Policy implications from agent-based models of non-renewable resource production

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Whether privately or publicly held, nonrenewable resources impact social welfare and, therefore, often come under public policy purview. Those who formulate policy typically have multiple and sometimes conflicting goals. Of interest to policy-makers is the relative effectiveness of the tools at their disposal given a nonrenewable natural resource, its ownership, and the market in which it's traded.

This paper extends a simple optimizing agent-based model (ABM) of a monopoly nonrenewable resource market to examine producer responses to different policy goals. Despite a simple optimization strategy, this ABM has been shown to find profit-maximizing production paths consistent with Hotelling's Rule in the absence of explicit costs. When costs are added, profits for the ABM range from zero to ten percent below optimum, depending on the cost structure and magnitude. In the present paper, costs in the form of taxes are introduced into the model. An analysis of outcomes as a function of fiscal regime is presented and compared with theoretical work. (JEL Q32)

Keywords: Hotelling's Rule; Agent-Based Modeling; Agent-Based Computation Economics; Natural Resource Policy; Natural Resource Taxation.

Optimality is in the eye of the beholder: what is optimal for a mine's holding company may not be optimal in terms of total welfare. For the policy-maker interested in maximizing social welfare, the preferred mechanism is to give the resource owner incentives to move

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the production plan closer to the socially optimal path. The challenge for the policy-maker is to eschew the unintended consequences that may arise from the unseen - and unseeable - measures of optimality employed by the firm or firms in the regulated industry.

This paper examines simulation results from an ABM of a monopoly producer of a nonrenewable natural resource. The model uses the stylized monopoly producer and demand function from Hotelling (1931, sec. 4). The agent-based models are presented in a previous paper (Dixon, 2010). Despite a highly simplistic optimization strategy, the basic ABM is effective at finding production paths that are optimum in terms of maximizing producer profit. The previous paper discusses how costs can result in a transfer of some of the producer profits to consumers in the form of lower user cost. In this paper, the costs themselves become revenue for a third party, a tax-levying entity. The cost structures considered in the earlier paper are now viewed as taxes. Those results are revisited here to provide insights into the impacts that can be expected from different fiscal regimes.

1 Policy objectives

Public economic policy concerns itself, generally, with social welfare. The exploitation of nonrenewable natural resources certainly impacts consumer and producer surplus. From a public policy point of view, however, social welfare often incorporates more than economic surplus. For example, the production of nonrenewable natural resource may incur externalities. Often, public fiscal policies are intended to transfer some of the public cost of externalities to the producer through taxation, thus internalizing that cost. In classic microeconomic equilibrium theory, the increased cost of taxation results in reduced equilibrium quantity, thereby diminishing the externalities. It will be shown that this is not always the case with dynamic optimization of nonrenewable natural resource production.

Many nonrenewable natural resources are publicly owned. Mineral rights, for example, are typically publicly owned and leased to private producers. In these cases, public policy strives to balance current demand for the resource with the wellbeing of future generations (Lecomber, 1979). For a number of U.S. States, natural resources are also a major source of tax revenue (See Table 1).

The broad goal of nonrenewable resource policies is to align privately optimal resource depletion with the social optimum (Burness, 1976). The policy mechanisms include sector-specific rules, such as restrictions and quotas, and taxation (Hartwick and Olewiler, 1986). This paper will consider the role of taxation in aligning private and public optima.

Considerations that may be included in the socially optimal production path include forestalling resource depletion (Hotelling, 1931) and internalizing externalities (Dasgupta and Heal, 1980, p. 52). Taxation is a public revenue source (Stiglitz, 2000, p. 718), which may be another consideration in social optimality. These are discussed in the following sections.

1.1 Policies to forestall depletion

The Conservationists in the United States at the turn of the twentieth century promoted the efficient development of nonrenewable resources, which typically meant slowing their exploitation (Hotelling, 1931, Gaudet, 2007). Since that time, this has been a main theme in U.S. natural resource policy, much of which includes government ownership of resources. There are efficiencies inherent in putting resources under a single owner (Lecomber, 1979, p. 113).

Policies to slow nonrenewable resource production are at odds with other policies to protect or promote the industries that develop them. Many extractive industries are subject to government subsides that effectively accelerate the depletion of nonrenewable resources. Extractive industries are also subsidized by government-funded research, which reduces the uncertainty and lowers development costs, thereby accelerating depletion (Lecomber, 1979, p. 119). The addition of conflicting social goals in the ABM is an intriguing topic for a future paper.

1.2 Policies to internalize externalities

The extraction and production of many nonrenewable resources leads to externalities in the forms of air pollution, water pollution, scenic degradation, or other amenity effects (Hanley et al., 1997). Policies to internalize externalities typically take the form of Pigouvian taxes (Dasgupta and Heal, 1980, p. 52). Additionally, U.S. States that are resource rich may seek compensation for the exportation of those resources (Burness, 1976, p. 294). Taxes, in turn, become a cost for the producer, in principal shifting the supply curve upward, thereby lowering the market-clearing equilibrium quantity (Pindyck and Rubinfeld, 2005, Ch. 18).

Krautkraemer (1998) makes a distinction between flow externalities and stock externalities. Flow externalities are those that arise because of the level of production, such as air pollution. Stock externalities are those that arise from the cumulative effects of production, such as site degradation and atmospheric accumulation of greenhouse gases. Flow externalities represent a per-unit social cost, while stock externalities represent a cumulative production social cost. It is not necessarily appropriate, however, to internalize these externalities in the same way: as a unit tax for a flow externality or as a cumulative production tax for a stock externality. This will become evident in examining the unintended consequences of each fiscal regime.

1.3 Taxes as revenue

Thirty-four U.S. States levy severance taxes, which make up nearly two percent of all state tax revenues.[1] For the six states listed in Table 1, however, natural resource taxes constitute more than ten percent of total tax revenue.

[1] From the U.S. Census Bureau

Table 1: Natural resource taxes as revenue: states for which natural resource taxes constitute more than ten percent of total tax revenue.

State	Percent of total tax revenue
Alaska	77.3%
Wyoming	43.6%
North Dakota	34.3%
New Mexico	19.2%
Montana	14.5%
Oklahoma	13.1%

Source: U.S. Census Bureau

2 The agent-based models in the policy context

The previous paper examined the behavior of the simple ABM for fixed costs, marginal costs, and stock costs. In this paper, those cost structures are viewed both as costs to the producer and as revenue to the fiscal authority. This will provide a means to investigate the efficiency of the fiscal policies in terms of transferring producer surplus to social welfare, where social welfare is composed of consumer surplus and tax revenue. The results from the previous paper are revisited here to provide insights into the impacts that can be expected from the fiscal policy objectives discussed in Section 1.

Tax policies are designed to use the market mechanism to align the owner's optimal production path with the social optimum. Restrictions and quotas are interesting topics from the agent-based modeling point of view, but are not examined in this paper. What are examined are taxes that impact profit in the form of fixed costs, per-unit costs, royalties, or stock (cumulative production) costs. The ABM results from each cost model are presented and discussed in the policy context.

In each of the following models, the basic monopoly model is extended to include the specified cost model, Monte Carlo samples are taken across the cost parameter range, and the ABM simulated over the lifetime of the resource. The ABM has a crude optimization behavior which is intended to mimic the behavior of a real-world production planner with limited information.

To summarize the behavior of the ABM, in each production period, the agent has the choice to reduce production, increase production, or maintain the current level. The amount by which the agent can reduce production is limited to a reduction that will exactly exhaust the total resource. The increment by which the agent can increase production is one percent. The choice to reduce, increase or maintain production is based on a crude estimate of lifetime income from the resource. Projected discounted future income is based on a rough estimate of the demand function based on the intertemporal change in price.

2.1 Franchise taxes

A franchise tax is a fixed cost incurred by the producer per day even if there is no production. A mineral rights lease is an example of a franchise tax. The State of Idaho, for example, auctions oil and gas leases for starting bids of $0.25 per acre, and the successful bidder also pays $1.00 annual rental per acre. Idaho also assesses an additional $1.00 per acre annual penalty if the lease is not producing after six years.[2]

The stylized fixed cost monopoly model from the previous paper is used to simulate a franchise tax. Figure 1 shows the result of 50 Monte Carlo simulations over fixed tax rates distributed over N(0.12, 0.0016). This range provides samples from near costless to 0.20, the rate at which the production path flattens out. Higher tax rates result in more rapid depletion of the resource, with the commensurate loss in total revenue. From the point of view of slowing the rate of depletion, this policy is an abject failure. For the same reason, it fails as a means to slow production to reduce a pollution externality. It is also inefficient at transferring producer profit to tax revenue. This is consistent with the findings of Burness (1976, Table I).

2.2 Unit severance taxes

Some U.S. States assess severance taxes based on the quantity of the resource extracted. The State of Ohio, for example, assesses a tax of $0.10 per barrel for oil, $0.09 per ton for coal, and $0.025 per 1,000 cubic feet of natural gas.[3] Burness (1976, Table II) finds that unit severance taxes will extend the resource lifetime in a competitive market, but have no effect on a monopolist's output. Also, in a monopoly market, taxes are paid entirely from producer profits.

The stylized marginal cost monopoly model from the previous paper is used to simulate a severance tax. Figure 2 shows the result of 50 Monte Carlo simulations over unit tax rates distributed over N(1.0, 0.110889). This range provides samples from near costless to 2.00 per unit, which, at the optimal starting production level, is about 0.20 per period (similar to the fixed rate in the previous section). In this model, the higher tax rate puts weak upward pressure on the stock lifetime, while efficiently transferring producer profit into tax revenue. As a policy to prolong the lifetime of the resource, this is mildly successful. As a means to lower production levels to reduce pollution externalities, it is not effective. It is an efficient means to generate tax revenue, however. The weak effect on resource lifetime places this outcome between the competitive and monopoly models of Burness.

2.3 Ad valorem taxes

Other U.S. States assess severance taxes based on the market value of the resource. The State of New Mexico, for example, imposes an oil and natural gas tax of 3.75 percent of

[2] http://www.idl.idaho.gov/bureau/minerals/min_leasing/leasing.htm (accessed 21 February 2011)
[3] http://codes.ohio.gov/orc/5749 (accessed 21 February 2011)

Figure 1: Franchise taxes.
The per-period cost leads to accelerated depletion. Higher tax rates lead to higher levels of production which, in turn, lead to lower total revenue. See the discussion in Section 2.1.

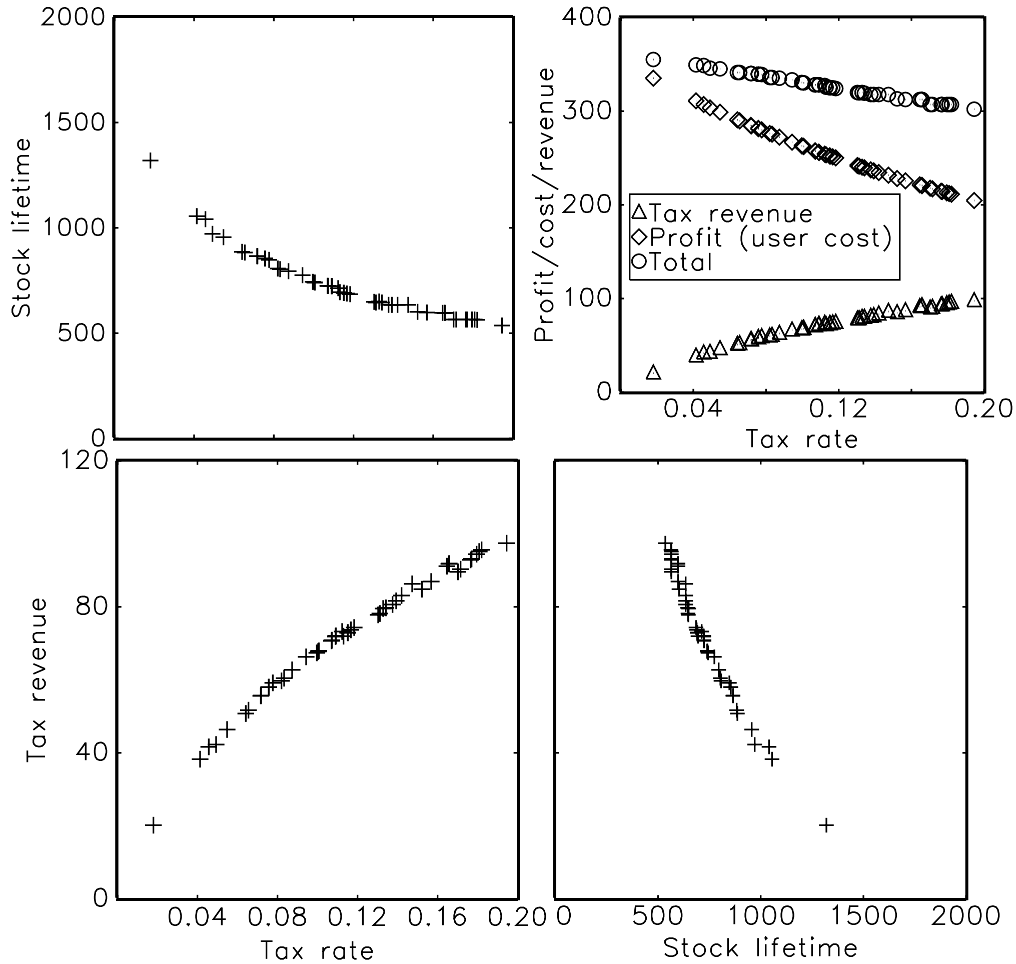
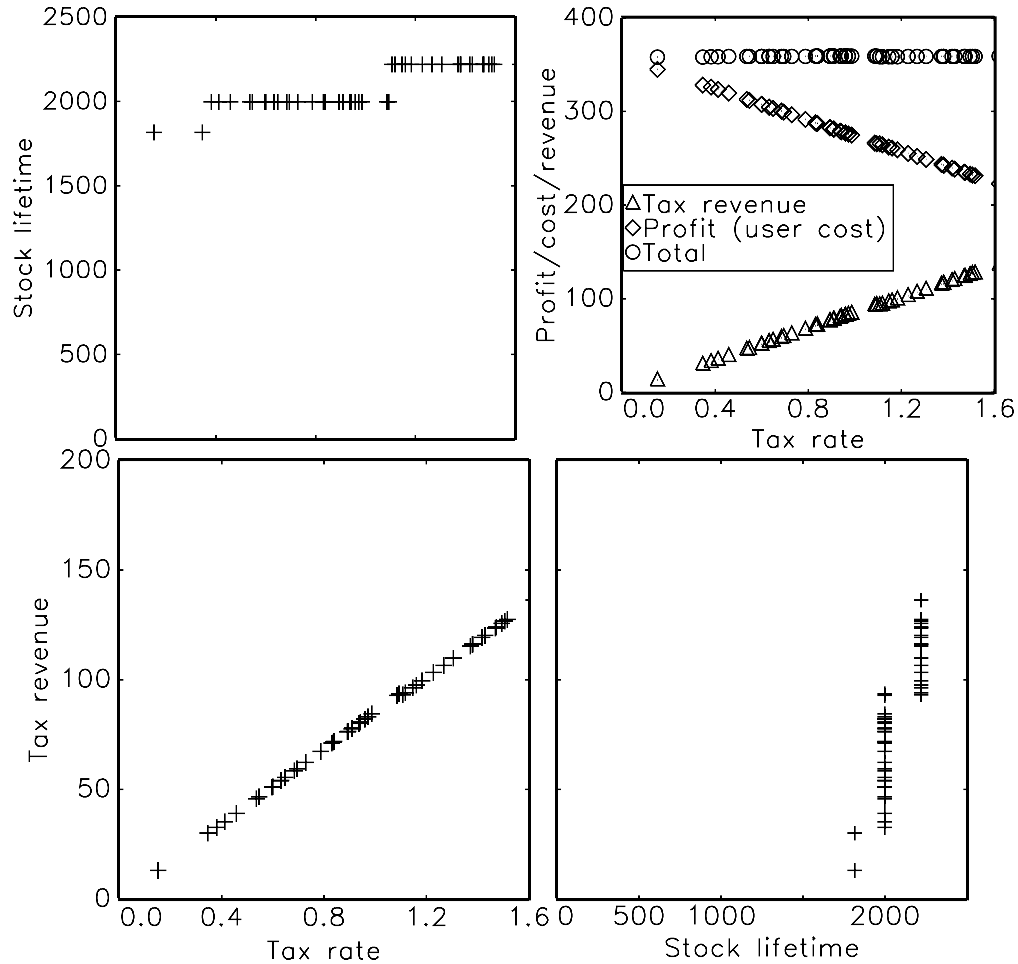


Figure 2: Severance taxes.
Higher tax rates extend the lifetime of the stock slightly. Total revenue is conserved: taxation is a direct transfer from the producer to the taxing authority. See the discussion in Section 2.2.



assessed value based on the price received.[4] An ad valorem tax has the effect of increasing the price in much the same way as a severance tax. Burness (1976) finds that an ad valorem tax has the same effect as a unit tax.

2.4 Royalties

While an ad valorem tax is applied to revenue, a royalty is applied to net profit. For oil and gas produced in the Gulf of Mexico, the U.S. government collects royalty payments ranging from 12 and a half percent for onshore and deep water wells (greater than 400 meters) and 16 and two-thirds percent for shallow water wells.[5]

The royalty cost model is not developed in the previous paper, but the derivation is straightforward. Consider the Hamiltonian for ad valorem tax rate ρ

$$\mathcal{H}\left(q\left(t\right),x\left(t\right),t,m\right) = \pi\left(q\left(t\right),x\left(t\right),t\right)-\rho\pi\left(q\left(t\right),x\left(t\right),t\right)-m\left(t\right)q\left(t\right) \quad (1)$$

The production path is functionally identical to a costless model with a constant multiplier $1-\rho$

$$\mathcal{H}\left(q\left(t\right),x\left(t\right),t,m\right)=\left(1-\rho\right)\pi\left(q\left(t\right),x\left(t\right),t\right)-m\left(t\right)q\left(t\right)$$

Tax revenue is total revenue times ρ and the optimal production path is identical to the costless model for this demand function.

The royalty model is a modified version of the stylized costless monopoly model from the previous paper. The model is modified to compute a cost in each period that is a fixed fraction of revenue in the current period. This model is used to simulate the producer response to a royalty tax. Figure 3 shows the result of 50 Monte Carlo simulations over royalty rates distributed over N(0.1, 0.00110889). This range provides samples from near costless to a 20 percent tax rate. In this model, the tax rate has no effect on the stock lifetime, and efficiently transfers producer profit into tax revenue. Thus, as a policy to prolong the lifetime of the resource or to lower production levels to reduce pollution externalities, it is not effective. It is an efficient means to generate tax revenue.

2.5 Cumulative production fees/bonds/taxes

Cumulative production taxes might represent the costs of site cleanup and mitigation, which increase as more earth is displaced or enhanced recovery techniques are employed. Under some circumstances, this fiscal policy may resemble the reclamation bonds required under the Surface Mining Control and Reclamation Act of 1977 (McDaniel, 1977). Heaps (1985) finds that cumulative production taxation will result in higher rates of extraction but over shorter periods of time, resulting in less total resource being extracted.

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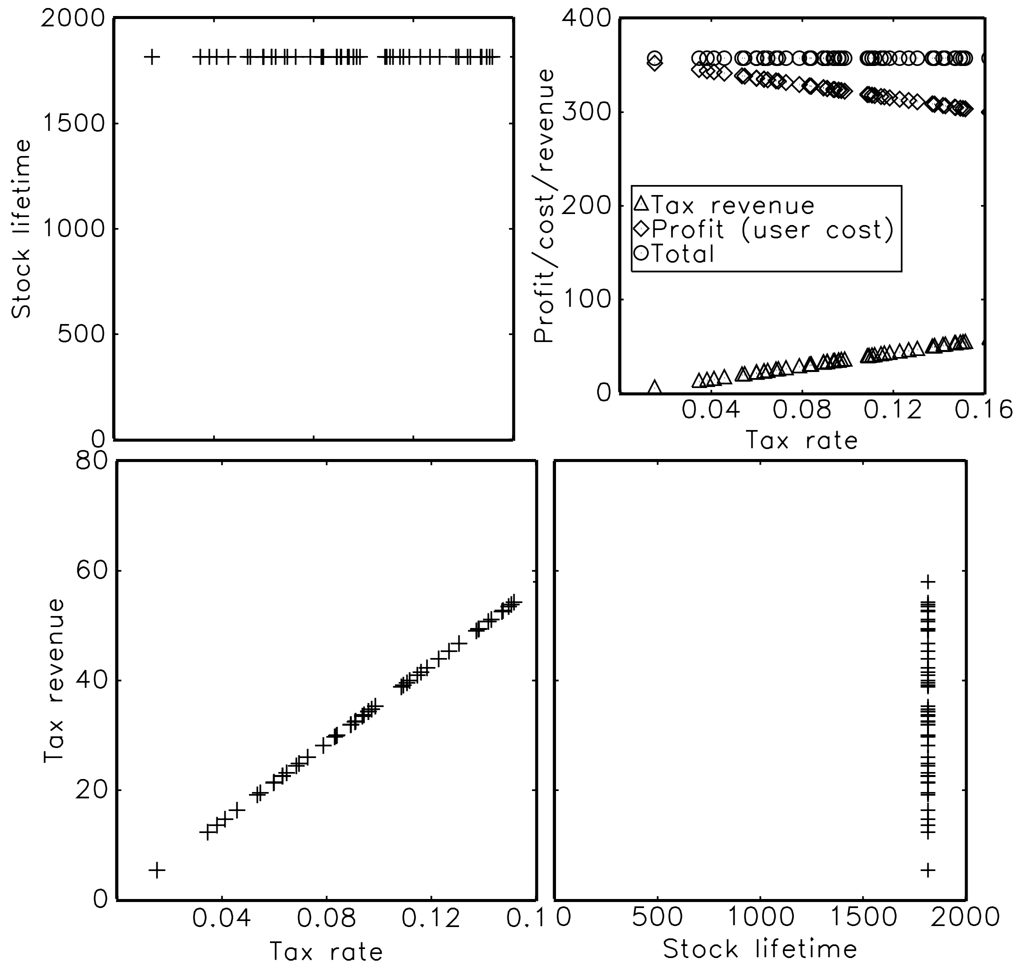
[4] http://www.tax.newmexico.gov/All-Taxes/Pages/Oil-and-Gas-Production-Taxes.aspx (accessed 21 February 2011)

[5] http://www.doi.gov/budget/2009/09Hilites/BH019.pdf (accessed 21 February 2011)

Figure 3: Royalties.

The rate is a fraction of total revenue. The lifetime of the stock is unaffected, as is total revenue. The tax is simply a transfer from the producer to the taxing authority. See the discussion in Section 2.4.



The stylized stock cost monopoly model from the previous paper is used to simulate a cumulative production tax. Figure 4 shows the result of 50 Monte Carlo simulations over cumulative production tax rates distributed over N(0.005, 0.000009). This range provides samples from near costless, to a cost that results in shutdown after producing only 50% of the physical stock. There is a distinct kink in the curves at a tax rate of about 100×10^{-4} (the critical point). Below this rate, the agent is able to optimize normally. At the critical point, future profits become negative, and the agent increases production until cost exceeds revenue. At this point, the agent ceases production, even if there is remaining stock. The stock remaining is shown in the upper right-hand graph. These results are consistent with those of Heaps.

As a policy tool, cumulative production taxation increases the rate of depletion, as shown by the first downward section of the upper-left-hand graph (pre-critical-point). The transfer of producer profit to tax revenue is highly inefficient, particularly in the pre-critical-point regime.

3 The efficiency of fiscal regimes

Figure 5 compares the efficiency of the fiscal regimes in terms of the deadweight losses they create, and the efficacy of the fiscal regimes in terms of slowing production and forestalling depletion. Deadweight loss in this case is presented as a fraction of the theoretical maximum producer profit as determined from Hotelling's Rule for a costless monopoly producer found in the previous paper. The formula is

$$DWL_{i,j} = 1 - \frac{\Pi_{ij} + C_{ij}}{\Pi^{max}}$$

where

$$\begin{aligned}
DWL_{ij} &= \text{deadweight loss for policy } i\text{and rate } j \\
\Pi_{ij} &= \text{producer profit under policy } i\text{at rate } j \\
C_{ij} &= \text{total tax revenue under policy } i \text{ at rate } j \\
\Pi^{max} &= \text{Hotelling's Rule maximum producer profit}
\end{aligned}$$

The results from a simple optimizing agent-based model (ABM) indicate that cumulative production (stock cost) taxation is largely counter-productive, while unit severance tax accomplishes efficient transfer of profits to taxes and extends the life of a nonrenewable resource. In the case of pollution by-product externalities, the two-pronged goal of internalizing costs and reducing excess supply is only achieved with unit severance taxes. These results are consistent with theoretical findings (Heaps, 1985, Burness, 1976).

Figure 4: Cumulative production taxation.

The tax is on cumulative production per period. The rate is multiplied by 10,000. The rate of 100 is the point at which terminal cost equals terminal marginal revenue. At higher cumulative production taxes, some stock remains, being too costly to produce. See the discussion in Section 2.5.

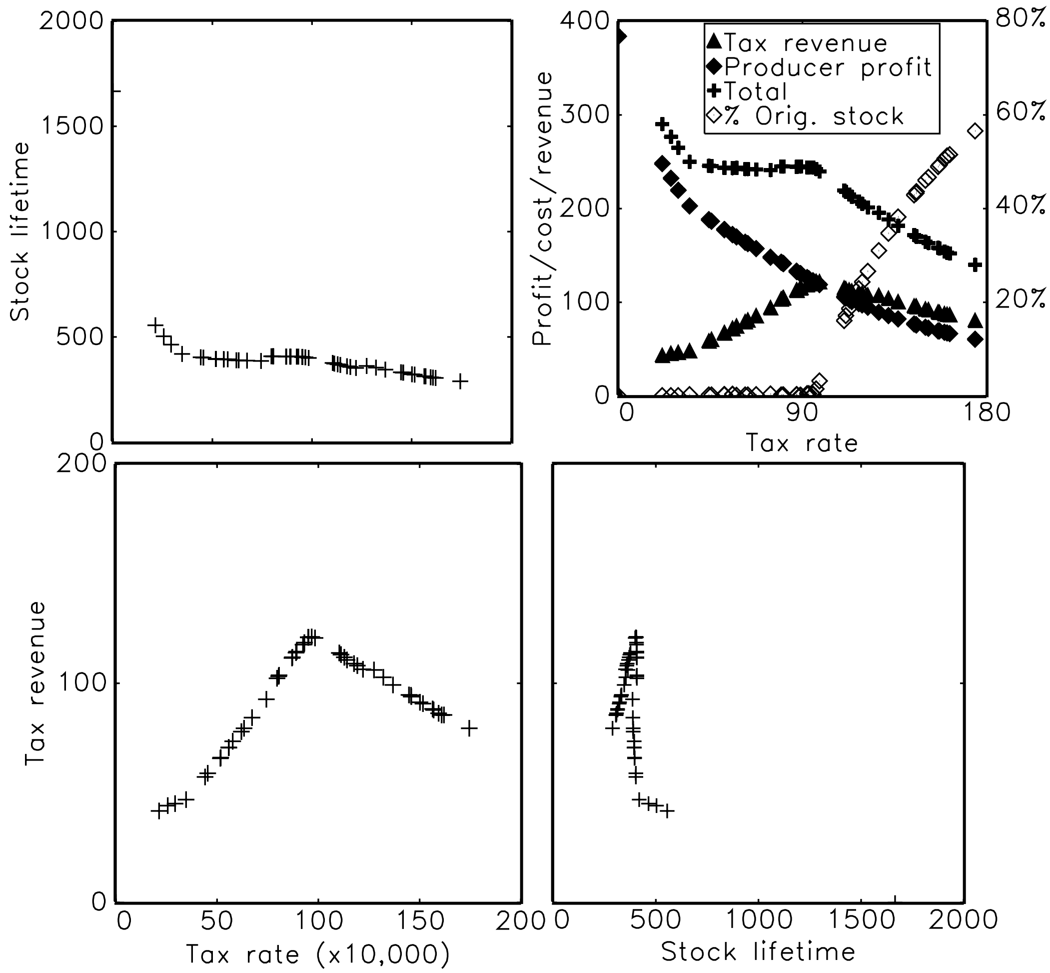
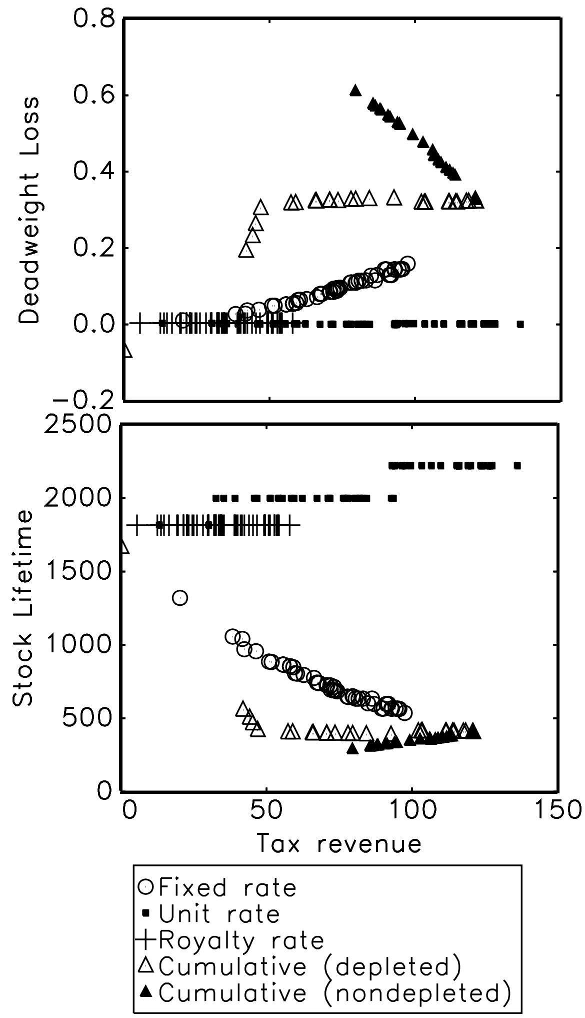


Figure 5: Fiscal policy efficiency and efficacy
Deadweight loss is expressed as a fraction of the maximum (Hotelling's Rule) producer profit. The cumulative production tax regime is divided into physical depletion (no stock remaining at the end) and non-depletion (cost exceeds revenue before the stock is physically depleted). See the discussion in Section 3.



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