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**Division of Nonrenewable Resource Rents:  
A Model of Asymmetric Nash Competition with State  
Control of Heterogeneous Resources**

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Division of Nonrenewable Resource Rents:  
A Model of Asymmetric Nash Competition with State Control of Heterogeneous Resources\*

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## **ABSTRACT**

This paper presents a model of nonrenewable resource extraction across multiple states which engage in strategic tax competition. The model incorporates rents due to both resource scarcity and capital scarcity as well as intra-state Ricardian rents. States set taxes on nonrenewable resource production strategically to balance tax revenues and local benefits from investment conditional on other states' tax rates. A representative firm then allocates production capital across states and time to maximize profits. Generally, we find that Nash equilibrium state severance tax rates are dependent on state oil reserves, industry production capital, and costs of investment. We use a parameterized example and find that Nash equilibrium tax rates are substantially higher than observed rates. States have an incentive to unilaterally increase their own tax rates even when industry capital can relocate. Both findings hold unless policymakers place a value on domestic economic activity of more than \$500,000 per oil sector job per year.

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## **1. Introduction**

Many governments across the world rely on revenue raised from nonrenewable resource extraction. Nine U.S. states collect at least ten percent of their tax revenues from severance taxes on oil and gas production. While nonrenewable resource taxes present governments with an opportunity to raise money, industry threats to leave a jurisdiction can limit the power of states to collect resource rents. Many US states have active debates about severance tax rates and whether current rates reduce beneficial investment in a state. Here, we investigate optimal state tax rates in a context of mobile extraction capital and competition between states with oil and gas reserves. We develop a model of state and firm behavior and use it to ask under what conditions industry would credibly threaten to exit if tax rates increase. Our results show that, for plausible parameterizations, industry threats to exit only hold at the margin and do not harm state governments unless they place a value on local oil sector employment in excess of \$500,000 per job per year.

This paper makes two distinct contributions. First, we develop a dynamic model of optimal severance taxes for nonrenewable resources in a state-level strategic competition model. In this dynamic context, industry and government explicitly compete for a share of resource rent. Second, we show that, for plausible parameterizations, states could increase tax receipts by increasing tax rates.

We embed a dynamic model of nonrenewable resource extraction in a strategic Nash competition game between states. States, which value government revenue in addition to local jobs, set severance tax rates to maximize their own objective functions. A representative extraction firm chooses to allocate production capital across states, considering state-level severance tax rates and exogenous state-varying productivity of capital. The game is solved via backwards induction. We find that, while extraction industries can move capital across states, the scarcity of immobile, cheaply accessible resource reserves allows states to collect a share of resource rents. Increasing taxes on profitable reserves deters investment but only temporarily, resulting in a shift in the timing of extraction.

There are two distinct literatures that provide context for this research. First, there exists an extensive literature on the production and taxation of natural resources (Pindyck 1978). A typical nonrenewable resource model represents a competitive extractive industry and a single government in a dynamic setting. Taxing resource extraction reduces production, can extend the time of production, and reduces the return to holding resources. The deadweight loss from taxation is typically low because production is relatively price-insensitive, although it is relatively higher if the producer has market power (Yücel 1986, 1989, Chakravorty, Gerking, and Leach 2011).

Next, strategic tax competition by regional governments has been explored in a variety of settings. In a context with a mobile industry and a moderate number of jurisdictions, governments may compete to attract the industry by setting low tax rates. A large public economics literature explores this competition both theoretically and empirically, internationally and domestically (Wilson 1999, Kolstad and Wolak 1983, Brueckner and Saavedra 2001, Devereux, Lockwood, and Redoano 2008, Janeba and Osterloh 2013). Empirical analysis provides evidence of tax competition between national governments, U.S. states, and local governments (Brueckner and Saavedra 2001, Chirinko and Wilson 2011, Devereux, Lockwood, and Redoano 2008, Devereux and Loretz 2013, Kolstad and Wolak 1983). One key finding is that outcomes of tax competition depend crucially on who has more power – the governments, or the firms (Janeba and Osterloh 2013). Our results implicitly consider power by varying the relative scarcity of industry production capital and natural resource stocks. Possession of scarce resources enhances the ability of an economic agent to capture production value.

Tax competition often occurs among asymmetric regions. If the competition occurs between otherwise similar large and small countries, small countries may benefit from lowering taxes as the losses from lower per-unit tax revenues are outweighed by attracting more productive activity from the large countries (Bucovetsky 1991, Kanbur and Keen 1993). Regions can also vary on initial endowment of factors of production or by productivity of capital (Itaya, Okamura, and Yamaguchi 2008, Peralta and van Ypersele 2005). In our case, competing US

states vary on both resource size and investment cost. There is an inverse relation between these factors – Texas has both the most resources and lowest investment costs.

We extend the analyses of tax competition by considering investment in nonrenewable resource production. In the case of nonrenewable resources, states control access to a necessary input to production that is fixed in space: the resource stock. This places a limit on the extent to which industry can seek higher returns in other locations. Especially if a state has abundant, low-cost reserves, industry threats to go elsewhere may not be credible. We model heterogeneity in the quantity and investment costs of state oil and gas endowments. Oil is produced by drilling wells and rigs to drill wells are mobile. Thus, industry capital is mobile, but the returns to capital vary across states based on geologically predetermined costs. The sharing of resource value between the firm and state governments depends on the relative scarcity of production and natural capital. If capital is scarce relative to resource deposits, then the firm's implicit threat to relocate is more powerful and the firm can collect a larger share of resource rents. However, if capital is plentiful relative to resource deposits, then states can collect a higher share of resource rents.

Section 2 develops a model of  $I$  states interacting strategically to tax a nonrenewable resource produced by a single representative firm. We develop illustrative intuition by solving the model for the case of two states. Section 3 numerically solves the model with a non-competing third, fringe state that sets the opportunity cost of drilling capital. Texas and North Dakota, which each produce much more oil than any other state (of the 48 contiguous US states), compete for scarce drilling capital. Section 4 presents numerical results. We use simulations to characterize important determinants of tax rates and the distribution of rent. Section 5 discusses model shortcomings and policy implications, and Section 6 concludes.

## 2. Theoretical Model

We present a two-stage model of competition between  $I$  states and a single representative firm. The competing states behave strategically to maximize an objective conditional on the behavior of other states. The oil and gas industry behaves rationally, allocating capital across states to maximize the present value of resource rent. The states, when setting tax rates, have full information about firm objectives and other states' tax rates. Finally, we do not model external costs of oil and gas investment such as environmental or public health externalities. In the first stage of the model, each state  $i \in I$  sets its own severance tax rate,  $\gamma^i$ . In the second stage, the representative firm allocates production capital across states. The game can be solved via backwards induction. Let us discuss the state and firm problems in detail.

The state's problem is to maximize the net present value of the sum of tax revenues and local benefits spillovers from investment as in equation 1. The states anticipate industry responses to changes in severance tax rates. While Gaudet and Long (1994) develop a model of firms who have differing endowments of a nonrenewable resource, our model represents states that control access to resource endowments of differing sizes and extraction costs. Many extraction firms allocate capital across states in a competitive market. The states compete in a game to maximize an objective conditional on the decisions of other states. This stands in contrast to models of relatively few firms with control over a nonrenewable resource who compete in an oligopoly game (Bencheikroun et. al., 2009).

This model departs somewhat from the classical general equilibrium tax competition literature which usually assumes that tax revenues are used to finance public goods. The government maximizes the utility of residents based on the consumption of produced goods and public goods. Instead, we use a partial equilibrium model focused solely on the resource extraction industry. This is a safe assumption if severance tax revenues are a small portion of revenues. Nationwide, severance taxes accounted for approximately 2 percent of state tax revenues in 2014. They were a small portion of revenues for all states in the Continental United

States except North Dakota (54 % of revenues from severance taxes in 2014) and Wyoming (39%).<sup>2</sup> Specifically, state  $i$ 's objective, accounting for industry behavior, is

$$\max_{\gamma^i} \int_0^{T^g} [\gamma^i p_t q_t^i(\gamma^i, \gamma^{-i}, p_t, r, x_0^i, x_0^{-i}) + g(q_t^i)] e^{-\rho t} dt \quad (1)$$

The first term of equation 1 describes the tax revenues of state  $i$  at time  $t$ . Tax revenues are the product of the quantity produced at time  $t$  in state  $i$ ,  $q_t^i$ , the exogenous output price  $p_t$ , and the severance tax rate  $\gamma^i$ .  $q_t^i$  is a quantity of drilling capital allocated to each state, expressed in units of output produced. Capital allocation is the firm's decision and depends on the severance tax rate, other states' tax rates  $\gamma^{-i}$ , price, discount rate  $r$ , state  $i$ 's initial resource stock  $x_0^i$ , and other states' initial resource stocks  $x_0^{-i}$ . The assumption of a fixed and exogenous output price  $p_t = p$ , as in Pindyck (1978), departs somewhat from the large Hotelling-based literature, but allows us to focus our analytics on the role of tax competition (Hotelling 1931).

The second term in equation 1,  $g(q_t^i)$ , describes the weight that policymakers place on local jobs or business in the spirit of Kolstad and Wolak (1985). Note that if  $g(q_t^i) = 0$ , the state seeks to maximize tax revenue. We depart slightly from Kolstad and Wolak (1985) in assuming that state employment impacts are proportional to capital investments, not just to costs. This is consistent with Jacquet (2006).

We assume that states choose their control variable once and do not change it over time. While in principle one could solve for optimal tax rate time paths, states do not regularly modify severance taxes in practice. For example, major oil-producing states including Texas, Oklahoma, and North Dakota have maintained

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<sup>2</sup> Authors' calculation based on 2014 U.S. Census Bureau Annual Survey of State Government Tax Collection. To date, Pennsylvania has used a per-well fee instead of a severance tax. State officials are discussing a severance tax, but it would only raise approximately 3 percent of state revenues (EIA Today In Energy 08/21/15 <http://www.eia.gov/todayinenergy/detail.cfm?id=22612> retrieved 08/24/15).

constant severance tax rates for more than a decade (see Figure 1)<sup>3</sup>. An exception to this includes California, where tax is per barrel instead of percent and is updated regularly.

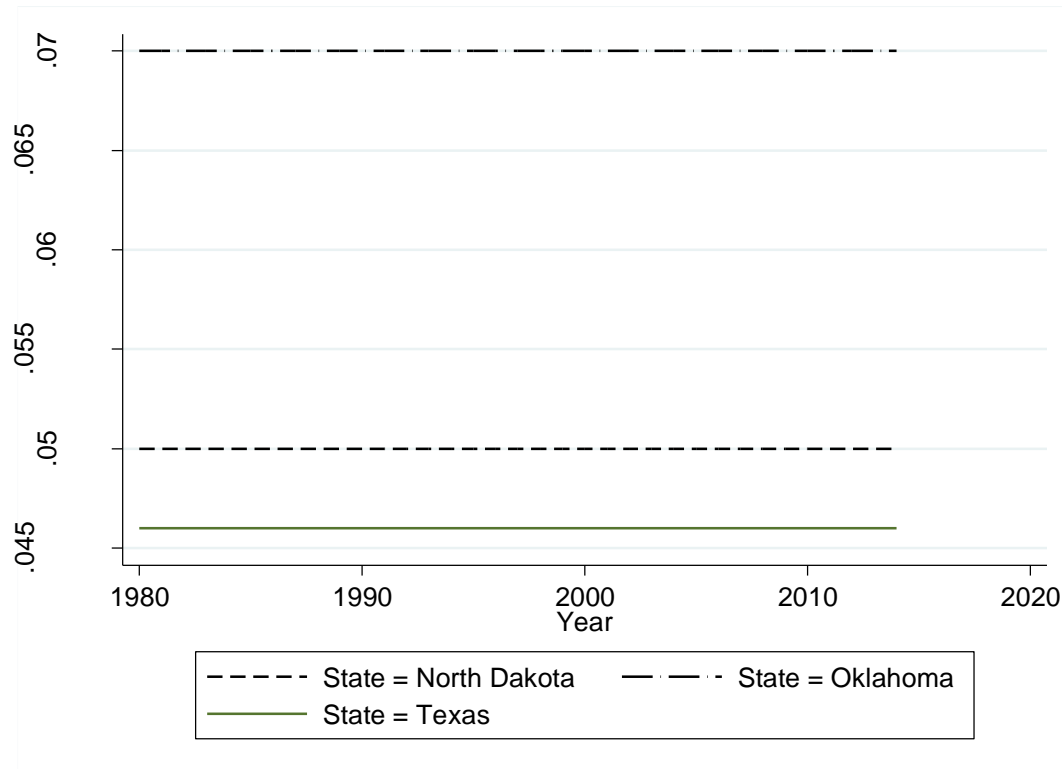


Figure 1: Tax Rates for Selected States Over Time

Table 1 reports 2014 severance tax rates for selected major oil-producing states. Severance tax rates on oil revenue average around 5% in the lower 48 US states. Our model can reveal if and when rate increases would cause states to lose revenue and jobs.

<sup>3</sup> These states also have other taxes and fees, such as environmental clean up taxes. These are typically much smaller in magnitude and have also been stable over our study period.



**Table 1: 2014 Tax Rates for Selected States**

State	2014 tax rate
California	\$ 0.2863572 per barrel <sup>4</sup>
Colorado	5% <sup>5</sup>
North Dakota	5%
Oklahoma	7%
Texas	4.6%

The extracting firm's problem is to allocate limited production capital across states to maximize the net present value of profits. The resource extracting firm receives revenue  $(1 - \gamma^i)pq_t^i$  from investment in time  $t$  while incurring costs,  $c^i(q_t^i, x_t^i)$ .  $x_t^i$  is the stock of the resource remaining in state  $i$  at time  $t$ . The shape of the cost curve is state-specific to capture geologic variation in extraction costs. We assume that  $\frac{\partial c^i(q_t^i, x_t^i)}{\partial q_t^i} > 0$ ,  $\frac{\partial^2 c^i(q_t^i, x_t^i)}{\partial q_t^{i2}} > 0$ ,  $\frac{\partial c^i(q_t^i, x_t^i)}{\partial x_t^i} < 0$ , and  $\frac{\partial^2 c^i(q_t^i, x_t^i)}{\partial x_t^i \partial q_t^i} \geq 0$ . The resource stock in state  $i$  evolves over time according to  $\dot{x}^i = -q_t^i$ . The sum of capital invested across all states cannot exceed the available capital,  $\bar{q}_t$ . This can be expressed as  $\sum_{i=1}^I q_t^i \leq \bar{q}_t$ . Let the co-state variable for the resource stock be  $\lambda_t^i$  and  $\mu_t$  is the multiplier associated with the capital constraint. We assume that the oil industry owns all mineral rights. This abstracts away from the case in practice where an additional bargaining game occurs between mineral rights holders and the extraction industry (discussed in (Timmins and Vissing 2014)). The industry objective is to

$$\max_{q_t^i} \int_0^T \left( \sum_{i=1}^I (1 - \gamma^i)pq_t^i - c^i(q_t^i, x_t^i) \right) e^{-rt} dt \quad (2a)$$

*s. t.*

$$\dot{x}^i = -q_t^i \quad (2b)$$

<sup>4</sup> A representative oil price (WTI) averaged approximately \$93 during 2014, making the California tax rate approximately 0.3%.

<sup>5</sup> The Colorado tax rate has several tiers. We report the highest.

$$\sum_{i=1}^I q_t^i \leq \bar{q}_t \quad (2c)$$

Note that  $q_t^i$  measures both production and production capacity. The representative firm chooses to allocate finite production resources across states. Similar to Anderson et al., (2014),  $\bar{q}_t$  represents a drilling capacity constraint on the industry. This can be thought of as allocating a limited number of drilling rigs, with time normalized such that the lifespan of a well is one time step. We make this simplification for analytical tractability and it implicitly assumes that all benefit from a drilled well occurs in the period of drilling. This is not true in reality as some wells last longer than others. We therefore fail to discount production that occurs at different times across different wells. Assuming a short well lifespan makes more sense in the context of hydraulic fracturing where wells need to be re-fracked (using drilling capital) to maintain extraction rates.

Also, we assume that marginal extraction costs are negligible while drilling a well is costly. Prices remain constant over time, as in a representative firm model, and production capacity can respond to industry rents.

The capital constraint  $\bar{q}_t$  can alternatively be thought of as representing a constraint on downstream processing in a state – for example, refinery capacity (in the absence of trade). In either case, capital enters (exits) at rate  $\alpha$  if there are positive (negative) marginal profits to capital,  $R_t$ :

$$\frac{\partial \bar{q}_t}{\partial t} = \alpha R_t \quad (3)$$

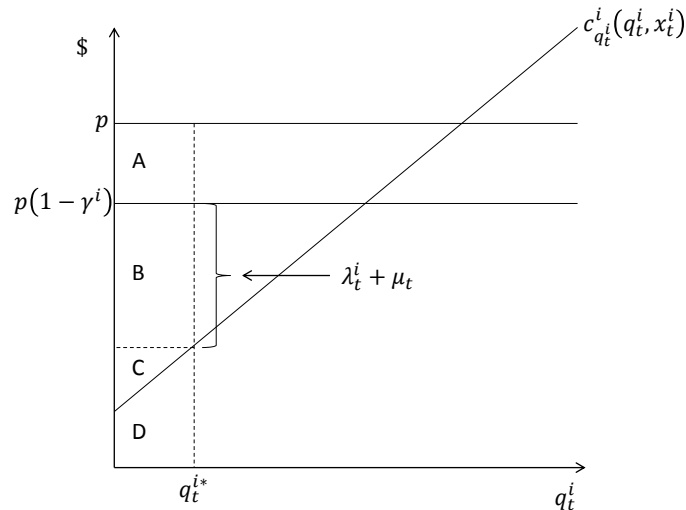
The marginal profits of capital are calculated as  $R_t = \mu_t$ . For the purpose of the firm problem, however, we assume that investment decisions do not account for the impact of marginal profits on entry. This imposes that the firms do not make decisions to limit entry into the market, an extension of our assumption of competitive resource markets.

## 2.1 Division of Resource Rents

Conceptually, a state and the oil and gas industry divide the surplus between the price and the marginal cost of investment – the sum of the areas A+B+C in Figure 2. Area A is the state's share and is equal to  $\gamma^i p_t q_t^i$ . Area B is the sum of the resource and capital rents captured by the industry, or  $(\mu_t + \lambda_t^i) q_t^i$ . Area C is the within-state Ricardian rents  $p q_t^i (1 - \gamma^i) - c^i(q_t^i, x_t^i) - (\mu_t + \lambda_t^i) q_t^i$  and is also captured by the industry. Finally, the cost of investment is Area D.

In our simplest model, the government seeks to maximize severance tax revenue A. Increasing the tax rate will decrease the investment level  $q_t^i$ , but will increase the government's share of the inframarginal Ricardian rents. Depending on the elasticity of investment  $q_t^i$  with respect to  $\gamma^i$ , the state may be able to increase its own revenue by increasing  $\gamma^i$ . This elasticity depends on marginal profitability of investment in other states as well as the dynamic impacts of extraction today.

**Figure 2: The Division of Resource Rent between Government and Industry**



## 2.2 Solving the model

The model is solved in two stages. First, we solve for the industry allocation of capital across states conditional on prices, costs, and state severance tax rates. Next, we solve the state competition game in which states set tax rates conditional on other states' rates and anticipated industry behavior. We assume that  $\alpha = 0$  in our interpretation of analytical results.

To solve the industry problem, we construct a Lagrangian that consists of the Hamiltonian plus the incorporation of constraint 2c (Kamien and Schwartz 2012).

This takes the following form:

$$L = \sum_{i=1}^I (1 - \gamma^i) p q_t^i - c^i(q_t^i, x_t^i) + \sum_{i=1}^I \lambda_t^i (-q_t^i) + \mu_t \left( \bar{q}_t - \sum_{i=1}^I q_t^i \right)$$

The necessary conditions state that:

$$\frac{dL}{dq_t^i} = (1 - \gamma^i) p - c_{q_t^i}^i(q_t^i, x_t^i) - \lambda_t^i - \mu_t = 0 \quad \forall i \quad (4a)$$

$$\dot{\lambda}_t^i - r \lambda_t^i = c_{x_t^i}^i(q_t^i, x_t^i) \quad \forall i \quad (4b)$$

$$\bar{q}_t = \sum_{i=1}^I q_t^i \quad (4c)$$

$$\dot{x}^i = -q_t^i \quad (\lambda_t^i) \quad (4d)$$

To develop intuition about how the firm allocates capital across states, we solve the firm problem for the case of two states and a binding capital constraint. In other

words,  $q_t^2 = \bar{q}_t - q_t^1$ . Specifying the cost function as  $C^i(q, x) = \frac{A^i q^2}{2x}$ ,  $A^i > 0$ , the firm's Lagrangian becomes

$$L = (1 - \gamma^1)pq_t^1 - \frac{A^1 q_t^{1^2}}{2x_t^1} + (1 - \gamma^2)p(\bar{q} - q_t^1) - \frac{A^2(\bar{q} - q_t^1)^2}{2x_t^2} + \lambda_t^1(-q_t^1) + \lambda_t^2(q_t^1 - \bar{q}) \quad (5)$$

Using the necessary conditions, we express  $q_t^{1*}$  as a function of exogenous parameters and endogenous state and co-state variables. While this does not represent the model solution, it provides intuition about the factors influencing the optimal allocation of scarce drilling capital.

$$q_t^{1*} = \frac{p(\gamma^2 - \gamma^1) + \bar{q}\left(1 - \frac{A^1}{x_t^{1*}}\right)}{\frac{A^1}{x_t^{1*}} + \frac{A^2}{x_t^{2*}}} + \frac{\lambda_t^{2*} - \lambda_t^{1*}}{\frac{A^1}{x_t^{1*}} + \frac{A^2}{x_t^{2*}}} \quad (6)$$

The first term describes how the firm balances contemporary profits across the two regions.  $q_t^{i*}$  decreases in the severance tax rate of state  $i$  but increases in the rate of state  $j \neq i$ .

The  $\left(1 - \frac{A^1}{x_t^{1*}}\right)$  term describes the impact of state-level investment cost. A higher value of  $A^1$  means that total and marginal investment costs are higher, conditional on stock and investment levels. From this term we see that higher marginal costs lead to lower investment levels. Investment costs can be higher either because of the cost parameter  $A^1$  or because of a lower stock  $x_t^{1*}$ .

The final term,  $\lambda_t^{2*} - \lambda_t^{1*}$ , characterizes the intertemporal costs considered by the firm. If  $\lambda_t^{2*} > \lambda_t^{1*}$ , then the resource is less scarce in state 1 than state 2. This means that the firm incurs a lower dynamic resource opportunity cost by extracting in state 1, leading to higher investment in state 1. Analytical solutions to the industry capital allocation problem are infeasible because there is no known

solution to the system of differential equations. Nevertheless, we can solve them numerically to understand how states respond to different levels of severance taxes.

Before solving the model numerically, we solve the state problem, which is to balance rent collection with local jobs created by the extraction industry. Plugging  $q_t^{i*}$  from the model solved above into equation 1, and using Leibniz' rule to take the first order condition, the optimal tax rate for state  $i$  solves the following equation

$$\int_0^T \left[ p q_t^{i*} \left( 1 + \frac{\gamma^i}{q_t^{i*}} \frac{\partial q_t^{i*}}{\partial \gamma^i} \right) + V^i J \frac{\partial q_t^{i*}}{\partial \gamma^i} \right] dt = 0$$

This condition assumes that conjectural variation,  $\frac{\partial \gamma^{-i}}{\partial \gamma^i} = 0$ .  $V^i$  is the money value that a state government places on an additional job created in the sector while  $J$  captures the number of jobs per unit of resource extracted. The first term represents the marginal benefit of raising severance tax rates and captures the additional revenue raised on all units extracted in a state as well as the change in units extracted with the higher tax rate. This term remains positive as long as  $\left| \frac{\gamma^i}{q_t^{i*}} \frac{\partial q_t^{i*}}{\partial \gamma^i} \right| < 1$ . This assumes that  $\frac{\partial q_t^{i*}}{\partial \gamma^i} < 0$ . If  $V^i = 0$ , the government raises taxes until the first term equals zero. On the other hand, given a positive value of local jobs created, the government balances this effect with the additional cost of losing investment in the state, equal to  $V^i J \frac{\partial q_t^{i*}}{\partial \gamma^i} < 0$ .

Analytical solutions to the states' problem are also infeasible because the analytical forms of  $q_t^{i*}$  do not exist. Therefore, we turn to a numerical application in order to gain understanding of the states' ability to collect resource rents in a context of state tax competition.

### 3. Numerical Solution and Application

To explore the properties of the solution to the asymmetric state competition model, we extend the two-state example to include a third, non-competitive state with a fixed severance tax rate. The third state sets the opportunity cost of drilling capital invested in the competing states. The objective of this exercise is to develop

an understanding of how model parameters affect the optimal tax rates and industry extraction paths. To characterize model solutions, we calibrate the model to an example from the two largest oil-producing US states (excluding Alaska) and we investigate how solutions respond to model parameters.

### *3.1 Model Calibration*

We parameterize the model using observed onshore oil reserves and extraction in Texas, North Dakota (ND), and the rest of the United States, excluding Alaska (rUS). We allow Texas and ND to compete by choosing severance tax rates while the rUS behaves as a non-competitive fringe. As of 2013, Texas and ND had over half of US reserves in the lower 48 states and represented more than half of total oil production. Given the dominant role played by the two states, they likely compete to attract investment in oil extraction.

Table 2 displays the parameters used for the base model of state tax competition. Unlike the Hotelling model of industry behavior, a given firm takes price as exogenous. Under the assumption that production even in two large US states does not influence world prices, we specify a constant oil price over time equal to \$85 per barrel. We assume a planning horizon for the industry of 50 years and that the state is also interested in rents and jobs over this period. Based on data from the US Energy Information Administration (EIA), we assume that each million barrels of oil extracted in a given year creates 100 jobs during that year. Total industry drilling capital is expressed in terms of the quantity of oil that can be extracted. This assumes a constant long-term ratio between drilling capital and a quantity of oil produced (though the cost of investment and extraction depend on reserve levels and state-specific costs). In the base model, we assume that industry capital is fixed but we also explore the impact of a capital stock that increases in response to industry rents. Because our model's stock variables represent total geologic stock and not merely current proven reserves, we assume that oil stocks are 10 times current proven reserves as reported by the EIA. The discount rate is assumed equal to 0.10 for both the industry and state governments. Finally, we

assume that both competing states value a job created in the state at \$100,000 of government revenue. Therefore,  $V^i = \$100,000$  for all  $i$ .

The rUS tax rate is fixed at 0.05, which is both comparable to current rates and substantially lower than the equilibrium rates obtained for Texas and ND across our core scenarios. This alleviates the concern that in non-cooperative games, equilibria typically approach competitive equilibrium as  $N$  gets large – the states which we model as noncompetitive are effectively playing a very aggressive strategy, as rates are much lower than suggested by tax competition with small  $N$ . This allows our model to approximate a game with a higher number of competitive states.

The cost parameter  $A_i$  is parametrized based on the assumption that the marginal cost of production in a state is equivalent to the breakeven price in the marginal field in the state. Based on the cost function  $\frac{A^i q^2}{2x}$ , we solve for the cost parameter

$$A_i = \frac{MC_i x_i}{q_i}$$

The marginal fields are the Barnett, Bakken non-core, and Mississippi Lime for Texas, ND, and the rUS respectively and their breakeven costs are presented in Table 2.



**Table 2: Base Parameter Values**

	Value
Price (Dollars per Barrel per Year)	85
T (Years)	50
Jobs per Million Barrels Produced	100
Industry Capital (Million Barrels per Year)	931.15
Discount Rate	0.1
<b>Texas</b>	
Marginal Extraction Cost (Dollars per Barrel)	93
A (Billion Dollars per Year)	105418.13
X0 (Million Barrels per Year)	104670
Production Capital (Million Barrels per Year)	923.4
Value of Oil and Gas Job	100000
<b>North Dakota</b>	
Marginal Extraction Cost (Dollars per Barrel)	90
A (Billion Dollars per Year)	1562477.06
X0 (Million Barrels per Year)	56770
Production Capital (Million Barrels per Year)	32.7
Value of Oil and Gas Job	100000
<b>Rest of USA</b>	
Marginal Extraction Cost (Dollars per Barrel)	84
A (Billion Dollars per Year)	137818.58
X0 (Million Barrels per Year)	148680
Production Capital (Million Barrels per Year)	906.2
Tax Rate	0.05
It is assumed that geologic oil stocks are 10x 2013 proven reserves.	
Marginal fields are Barnett, Bakken Non-core, and Mississippi	
Lime for Texas, North Dakota, and the Rest of the USA.	
All reserve and production data from 2013.	

The 3-state model with two competitive states is solved numerically to explore how the division of resource rent is affected by state tax competition. The derivation of the 6-variable system of ordinary differential equations that govern industry behavior is presented in Appendix I. The system of ordinary differential equations is solved numerically using `bvp4c` in Matlab. Initial conditions for state variables combine with transversality conditions that  $\lambda_T^i = 0$  to close the model. State  $i$

chooses tax rates to maximize its objective function conditional on other states' behavior. A nonlinear programming function (Matlab's `fminunc`) is used to maximize each state's objective function conditional on a range of rates from the other state and on industry behavioral responses to tax levels. The two best response functions are fit to optimal response points using a linear spline. Their intersection determines the Nash equilibrium tax rates in the state tax competition model.

#### **4. Numerical Results**

Our core result is that optimal state tax rates with state tax competition are substantially larger than observed tax rates. This holds across a wide array of parameterizations. To rationalize severance tax rates below 10%, production capital must be scarce or policymakers must value industry presence at \$500,000 a year per job. As a back-of-the envelope calculation, \$500,000 per job implies an employment multiplier of 10.5<sup>6</sup>, as compared with recent literature estimates of approximately 2.3 (Weber 2014). We also show that the impact of tax competition is asymmetric. Texas's optimal tax rate is insensitive to North Dakota's tax rate, whereas North Dakota is responsive to Texas rates.

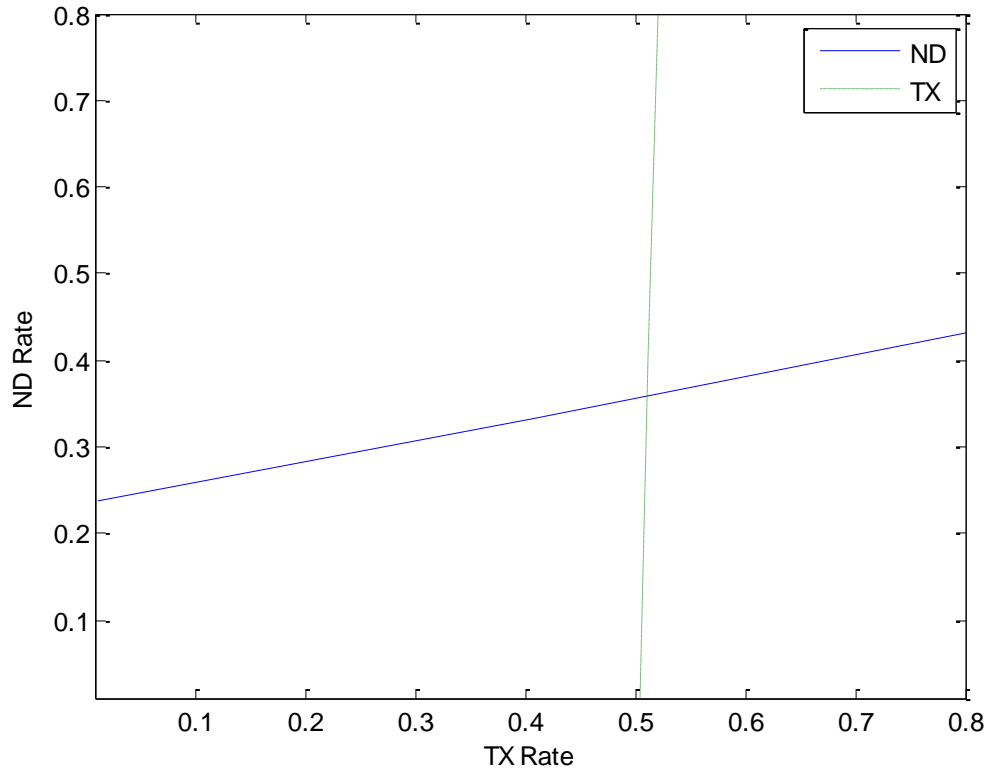
Using the base parameters, we calculate each competitive state's best response function and find their intersection to solve for the model equilibrium. Figure 3 shows that the Nash equilibrium (NE) tax rate for Texas remains around 0.5 and does not respond substantially to changes in the ND rate. On the other hand, as Texas charges a higher rate, the ND NE rate increases, but stays in the range of 0.2 to 0.4. These results are driven by Texas' control of larger, more cheaply accessible resource stocks. In this way, Texas controls a relatively scarce input into resource extraction and can maintain a high tax rate with a smaller effect on industry investment in the state. Lower extraction costs mean that Texas oil brings more rent than other, more expensive locations. The state can take a larger share of these rents before outflows of capital dominate increases in revenue from higher tax

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<sup>6</sup> Based on dividing government value of industry employment (\$500,000) by the May 2014 US mean full-time wage of \$47,230 from BLS.

rates. As ND decreases its tax rate, this incentivizes only a small amount of extraction capital to exit Texas.

**Figure 3: Best Response Functions for Texas and North Dakota**



*Texas and North Dakota compete by setting severance tax rates; other US states (excl. Alaska) have a fixed rate of 5%.*

If ND raises rates on its more expensive oil reserves, capital can go to Texas where costs are lower. Note that the ND best response tax rate is not always less than the Texas rate. This occurs because at very low Texas rates, ND can keep rates higher, earning a higher rate on lower investment. As the Texas rate increases, ND increases its best response tax rate at a slower rate. Beyond a Texas rate of approximately 30%, the ND equilibrium rate becomes lower than Texas' in order to maintain investment in the state.

Consistent with the best response functions presented in Figure 3, Table 3 shows that both states have a unilateral incentive to deviate from current tax levels. While ND rents are always small compared to Texas, state severance tax revenue can be increased by more than 40% by unilaterally increasing rates to 25%. There is a limit to ND's ability to raise revenue because Texas has relatively cheap and abundant oil reserves. This means that Texas can increase its objective by increasing rates to approximately its Nash equilibrium rate even when ND maintains a low severance tax rate.

**Table 3: Impacts of Deviations from Current (5%) Tax Rates**

	Texas Objective	North Dakota Objective
Texas Tax Rate		
5%	67.63	2.63
15%	98.03	2.85
25%	120.97	3.07
35%	136.42	3.30
45%	144.36	3.53
55%	144.77	3.76
65%	137.63	3.99
ND Tax Rate		
5%	67.63	2.63
15%	67.85	3.45
25%	68.07	3.71
35%	68.29	3.41
45%	68.51	2.55
55%	68.74	1.13
65%	68.95	0.03
Objectives are expressed in billions of USD and are the present value of flows over 50 years		

For simplicity, the model developed here contains no externalities. Therefore, from an efficiency perspective, taxes only decrease the net value of resource extraction over time. If the external impacts of oil and gas extraction are considered, this may no longer hold. Table 4 demonstrates that taxes decrease the total net value of

extraction through the impact on total extraction costs. Because  $\bar{q}_t$  is assumed constant in base models, total quantity extracted over the period does not change with the tax rate. Instead, taxation changes the timing and location of extraction. With a zero tax, the industry equates the full marginal costs of extraction (including dynamic costs but not externalities) across states. The introduction of taxation shifts investment away from the cost-minimizing extraction paths. As seen in Table 4, total extraction costs are higher with NE tax rates. Interestingly, the additional extraction costs are incurred in the non-competing states because of lower overall investment in competing states.

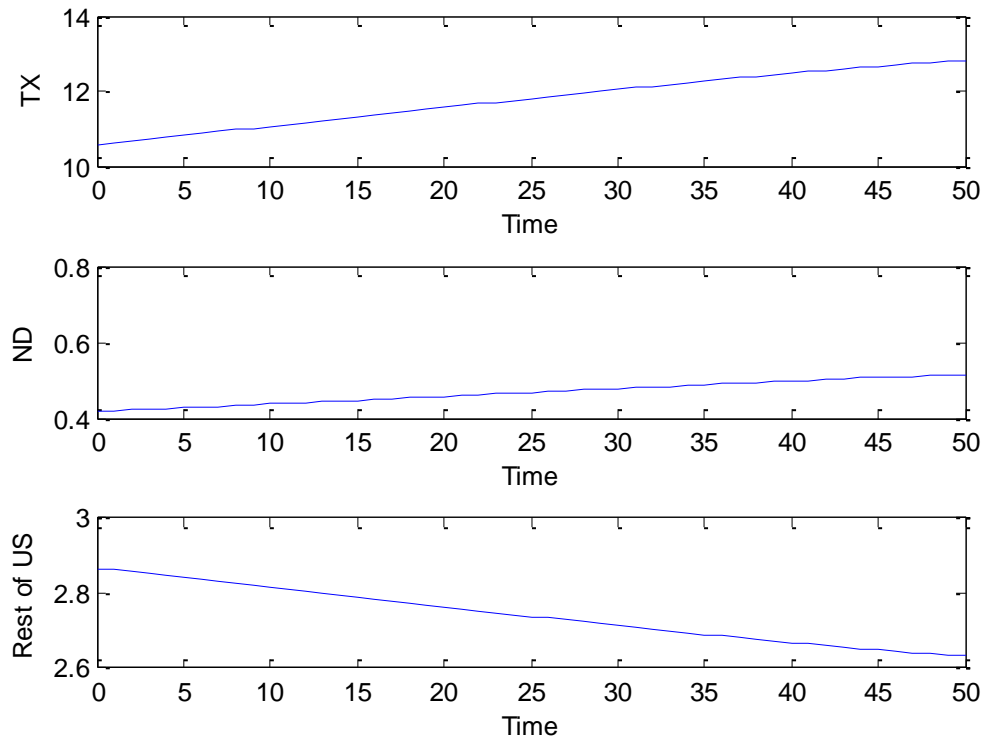
**Table 4: Present Value of Total Extraction Costs**

	Billions of Dollars, NPV over 50 Years			
	Texas	North Dakota	Rest of US	Total
No Tax	108.38	4.30	120.15	232.84
NE Tax Rate	36.44	3.09	232.44	271.98

#### *4.1 Division of Rents*

Figure and Figure demonstrate the time paths of rent collected by states and industry in each of the three states modeled here. The higher taxes in Texas and ND compared to the rUS cause state government rents to increase over time. As the rUS depletes oil reserves and extraction costs rise, this creates an incentive for oil firms to move into the higher-tax states with more abundant resource stocks. Therefore, the higher equilibrium taxes change the timing of oil extracted in each state. The higher Nash equilibrium rates also cause a 37% and 14% decrease in total oil extracted in Texas and ND over the 50 year planning horizon. The rUS sees an increase in total oil extracted of almost 34%. Extraction paths can be found in Appendix II and it becomes apparent that higher taxes delay oil extraction. Texas extraction is lower in all periods, which suggests that higher value on job creation could push the optimal rate for Texas to lower levels.

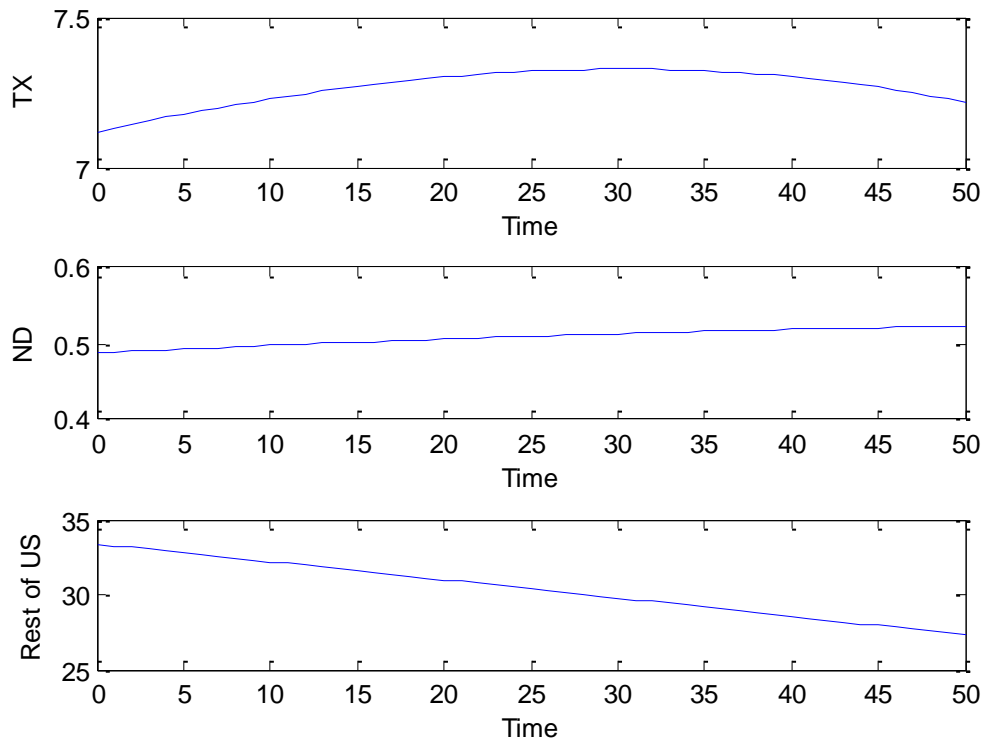
**Figure 4: State Severance Tax Revenue from Nash Equilibrium Tax Rates**



*Annual revenue is expressed in billions of US dollars. Texas and North Dakota compete by setting tax rates while the rest of the US keeps a constant 5% tax rate.*

Comparison of industry profit to government revenues demonstrates that in Texas, the state government can collect a relatively large share of resource rents. In the rUS, industry rents go down over time as extraction costs increase and capital reallocates to Texas and ND.

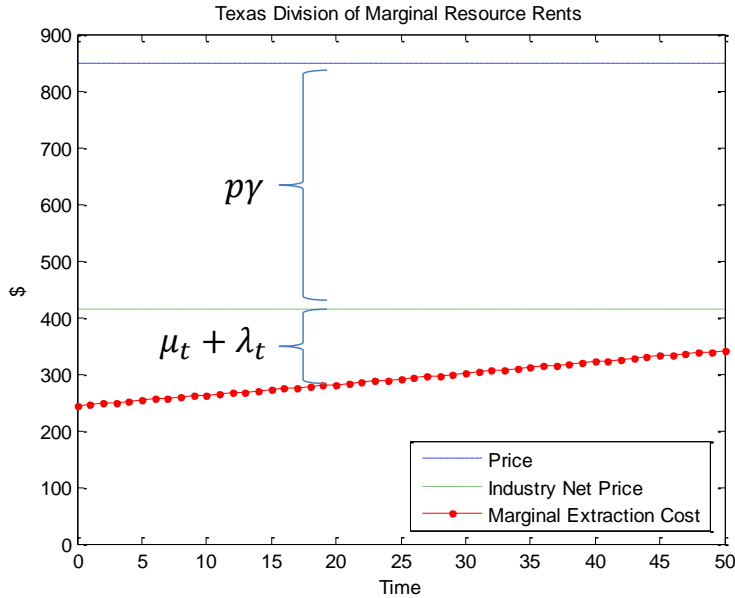
**Figure 5: Industry Profit Paths Given Nash Equilibrium State Tax Rates in TX and ND**



*Profits are expressed in billions of US dollars. Texas and North Dakota compete by setting tax rates while the rest of the US keeps a constant 5% tax rate.*

Figure 6 presents the numerical division of resource value between government and industry in Texas. Marginal extraction costs rise over time, resulting in a decrease in marginal earnings for the industry. This differs from a conventional model of nonrenewable resource extraction in which marginal earnings increase over time. This occurs because industry extraction remains constant over time. Again, it becomes apparent that, on the margin, the Texas government gets a high share of net resource value.

**Figure 6: Division of Rents in Texas**



#### 4.2 Qualitative Parameter Impacts

This numerical exercise can also highlight the role of the parameters in this state tax competition model. Table 5 demonstrates a clear relationship between the relative scarcity of industry capital and natural resource stocks and equilibrium tax rates. For these simulations, we vary the initial capital level (top panel) or total resource base (middle panel), holding all else constant. In each case, the entry speed of production capital is set to zero (i.e.,  $\alpha = 0$ ). As industry capital becomes scarcer, marginal returns to the industry increase. This translates into a larger share of total rents. If capital is abundant, states can increase rates without affecting total investment in the state over time. In this case, the input controlled by the state is relatively scarce, meaning the state collects a larger share of resource rents.

Capital abundance (or scarcity) is relative to stocks. If capital stock is held constant and the resource base is increased as in the middle panel of Table 5, the capital becomes relatively scarcer and industry has more options for allocating capital. The opportunity to exit a given state becomes more credible as other investment opportunities increase. Therefore, as resource stocks become more abundant across all states, equilibrium tax rates lower.



In addition to resource stocks, tax rates depend on the relative investment costs in each state. In Table 5, we vary the relative costliness of Texas and North Dakota by varying the cost parameter,  $A$ . (In our core parameterization, the ratio of  $A_{TX}$  to  $A_{ND}$  is 0.067). We see that as investment gets more expensive in Texas, North Dakota is able to raise its tax rates substantially. The effect of relative costs is similar to the effect of relative stock abundance across states. As the Texas stock decreases, costs increase and the ND NE rate increases.

The first panel of Table 6 demonstrates that the capital speed of entry influences equilibrium tax rates. If capital can enter the industry quickly, this essentially makes capital less scarce over the relevant time horizon, which would suggest higher equilibrium tax rates. Interestingly, the ability of the industry to respond to rents and increase the total quantity invested over time leads to higher total rents from the sector. For these illustrative parameterizations, rent actually increases for all three governments and industry but rent captured by the states increases by more than that of the industry.

Finally, the second panel of Table 6 demonstrates that if a state places a higher value on local jobs relative to increased government revenue, then optimal rates decrease. This attracts more investment to both competing states. Importantly, in these scenarios the total production capital stock is fixed. This means that lower tax rates do not attract more capital or lead to more production – instead they are the non-cooperative equilibrium of a game in which states are more motivated to attract a share of fixed extraction capital (and economic activity) by lowering tax rates.

## **5. Discussion and Policy Implications**

The model presented here qualitatively describes how state tax competition influences optimal severance tax rates in a context of scarce industry extraction capital and resource stocks. As predicted, control of scarce natural resource stocks allows states to set relatively high severance taxes without deterring oil and gas investment at a large scale. This results in a relatively high optimal tax rate that

balances government revenue with local job creation. While we do not attempt to solve for optimal rates in practice, several implications follow from our qualitative numerical analysis. First, states with abundant resources can raise severance tax rates from low initial levels without causing a large outflow of capital. Some capital leaves and/or changes the timing of extraction but there is no knife edge response from the oil and gas industry from marginal changes in tax rates. An increase from low initial tax rates can increase revenue per unit extracted and more than offset the decrease in revenue and economic activity from marginal decreases in extraction in early periods. Therefore, if states need to increase tax revenues, severance taxes may provide an opportunity.

Also, we find higher equilibrium tax rates than (Kolstad and Wolak 1985). Our model explicitly captures the division of resource rents that come from the internalization of the dynamic costs of using natural assets today. On the other hand, rents generated in the static model of Kolstad and Wolak (1985) come from state market power. Therefore, the shared rents in our model differ in nature from those generated in the Kolstad and Wolak (1985).

While the model presented here develops important insights into the role of natural resource stocks in determining the optimal division of resource rents in a context of mobile capital, we have made several simplifying assumptions that could affect the level of optimal taxes in the model. For example, we assume no cost of moving capital across states. In reality, transportation and regulatory costs associated with crossing states lines could be high. This could trap capital in a given state and put upward pressure on optimal tax rates. This may partially explain high severance tax rates in the US state of Alaska (the current rate is 25%), where large oil stocks are in remote locations associated with high costs of moving capital.

We have also ignored the potential for price or technology changes over time. Foreseeable cost decreases in a given state would incentivize the industry to delay extraction. If that state places high value on revenue in the near future, this could cause a decrease in optimal tax rates. We also assume that state resource stocks are exogenous. In reality, they may be a function of tax rates if lower rates increase the incentive to invest in exploration.

In practice, the setting of state tax rates involves a complex, politically-driven process. Legal restrictions may limit a state's ability to tax residents. There also exist important interactions between severance taxes set at different levels of government (e.g., county, state, and federal). Therefore, our model is not meant to predict the levels of state taxes. Instead, it focuses on the role of state tax competition in affecting tax rates to examine the conditions under which states should worry about industry threats to leave if tax rates rise. If the industry is competitive, increases in tax rates could change the timing of investments and prevent investment in marginal stocks, at least over the 50-year time horizon of the model. Nevertheless, in the case examined here, the benefit of increased revenue on the extracted stock more than compensates for any reduced extraction. This holds in this case, but in general depends on the relative scarcity of extraction capital and resource stocks.

The results presented here have lessons for other resource-dependent regions of the world. For example, 70% of Nigeria's government revenue comes from the oil sector. Other African countries (e.g., Tanzania) with newly discovered reserves have begun to construct policy frameworks to divide resource rent between industry and government. As severance tax rates are set, countries where oil and gas extraction depend disproportionately on external investment must choose tax rates that maintain investment levels while at the same time ensuring that sufficient resource rents are captured and invested locally to replace the loss of resource stocks. Our results suggest that countries with relatively large, cheaply accessible resource stocks can set relatively high tax rates without deterring investment. Of course, in some cases, firms may need an additional incentive to invest in politically risky countries. We have not considered this additional factor.

Finally, the benefit of raising taxes to fund public goods must be weighed against the cost to the oil and gas industry. We have not modeled the external costs of oil and gas extraction, meaning that taxes decrease welfare in the modeled sector. To gain a full understanding of socially optimal tax levels, a general equilibrium model is required. If oil and gas taxes can reduce pollution while raising revenue and lowering taxes elsewhere, this can lead to a welfare improvement.

## 6. Conclusion

This work develops a model in which states strategically set severance tax rates to capture a share of resource rents while valuing local economic activity. While solving the model requires several simplifying assumptions, we find that industry threats to leave a state with substantial oil resources are not credible for plausible parameterizations. Therefore, it is in states' interest to unilaterally raise severance taxes and optimal Nash equilibrium rates are substantially higher than current rates.

The model presented here provides motivation for future empirical work that investigates the discrepancy in practice between high Nash equilibrium rates and relatively low rates in practice. An empirical exploration of the factors influencing severance tax rates in practice can reveal the relative importance of tax competition and other factors. Possibilities include high multiplier effects or large positive externalities from oil and gas investment, political economy explanations, or inefficient policy regimes. Future work should also follow the empirical tax competition literature to test if US states behave strategically when setting oil and gas severance tax rates.

**Table 5: Role of Industry Capital and Resource Reserves**

			Total Rent (Billions of Dollars, NPV over 50 Years)				Total Rent	Industry Rent Share
	Texas NE Rate	ND NE Rate	Texas Rent	ND Rent	Rest of US Rent	Industry Rent		
Industry Capital, Million Barrels per Year								
300	13%	7%	12.85	0.38	8.69	231.58	253.51	91%
500	25%	16%	34.95	1.24	15.68	338.68	390.55	87%
700	37%	25%	67.93	2.57	22.67	407.10	500.27	81%
900	49%	34%	112.45	4.43	29.66	435.27	581.81	75%
1100	62%	44%	169.21	6.85	36.66	421.52	634.23	66%
1300	76%	54%	238.98	9.91	43.65	364.00	656.55	55%
1500	90%	65%	322.59	13.67	50.65	260.76	647.67	40%
Total Reserves, Relative to Base								
0.8	67%	47%	152.05	6.21	31.11	326.38	515.75	63%
1	51%	36%	120.46	4.76	30.75	435.93	591.91	74%
1.2	41%	29%	100.13	3.85	30.39	507.15	641.53	79%
1.4	39%	23%	85.91	3.23	30.03	557.22	676.39	82%
1.6	29%	20%	75.38	2.76	29.67	594.37	702.19	85%
1.8	26%	17%	67.26	2.40	29.32	623.07	722.05	86%
2	23%	14%	60.78	2.12	28.96	645.92	737.77	88%
Ratio of Texas A to ND A (ND A held constant)								
0.010	50%	23%	209.53	2.33	21.64	497.58	731.07	68%
0.100	51%	39%	97.63	5.51	32.98	420.91	557.03	76%
0.200	52%	44%	61.99	6.78	36.41	397.76	502.94	79%
0.300	52%	46%	45.51	7.41	37.99	387.12	478.03	81%
0.400	52%	48%	35.97	7.79	38.89	380.97	463.63	82%
0.500	52%	49%	29.75	8.05	39.48	376.96	454.25	83%

**Table 6: Role of Capital Entry Speed and State Government Value of Local Jobs**

Table 4: Industry Capital, Nash Equilibrium Tax Rates, and Rent								
Total Rent (Billions of Dollars, NPV over 50 Years)								
	Texas NE Rate	ND NE Rate	Texas Rent	ND Rent	Rest of US Rent	Industry Rent	Total Rent	Industry Rent Share
Capital Speed of Entry, Million Barrels per Hundred Thousand Dollars of Industry Rent								
0.001	51%	36%	120.78	4.77	30.77	436.26	592.59	74%
0.01	51%	36%	123.46	4.84	30.98	439.01	598.29	73%
0.1	48%	38%	141.06	5.40	32.56	453.82	632.84	72%
1	46%	42%	169.71	6.50	35.70	471.00	682.90	69%
Government Value of Local Industry Jobs, Dollars per Job								
-	57%	43%	122.34	5.21	31.88	421.52	580.96	73%
90,000	52%	37%	120.77	4.82	30.86	434.43	590.88	74%
100,000	51%	36%	120.46	4.76	30.75	435.93	591.91	74%
200,000	45%	29%	116.02	4.14	29.62	451.70	601.48	75%
300,000	39%	21%	109.02	3.33	28.49	468.81	609.66	77%
400,000	33%	14%	99.47	2.35	27.36	487.28	616.46	77%
500,000	27%	7%	87.38	1.19	26.24	507.08	621.89	77%

*Note: Rent refers to net value of extracted resource. It does not include the value government places on job creation.*

## Appendix I

Derivation of 3-state model with 2 competitive states.

$$H = (1 - \gamma_1)pq_1 - \frac{A_1q_1^2}{2x_1} + (1 - \gamma_2)pq_2 - \frac{A_2q_2^2}{2x_2} + (1 - \gamma_3)p(\bar{q} - q_1 - q_2) - \frac{A_3(\bar{q} - q_1 - q_2)^2}{2x_3} + \lambda_1(-q_1) + \lambda_2(-q_2) + \lambda_3(-(\bar{q} - q_1 - q_2))$$

$$\frac{dH}{dq_1} = (1 - \gamma_1)p - \frac{A_1q_1}{x_1} - (1 - \gamma_3)p + \frac{A_3(\bar{q} - q_1 - q_2)}{x_3} - \lambda_1 + \lambda_3 = 0$$

$$\frac{dH}{dq_2} = (1 - \gamma_2)p - \frac{A_2q_2}{x_2} - (1 - \gamma_3)p + \frac{A_3(\bar{q} - q_1 - q_2)}{x_3} - \lambda_2 + \lambda_3 = 0$$

$$\dot{\lambda}_1 = r\lambda_1 - \left( \frac{A_1q_1^2}{2x_1^2} + \right)$$

$$\dot{\lambda}_2 = r\lambda_2 - \left( \frac{A_2q_2^2}{2x_2^2} \right)$$

$$\dot{\lambda}_3 = r\lambda_3 - \left( \frac{A_3(\bar{q} - q_1 - q_2)^2}{2x_3^2} \right)$$

Obtain system of ODEs in state and co-state:

Step one, use  $q_2$  foc to solve for  $\hat{q}_2(q_1)$

$$\hat{q}_2 = \frac{\left( p(\gamma_3 - \gamma_2) + \frac{A_3\bar{q}}{x_3} - \frac{A_3q_1}{x_3} - \lambda_2 + \lambda_3 \right)}{\frac{A_3}{x_3} + \frac{A_2}{x_2}}$$

Step 2: plug  $\hat{q}_2$  in to  $q_1$  foc and solve for  $q_1^*$ .

$$q_1^* = \frac{\left( \frac{A_3\bar{q}}{x_3} - \frac{A_3}{x_3} \left( \frac{\left( p(\gamma_3 - \gamma_2) + \frac{A_3\bar{q}}{x_3} - \lambda_2 + \lambda_3 \right)}{\frac{A_3}{x_3} + \frac{A_2}{x_2}} \right) - \lambda_1 + \lambda_3 + p(\gamma_3 - \gamma_1) \right)}{\frac{A_1}{x_1} + \frac{A_3}{x_3} - \frac{\frac{A_3^2}{x_3^2}}{\frac{A_3}{x_3} + \frac{A_2}{x_2}}}$$

Step 3: plug  $q_1^*$  into  $\hat{q}_2$  to get  $q_2^*$ :

$$q_2^* = \frac{\left( p(\gamma_3 - \gamma_2) + \frac{A_3\bar{q}}{x_3} - \frac{A_3q_1^*}{x_3} - \lambda_2 + \lambda_3 \right)}{\frac{A_3}{x_3} + \frac{A_2}{x_2}}$$

System of ODEs with 3 states:

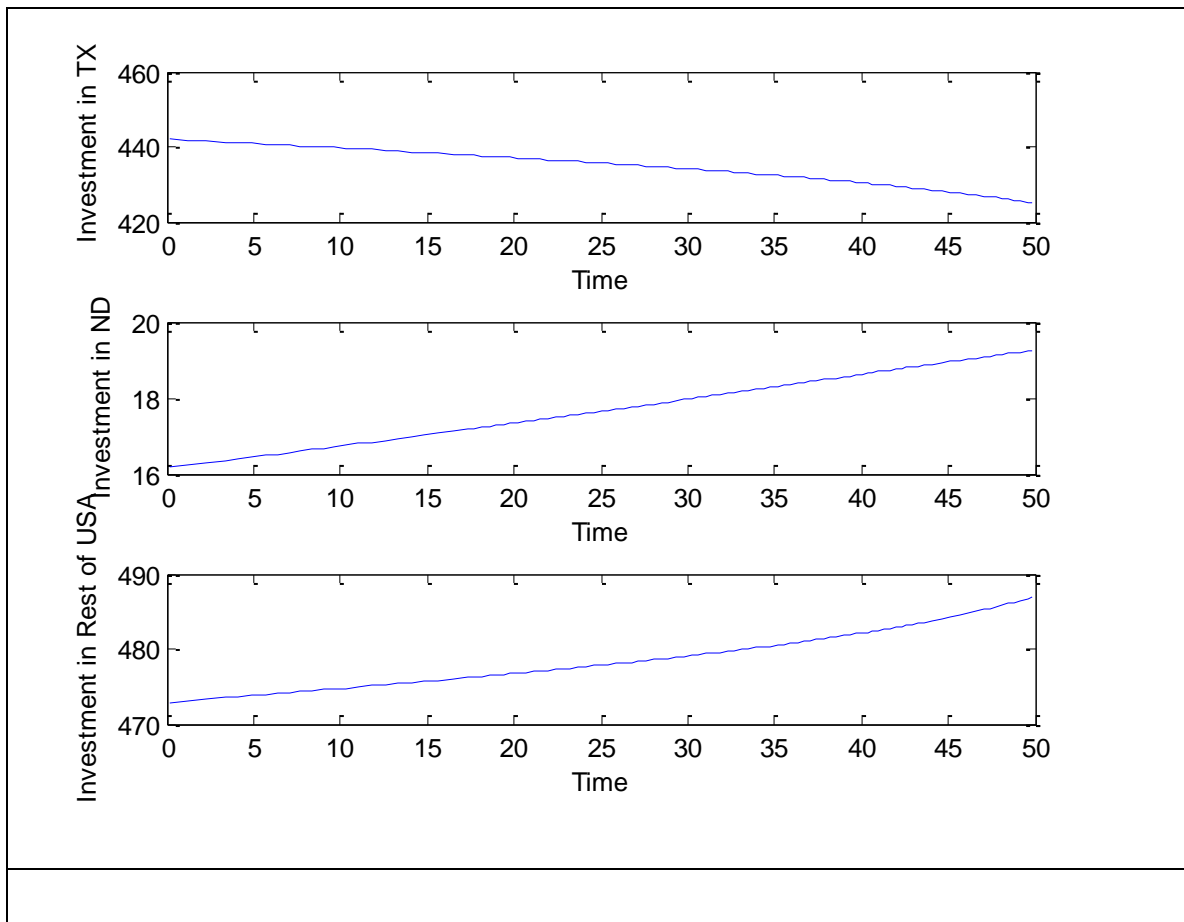
$$\begin{aligned}
 \dot{x}_1 &= -q_1^* \\
 \dot{x}_2 &= -q_2^* \\
 \dot{x}_3 &= -(\bar{q} - q_1^* - q_2^*) \\
 \dot{\bar{q}} &= \alpha \left( (1 - \gamma_1)p - \frac{A_1}{x_1} q_1^* - \lambda_1 \right) \\
 \dot{\lambda}_1 &= r\lambda_1 - \left( \frac{A_1 q_1^2}{2x_1^2} \right) \\
 \dot{\lambda}_2 &= r\lambda_2 - \left( \frac{A_2 q_2^2}{2x_2^2} \right) \\
 \dot{\lambda}_3 &= r\lambda_3 - \left( \frac{A_3 (\bar{q} - q_1 - q_2)^2}{2x_3^2} \right) \\
 &\quad \lambda_{T1}, \lambda_{T2}, \lambda_{T3}, \\
 &\quad x_{01}, x_{02}, x_{03}, \bar{q}_0 \text{ given}
 \end{aligned}$$



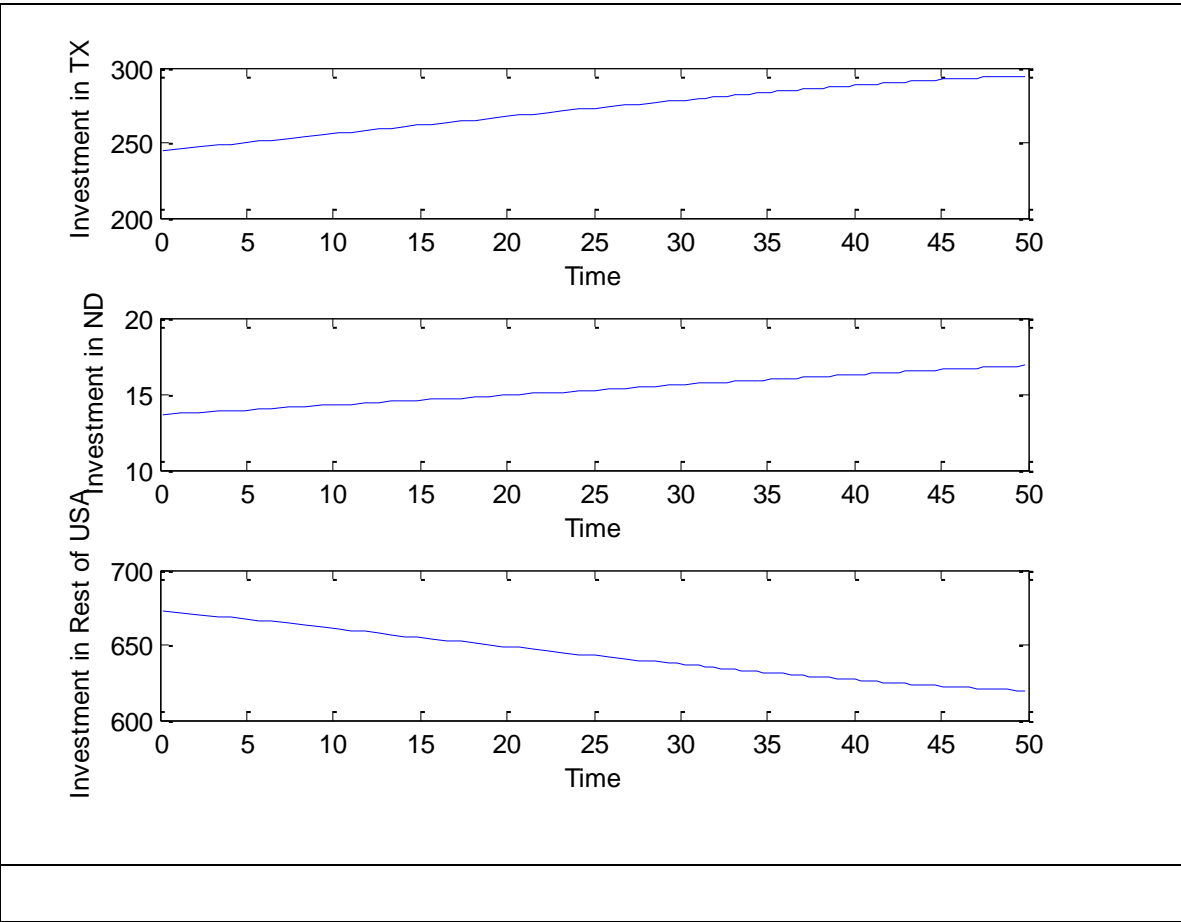
## Appendix II: Investment paths

Here, we compare investment paths when all states have a 5% severance tax and when all states have NE tax rates. Comparing extraction between figure 1 and figure 2 demonstrates that the higher tax rates result in reduced extraction in competitive states, particularly early in the planning horizon. Higher rates keep stocks higher and bring investment at later dates.

Appendix Figure 1: Extraction Paths Given Current Tax Rates



Appendix Figure 2: Investment Paths Given Nash Equilibrium Tax Rates, Million Barrels



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