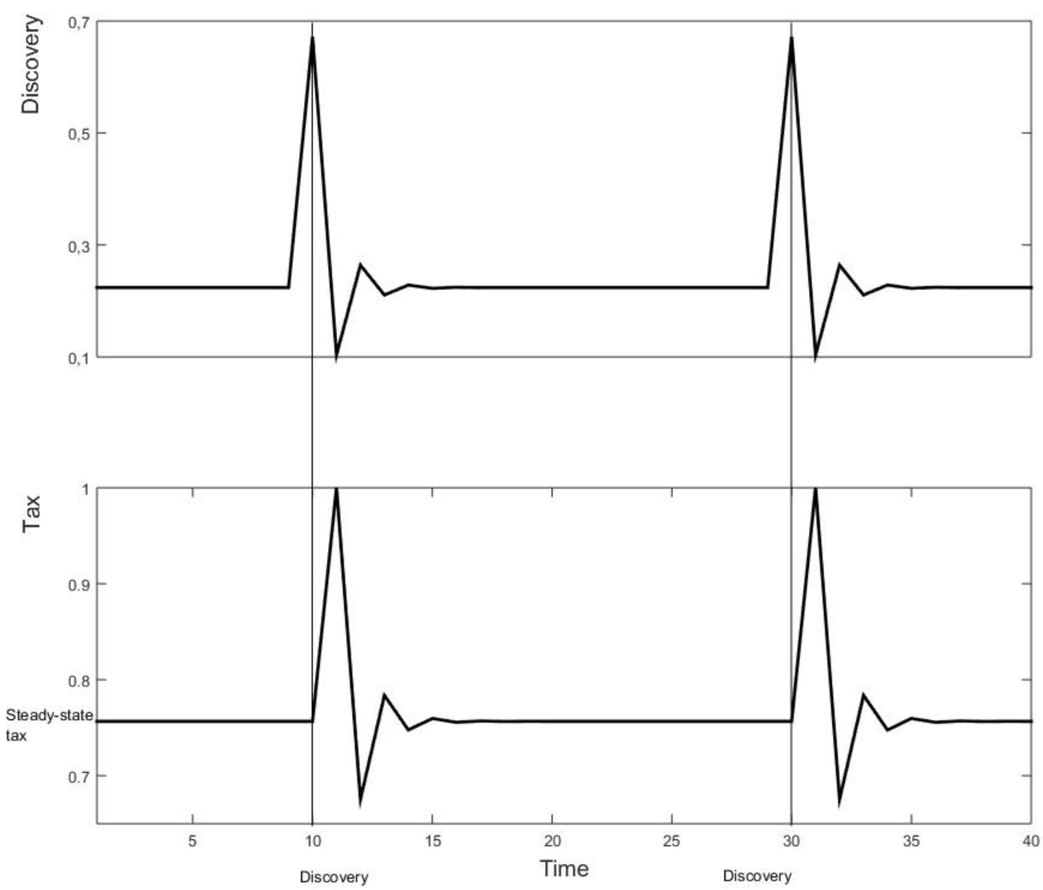
In equilibrium, of course, all policy rules adjust. A more responsive tax policy in the future will constrain the equilibrium exploration rate more tightly. This is because a reduction in taxes today has a weaker effect on exploration if the next government is expected to respond to more investment by raising taxes a lot next period. Thus exploration becomes less responsive to current taxes ($\partial C/\partial \beta^G > 0$, recalling $C < 0$). This change in the market response further increases the government's incentives to set a highly responsive tax policy: if raising taxes today has less of an effect on investment, there is a greater incentive to set them high (if the pre-existing stock is high), reinforcing the direct effect of higher patience. Overall, then, tax policy is certainly more responsive: $\partial A/\partial \beta^G > 0$. Thus, more responsive tax policy and less responsive investment have countervailing effects on the overall persistence of tax cycles, but the former dominates the latter, so that increasing government patience makes cycles more persistent.

[23] We also document a further result on steady-state tax rates in Appendix A.2.

5 Illustrating resource discovery shocks

In resource markets, it happens from time to time that a surprisingly large discovery is made or that exploration does not bear the expected fruits. We briefly illustrate the effect of such shocks in this section. Since our model is deterministic, discoveries are directly determined by the exploration effort of the firms, and the tax and effort oscillate over time until a steady state is reached where the tax and effort are constant. Suppose now the economy is in this steady state but that, suddenly, an unexpectedly large discovery is made in one period. This one-time shock will initiate the oscillatory behavior once again. This is illustrated in Figure 4. Here the discoveries are endogenous in all periods but there is an exogenous and unexpected shock to discoveries in period 10 and in period 30. As can be seen, in this case, the large discovery in period 10 leads to full expropriation in period 11 when the government wants to take as much as possible from the large discovery. This depresses new exploration and hence discoveries in period 11.

Figure 4: Illustration of the Effect of Discovery Shocks On the Economy



Notes: One-period positive shocks happen in periods 10 and 30. In all other periods the discoveries are determined endogenously.

The important message with this example is that discovery shocks not only lead to revised taxation but also initiate cycles, even if no shocks will happen later. This of course holds for any shock, be it a temporary price spike or a new technology that changes the extraction profile.

One possible extension of the model is to let agents have expectations of these shocks. The qualitative features of our model would remain under such an extension, but there would be another source of tax instability on top of the cyclical pattern that arises due to the dynamic interaction that we have in the model.

6 Conclusions

This paper has presented the first forward-looking resource taxation model with rational expectations by firms who cannot commit to exiting a country and governments who cannot commit to tax rates. Resources are developed through costly exploration investments, but the government cannot commit to tax rates beyond a single period. This is a highly policy-relevant problem, not only in developing countries lacking strong institutions, but also in developed countries.

We have shown how this model predicts repeated cycles of tax rates and investment, which is in line with the empirical reality in many resource-producing countries. We provide two detailed case studies and multiple shorter examples of cyclical taxation. Governments often promise firms low tax rates to encourage exploration and investment, but if large discoveries follow, these will tempt the government into revising taxes upward. These cycles are more pronounced for resources which take longer to develop. We have also analyzed how price changes and increasing government patience affect these tax oscillations. As such, the model offers many testable implications that can be taken to the data.[24]

Our model is rich enough to reflect tax and investment cycles with agents that hold rational expectations, but without the need to exogenously assume expropriations. It is also simple enough to serve as a starting point for further analysis of optimal natural resource taxation under imperfect commitment. For example, the model can be extended to consider changing land prospectivity, imperfect competition among resource extraction firms, different price expectations, endogenous extraction profiles and side payments to corrupt politicians. The model could also include any costs of expropriation – e.g., from reputation loss, international arbitration, and the loss of technological expertise if private investors leave following a full-scale nationalization and production and exploration are left to state-owned companies. One could also introduce taxes that differ by vintage or by project or more sophisticated taxation schemes that aim at getting around the commitment problem (e.g., exploration subsidies). Hence our model can also be used to study normative issues

[24]Possible sources for fiscal data include WoodMackenzie's Global Economic Model (`http://www.woodmac.com/new-products/12272568`) and Rystad Energy's UCube Upstream Database (`http://www.rystadenergy.com/Databases/UCube`). We view this paper's scope and contribution mainly on the theoretical and modeling side, and to document and explain repeated taxation cycles as commonly observed in many countries. We therefore leave further empirics as future work.

related to the structure of resource taxation.

Finally, we mention that our model applies to any setting in which capital is immobile and has a productive lifetime that exceeds the government's commitment period. Besides exhaustible natural resources like oil, gas and metals, other applications could include wind farms, forestry, and certain non-resource capital such as capital-intensive manufacturing facilities.

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Appendices

A Additional proofs

A.1 Proof of Lemma 1

Proof. We derive the result for a more general case, using a time-varying exploration efficiency path α_t. Thus, in period t, effort e_t yields $\alpha_t e_t$ units of the resource. The firm's and government's problems are modified accordingly (in particular, the revenues from the previous period for the government at time t are now $\alpha_{t-1}e_{t-1}$). Substituting (4) into (3) and solving for τ_t^*, we obtain

$$\tau_t^* = \frac{1+\beta\tilde{p}^e_{t+1}\alpha_t(1-\delta)A_{t+1}}{2\alpha_t\delta p_{t,2}}\frac{\alpha_{t-1}}{\alpha_t}\frac{\tilde{p}_t}{p_{t,2}}\frac{1-\delta}{\delta}e_{t-1} + \frac{1+\beta\frac{\tilde{p}^e_{t+1}}{p_{t,2}}\frac{1-\delta}{\delta}(1-B_{t+1})}{2}$$

This has the linear form we conjectured $\tau_t^* = A_t e_{t-1} + B_t$ but the coefficient A_t is a function of A_{t+1}:

$$A_t = X_t + \Psi_t A_{t+1}$$

where $X_t \equiv \frac{1}{2\alpha_t\delta p_{t,2}}\frac{\tilde{p}_t}{p_{t,2}}\frac{\alpha_{t-1}}{\alpha_t}\frac{1-\delta}{\delta}$, $\Psi_t \equiv \frac{\beta}{2}\frac{\alpha_{t-1}}{\alpha_t}\frac{\tilde{p}^e_{t+1}\tilde{p}_t}{p^2_{t,2}}\left(\frac{1-\delta}{\delta}\right)^2$. Note that $X_{t+1} = \frac{\alpha_t^3}{\alpha_{t+1}^2\alpha_{t-1}}\left(\frac{p_{t,2}}{p^e_{t+1,2}}\right)^2\frac{\tilde{p}^e_{t+1}}{\tilde{p}_t}X_t$ and $\prod_{i=0}^n \Psi_{t+i} = \left(\frac{\beta}{2}\left(\frac{1-\delta}{\delta}\right)^2\right)^{n+1}\frac{\alpha_{t-1}}{\alpha_{t+n}}\frac{\tilde{p}^e_{t+n+1}}{\tilde{p}_t}\prod_{i=0}^n\left(\frac{\tilde{p}^e_{t+i}}{p_{t+i,2}}\right)^2$. Then

$$\begin{aligned}
A_t &= X_t + \Psi_t\left(X_{t+1} + \Psi_{t+1}A_{t+2}\right) \\
&= X_t + \Psi_t X_{t+1} + \Psi_t\Psi_{t+1}\left(X_{t+2} + \Psi_{t+2}A_{t+3}\right) \\
&= \dots \\
&= X_t + \sum_{i=0}^{\infty}\left(\prod_{j=0}^{i}\Psi_{t+j}\right)X_{t+i+1} \\
&= X_t\left(1 + \frac{\beta}{2}\left(\frac{1-\delta}{\delta}\right)^2\left(\frac{\alpha_t}{\alpha_{t+1}}\right)^2\left(\frac{\tilde{p}^e_{t+1}}{p^e_{t+1,2}}\right)^2\right. \\
&\quad \left. + \left(\frac{\beta}{2}\left(\frac{1-\delta}{\delta}\right)^2\right)^2\left(\frac{\alpha_t}{\alpha_{t+2}}\right)^2\left(\frac{\tilde{p}^e_{t+1}}{p^e_{t+1,2}}\frac{\tilde{p}^e_{t+2}}{p^e_{t+2,2}}\right)^2 + \dots\right) \\
&= X_t\sum_{i=0}^{\infty}\left(\frac{\beta}{2}\left(\frac{1-\delta}{\delta}\right)^2\right)^i\left(\frac{\alpha_t}{\alpha_{t+i}}\right)^2\prod_{j=1}^{i}\left(\frac{\tilde{p}^e_{t+j}}{p^e_{t+j,2}}\right)^2
\end{aligned}$$

which yields

$$A_t = \frac{1}{2\delta\alpha_{t-1}\tilde{p}_t}\frac{1-\delta}{\delta}\sum_{i=0}^{\infty}\left(\frac{\beta}{2}\left(\frac{1-\delta}{\delta}\right)^2\right)^i\left(\frac{\alpha_{t-1}}{\alpha_{t+i}}\right)^2\prod_{j=0}^{i}\left(\frac{\tilde{p}_{t+j}}{p_{t+j,2}}\right)^2.$$

We obtain B_t similarly; defining $\tilde{\Psi}_t \equiv \beta\frac{1-\delta}{\delta}\frac{\tilde{p}^e_{t+1}}{p_{t,2}}$,

$$\begin{aligned}
B_t &= \frac{1}{2}(1+\tilde{\Psi}_t) - \frac{1}{2}\tilde{\Psi}_t B_{t+1} \\
&= \frac{1}{2}(1+\tilde{\Psi}_t) - \frac{1}{4}\tilde{\Psi}_t(1+\tilde{\Psi}_{t+1}) + \frac{1}{8}\tilde{\Psi}_t\tilde{\Psi}_{t+1}(1+\tilde{\Psi}_{t+2}) - \dots \\
&= \frac{1}{2} - \frac{1}{4}\tilde{\Psi}_t + \frac{1}{8}\tilde{\Psi}_t\tilde{\Psi}_{t+1} - \dots \\
&\quad\; + \frac{1}{2}\tilde{\Psi}_t - \frac{1}{4}\tilde{\Psi}_t\tilde{\Psi}_{t+1} + \dots
\end{aligned}$$

which yields

$$B_t = \frac{1}{2} - \frac{1}{2}\sum_{i=1}^{\infty}\left(-\frac{\beta}{2}\frac{1-\delta}{\delta}\right)^i\prod_{j=1}^{i}\frac{\tilde{p}^e_{t+j}}{p_{t+j-1,2}}.$$

Setting $\alpha_t = \alpha$, $\forall t$, yields the formulae in Lemma 1, which clearly only apply as long as the sums converge. Further, as we have assumed linear policy and exploration functions, the coefficients yield equilibrium policy rules only as long as the resulting taxes and exploration quantities are always interior (otherwise $\exists t'$ s.t. $\tau^*_{t'+1} = 1, \partial\tau^*_{t'+1}/\partial e_t = 0 \neq A_{t+1}$). □

A.2 Patient government case

We first construct the equilibrium for the patient government case. For simplicity, we consider only the case with a flat extraction profile ($\delta = \frac{1}{2}$). We also set $p_{t,s} = p$, $\forall t, s$. The representative firm's problem is as before, and guessing (and later verifying) the government follows a linear policy function (4) and equilibrium effort is still given by (6). This implies a tax transition rule

$$\tau^*_{t+1}(e^*_t(\tau_t)) = A_{t+1}D_t + B_{t+1} + A_{t+1}C_t\tau_t.$$

The government discounts future tax revenues with discount factor β^G. The government's value function, given an existing stock of reserves e_{t-1}, is

$$V(e_{t-1}) = \max_{\tau_t}\tau_t\left(\frac{p\alpha e_{t-1}}{2} + \frac{p\alpha e^*_t(\tau_t)}{2}\right) + \beta^G V(e^*_t(\tau_t))$$

By the envelope theorem,

$$V'(e_{t-1}) = \frac{p\alpha\tau^*_t}{2} > 0. \tag{13}$$

Supposing the next period's government will follow a linear policy function, the first-order condition now takes into account the effect of present exploration on future tax revenues:

$$\frac{p\alpha}{2}\left(e_{t-1} + e_t^*(\tau_t^*) + \tau_t e_t'(\tau_t^*) + \beta^G \tau_{t+1}^* e_t'(\tau_t^*)\right) = 0, \tag{14}$$

in which the last term reflects the change in continuation value (obtained using (13)).

Substituting in the (supposed linear) policy function (4) and equilibrium exploration effort (6) into (14), and solving for τ_t, we can obtain the coefficients A_t and B_t; we obtain C_t and D_t by substituting the constant price p and $\delta = \frac{1}{2}$ into (5):

$$\begin{aligned}
A_t &= -\frac{1}{C_t}\frac{1}{2 + \beta^G A_{t+1} C_t} \\
B_t &= -\frac{1}{C_t}\frac{D_t + \beta^G (B_{t+1} + A_{t+1} D_t) C_t}{2 + \beta^G A_{t+1} C_t} \\
C_t &= -\frac{\frac{p\alpha}{2}}{1 + \frac{\beta p \alpha_t A_{t+1}}{2}} \\
D_t &= \frac{p\alpha}{2}\frac{1 + \beta(1 - B_{t+1})}{1 + \frac{\beta p \alpha A_{t+1}}{2}}.
\end{aligned}$$

It is straightforward to verify that $\beta^G \to 0$ takes us back to the model with a perfectly impatient government.[25] Also, there clearly exists a stationary solution with A_t, B_t, C_t, D_t all independent of t. Call the coefficients then A, B, C, D. We can solve for the autonomous coefficients to get

$$\begin{aligned}
A &= \frac{2}{p\alpha}\frac{1 - \sqrt{1 - \beta^G}}{\beta^G - \beta + \beta\sqrt{1 - \beta^G}} \\
B &= \frac{(1 + \beta)\sqrt{1 - \beta^G}}{1 + \beta^G + (1 + \beta)\sqrt{1 - \beta^G}} \\
C &= -\frac{p\alpha}{2}\frac{\beta^G - \beta + \beta\sqrt{1 - \beta^G}}{\beta^G} \\
D &= \frac{p\alpha}{2}\frac{1 + \beta}{\beta^G}\frac{1 + \beta^G + \sqrt{1 - \beta^G}}{1 + \beta^G + (1 + \beta)\sqrt{1 - \beta^G}}\left(\beta^G - \beta + \beta\sqrt{1 - \beta^G}\right).
\end{aligned}$$

The steady-state tax rate is

$$\tau_{ss} = \frac{AD + B}{1 - AC}$$

and deviations from the steady state die out at the rate

$$\left|\frac{\tau_{t+1}^* - \tau_{ss}}{\tau_t - \tau_{ss}}\right| = |AC|. \tag{15}$$

We can solve the equation for A to get a quadratic in the slope of the tax transition

[25] As $\beta^G \to 0$, the expressions for A, C and D tend to $\frac{0}{0}$; we can use L'Hôpital's Rule to verify that the limits equal the values derived in Section 3.2.

function $AC < 0$. This has two roots, but one of them satisfies $AC < -1$. An equilibrium has to involve a stable tax transition rule, so that taxes converge to τ_{ss}, as otherwise the economy eventually hits a corner solution; this would invalidate the conjecture made when solving for equilibrium exploration, that the government uses a linear policy rule. From (15), this implies the root $AC < -1$ is ruled out and there is one admissible root:

$$AC = -\frac{1}{\beta^G}\left(1 - \sqrt{1-\beta^G}\right).$$

Proof of Proposition 2. From (15), it is clear that deviations from the steady state decay faster, the lower is AC in absolute value. Note that $\partial|AC|/\partial\beta^G > 0$ as

$$\frac{\mathrm{d}AC}{\mathrm{d}\beta^G} = -\frac{2-\beta^G-2\sqrt{1-\beta^G}}{2{\beta^G}^2\sqrt{1-\beta^G}} < 0$$

so that an increase in the government's discount factor makes the decay rate slower. Further, AC is monotonic in β^G and takes values in $[-1, -\frac{1}{2}]$, so that tax cycles clearly exist for any $\beta^G \in [0, 1]$. This proves the proposition. □

We now state a further result on steady-state tax rates when the government is patient:

Proposition 3. *The steady-state tax rate is U-shaped in government patience β^G: there exists a threshold level $\beta^{G*}(\beta)$ s.t. for $\beta^G < (>)\beta^{G*}(\beta)$, $\partial\tau_{ss}/\partial\beta^G < (>)0$.*

Proof. The steady state is then given by

$$\tau_{ss} = \frac{2\beta^G(1+\beta)}{3\beta^G - \beta + \beta^G(\beta+\beta^G) + \beta(1+\beta^G)\sqrt{1-\beta^G}}$$

which can be differentiated with respect to β^G:

$$\frac{\mathrm{d}\tau_{ss}}{\mathrm{d}\beta^G} = \frac{\tau_{ss}}{2\beta^G\sqrt{1-\beta^G}}\,\frac{-2(\beta+{\beta^G}^2)\sqrt{1-\beta^G} + 2\beta - \beta\beta^G(1-\beta^G)}{3\beta^G - \beta + \beta^G(\beta+\beta^G) + \beta(1+\beta^G)\sqrt{1-\beta^G}}.$$

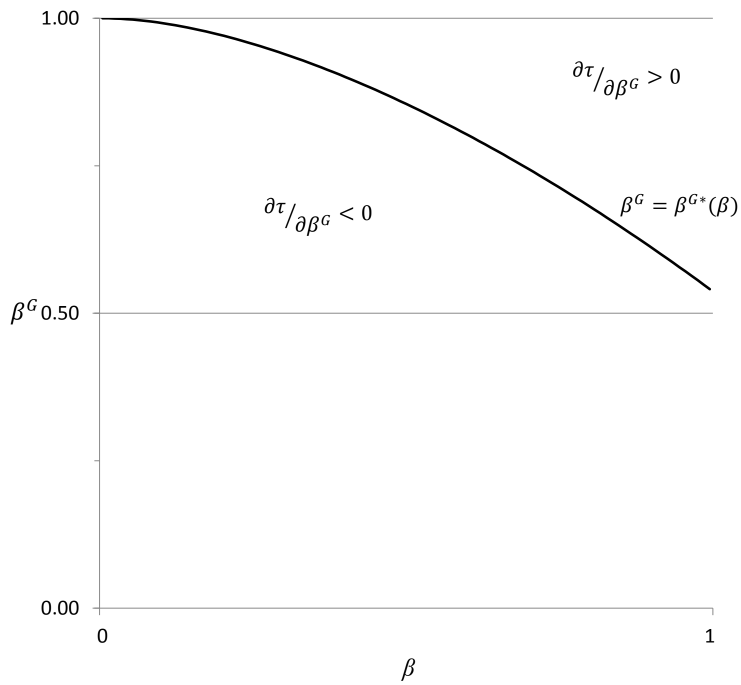
The denominator can be easily shown to be strictly positive in the relevant range $\beta^G \in (0, 1)$. The numerator is positive if and only if $4{\beta^G}^3 + {\beta^G}^2(\beta^2 - 4) + \beta^G(8\beta - 2\beta^2) + \beta(5\beta - 8) \geq 0$. Setting this to hold with equality defines a locus $\beta^{G*}(\beta)$, which satisfies $\beta^{G*}(0) = 1$, $\mathrm{d}\beta^{G*}(0)/\,\mathrm{d}\beta = 0$, $\mathrm{d}^2\beta^{G*}(0)/\,\mathrm{d}\beta^2 < 0$, $\partial\beta^{G*}(\beta)/\partial\beta \leq 0$, and $\beta^{G*}(1) = .541$. For $\beta^G < (>)\beta^{G*}(\beta)$, $\partial\tau_{ss}/\partial\beta^G < (>)0$.[26] We can follow the same process for the steady-

[26] $\beta^{G*}(0) = 1$ is easily calculated, and $\beta^{G*}(1)$ is computed numerically. Now denote the cubic formula in the inequality in the text by LHS. Using the implicit function theorem, we have $\mathrm{d}\beta^{G*}/\,\mathrm{d}\beta = -(\partial\mathrm{LHS}/\partial\beta)/(\partial\mathrm{LHS}/\partial\beta^G)$, and

$$\frac{\mathrm{d}^2\beta^{G*}}{\mathrm{d}\beta^2} = -\left(\frac{\partial LHS}{\partial\beta^{G*}}\right)^{-1}\left(\frac{\partial^2 LHS}{\partial\beta^2} + 2\frac{\mathrm{d}\beta^{G*}}{\mathrm{d}\beta}\frac{\partial^2 LHS}{\partial\beta\partial\beta^{G*}} - \left(\frac{\mathrm{d}\beta^{G*}}{\mathrm{d}\beta}\right)^2\frac{\partial^2 LHS}{\partial{\beta^{G*}}^2}\right)$$

For any $\beta, \beta^G \in [0, 1]$, $\partial^2\mathrm{LHS}/\partial\beta^2 > 0$. As long as $\partial\mathrm{LHS}/\partial\beta^G$ does not go to zero, then any point such that $\mathrm{d}\beta^{G*}/\,\mathrm{d}\beta = 0$ implies $\mathrm{d}\beta^{*G}/\,\mathrm{d}\beta$ is negative; that is, $\beta^{G*}(\beta)$ will not bend up in $\beta \in (0, 1)$. In particular, evaluated at $\beta = 0$, $\beta^G(0) = 1$, we get $\partial\mathrm{LHS}/\partial\beta = 0$ and $\partial\mathrm{LHS}/\partial\beta^G = 0$, so that the derivatives

Figure 5: The Effect of Government Discounting On the Steady-State Tax



state investment quantity. The condition for steady-state investment to rise in response to an increase in β^G is identical to the condition for steady-state taxes to fall. $\square$

There are countervailing effects on the steady-state tax. Higher patience also makes the government want to set a lower "baseline" tax rate ($\partial B/\partial\beta^G < 0$), to encourage exploration, as the government cares more about revenues in the future. This pushes the steady-state tax rate down. However, the changes in the sensitivity of both government and equilibrium investment both push the equilibrium rates up. The latter effects dominate when the government becomes very patient (as $\beta^G \to 1$). Figure 5 illustrates how the steady-state taxes depend on the discount rates: for small β^G ($\beta^G < \beta^{G*}(\beta)$), the steady-state tax falls with increasing β^G, but once $\beta^G > \beta^{G*}(\beta)$, the steady-state tax starts to increase again.

evaluated at $\beta^G = 0$ follow. It remains to be shown that $\beta^{G*}(\beta)$ decreases monotonically. Suppose this is not the case. From the above, it is clear this could only occur if $\exists\beta' : \lim_{\beta\to\beta'} \partial\text{LHS}/\partial\beta^G = 0$. Plotting LHS as a function of β^G for $\beta = 0$ yields a cubic with a local maximum (with LHS $= 0$) at $\beta^G = 0$, and LHS < 0 for $\beta^G \in (0, 1)$. As β increases, the function rotates counter-clockwise, so that the root $LHS = 0$ shifts to the left of $\beta^{G*}(0) = 1$. If β' exists, it must be that for $\beta = \beta'$ the function has a local minimum at β^{G*}, with LHS $= 0$ at that point. But as $\partial^2\text{LHS}/\partial\beta^2 > 0$, then we would have to have the function rotate further counter-clockwise, so that the root would no longer exist; for $\beta > \beta'$, $\beta^{G*}(\beta)$ would lie to the left of the local minimum of LHS. But this is not the case for $\beta = 1$. Thus the conjectured β' cannot exist.