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Julien Daubanes

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Julien Daubanes*

CER-ETH at ETH Zürich and LERNA at Toulouse SE

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Abstract

In a standard partial equilibrium model of resource depletion, this paper characterizes and examines the solution to the optimal taxation problem when extraction is monopolistic. The main result is that the family of subgame perfect efficiency-inducing tax/subsidy schemes may include some strict tax policies. This illustrates how the static trade-off between inducing efficiency and raising tax revenues in the presence of market power is relaxed under exhaustibility.

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*CER-ETH, Center of Economic Research at ETH Zürich, ZUE F 14, Zürichbergstrasse 18, 8092 Zürich, SWITZERLAND
E-mail address: *jdaubanes@ethz.ch*
Phone: +41 44 632 24 27
Fax: +41 44 632 13 62

1 Introduction

The optimal linear tax on the output of a single-product monopoly is generally a subsidy to the monopoly. This paper shows that this subsidy may be avoided when the monopoly is subject to a boundary on her cumulated output, that is when she is an extractor: it may be possible to induce the monopolist extractor to behave efficiently while collecting tax revenues at all dates.

Since Hotelling (1931), monopolistic extraction of an exhaustible resource has been explored by Solow (1974), Stiglitz (1976) and Dasgupta and Heal (1979), among others. Their analyses show why the equilibrium extraction path under monopoly is distorted away from the competitive one, which is socially optimal. A monopoly extracts the resource such that marginal revenue minus marginal cost of extraction rises at the rate of interest. This does not generally ensure a socially optimal allocation of the resource. Indeed, the perfect competition extraction is such that the difference between price and marginal cost rises at the rate of interest.

Based on partial equilibrium models of monopolistic extraction of an exhaustible resource, some studies have examined how linear output taxation should be designed to restore social optimum. The seminal paper by Bergstrom et al. (1981) provides the first solution to this problem under the assumption that the regulator is able to precommit to a tax/subsidy trajectory. They prove that there is a family of optimal time-dependent tax/subsidy schemes. In the same vein, but under particular functional forms (isoelastic demand and constant marginal cost of extraction), Im (2002) finds that a constant ad valorem subsidy induces the monopoly to behave efficiently. Without the assumption of precommitment ability, the policies proposed by these papers are shown by Karp and Livernois (1992) not to be generally subgame perfect. However, the latter authors prove the very nice and useful property that the Markov perfect (thus subgame perfect) optimal policies are identical to the policies obtained under precommitment in special cases, including that of isoelastic demand and constant marginal cost.

This paper proposes a full and explicit solution to the optimal taxation problem in a standard model of monopolistic supply of an exhaustible resource. Beyond that, it aims at providing an investigation of a particular question: is it necessary to transfer a subsidy to the monopoly at any date to induce her to behave efficiently?

The interest of this question is clear. The above studies on this topic highlight that there are generally multiple optimal taxation policies. This suggests the flexibility offered by the exhaustibility constraint to the regulator. However, they do not focus on the instantaneous transfers between the regulator and the extractor that are induced by these policies. The reasons why these transfers deserve particular attention are mentioned in many textbooks. Mainly, subsidies to monopolies, even temporary, are likely to be politically unacceptable from a distributional viewpoint (Tirole, 1988). Other reasons for taxing rely on the double-dividend argument or institutional and budget constraints of the regulator (See also Benchekroun and Long, 2008)[1].

Under standard functional forms (isoelastic demand and constant marginal cost of extraction) and assuming the regulator's ability to precommit, I explicitly characterize the full set of optimal taxation schemes. From Karp and Livernois (1992), this family is equivalent to the Markov perfect (thus subgame perfect) efficiency-inducing taxation policies. Hence, the results are valid without the ability of the regulator to precommit. Among the optimal policies, the subsidy proposed by Im (2002) appears as a particular instrument. I analyze the dynamic properties and the boundaries of this set. It appears that, depending on the magnitude of the cost of extraction, it may not be necessary to subsidize the monopoly at any date to induce her to behave efficiently.

The paper is organized as follows. Section 2 introduces the general model of monopolistic extraction and exposes the core of the optimal taxation problem. Section 3 solves

[1]Although Benchekroun and Long (2008) do not deal with the extraction of an exhaustible resource, their objective is close to that of this paper. They look at dynamic subsidy rules helping reduce the amount transferred to the monopolist while inducing her to choose an optimal level of output.

the case of isoelastic demand and constant marginal cost of extraction and presents the main results. Section 4 concludes.

2 The general problem

2.1 Basics

At each time $t \geq 0$, the flow of extraction in units of resource is $R(t) \geq 0$. Let $S(t) \geq 0$ be the size of the reserves remaining at date t. Then:

$$S(t) = S(0) - \int_0^t R(s)\, ds,\ S(t) \geq 0,\ S(0) = S_0 \text{ given.} \tag{2.1}$$

The cost of extracting R is given by the cost function $C(R)$ which is assumed to be increasing, convex and such that $C(0) = 0$.

The representative household takes the price as given. Her inverse-demand function is $P(R)$, assumed to be continuous, strictly decreasing and of the class of functions such that $U(R) = \int_0^R P(x)\, dx$ is finite and that[2] $\lim_{R \mapsto 0} P(R) = +\infty$.

The social discount rate is denoted by $r \geq 0$.

2.2 Resource extraction under perfect competition and monopoly

There is no uncertainty and all agents perfectly foresee the future. The extraction industry will be alternatively considered to be competitive and monopolistic.

Due to the necessity of the resource, $R(t) > 0$ for all $t \geq 0$.

The competitive extraction sector maximizes the discounted sum of its instantaneous profits subject to (2.1). The associated Hamiltonian is $H(S, \lambda^*, R, t) = \big(p(t)R -$

[2] In what follows, we shall refer to this assumption as the necessity of the resource.

$C(R)\big)e^{-rt} - \lambda^* R$ and the extraction path under perfect competition satisfies:

$$\Big(P(R^*(t)) - C'\big(R^*(t)\big)\Big)e^{-rt} = \lambda^*, \tag{2.2}$$

where $p(t)$ is the price of the resource, λ^* is the positive and constant costate variable, and superscript * is used to denote the first-best.

The regulator sets a tax/subsidy scheme to correct the distortion that arises due to market power. Let $\{\theta(t)\}_{t\geq 0}$ be an ad valorem producer tax so that the producer price is $p(t)\tau(t) = p(t)\big(1 - \theta(t)\big)$. Assume that $\theta(t) < 1$, so that $\tau(t) > 0$, and let us restrict attention to tax profiles differentiable with respect to time[3] [4]. Suppose that the regulator is able to credibly announce $\{\theta(t)\}_{t\geq 0}$ from date 0.

The monopolist extractor maximizes the discounted stream of her spot profits subject to (2.1). Strategically, she internalizes $P(R)$. The associated Hamiltonian is $H^M(S, R, \lambda^M, t) = \big(\tau(t)P(R)R - C(R)\big)e^{-rt} - \lambda^M R$ and, assuming the concavity of the gross revenue $P(R)R$, the extraction path under monopoly satisfies:

$$\Big\{\tau(t)\Big(P(R^M(t)) + P'(R^M(t))R^M(t)\Big) - C'\big(R^M(t)\big)\Big\}e^{-rt} = \lambda^M, \tag{2.3}$$

where λ^M is the positive and constant costate variable and superscript ^{M} is used to mean monopolistic.

Under perfect competition, as well as under a monopoly subject to any tax/subsidy scheme, the resource supply is always positive: $R^*(t) > 0$, $R^M(t) > 0$, for all $t \geq 0$. This implies that the discounted marginal rents must always be strictly positive, $\lambda^*, \lambda^M > 0$,

[3]This assumption is made for simplicity. One can show that all the optimal tax profiles are indeed differentiable with respect to time.

[4]For the sake of notational simplicity, we shall prefer to use the multiplicative tax denoted by τ instead of the ad valorem tax denoted by θ.

and that the resource is asymptotically depleted:

$$\int_0^{+\infty} R^*(t)\,dt = \int_0^{+\infty} R^M(t)\,dt = S_0. \tag{2.4}$$

The Hotelling rule resulting from the differentiation of (2.2) and the boundary condition (2.4) uniquely determine the optimal extraction path: $\{R^*(t)\}_{t\geq 0}$. Given a certain taxation policy $\{\tau(t)\}_{t\geq 0}$, the modified Hotelling rule from (2.3) and condition (2.4) uniquely determine the monopolist's extraction path.

2.3 Core of the problem

The objective is to design a tax/subsidy scheme $\{\tau^*(t)\}_{t\geq 0}$ that induces the monopoly to reproduce the first-best extraction path. To do so, one has to look for all tax profiles such that the solution to (2.3), for any positive λ^M and under (2.4), is $\{R^*(t)\}_{t\geq 0}$, i.e. all positive functions $\tau^*(t)$ that satisfy:

$$\Big\{\tau^*(t)\Big(P(R^*(t)) + P'(R^*(t))R^*(t)\Big) - C'\big(R^*(t)\big)\Big\}e^{-rt} = \lambda^M, \tag{2.5}$$

where λ^M is any positive constant.

In a related framework, Bergstrom et al. (1981) study the optimal taxation problem and find that there exists a family of optimal time-dependent tax/subsidy schemes $\tau^*(t)$, indexed by the present-value marginal return to the monopoly, λ^M. Karp and Livernois (1992) show that the obtained policies are subgame perfect only under certain special functional forms. This paper aims at fully characterizing the optimal taxation schemes and at analyzing their properties in a case where subgame perfection is ensured: isoelastic demand and constant marginal cost.

2.4 About the cost of regulation

As said in the introduction, the regulator may not be indifferent about the split of the social surplus resulting from the taxation policy and on the use, even temporary, of taxes or subsidies.

But the regulator is constrained in the exercise of fund raising through his taxation policy. The constraint he faces is the participation constraint $\lambda^M > 0$: without leaving a positive marginal rent to the monopoly, the latter won't be willing to reproduce the optimal extraction path. Bringing this costate variable near to zero allows the regulator to extract as much rent as possible from the extraction industry.

The next section aims at showing that if the cost of extraction is low enough, there always exist some optimal strict tax schemes, thus allowing the regulator not to subsidize the monopoly at any date.

3 Results in the isoelastic case with constant unit cost of extraction

The demand function is isoelastic: $P(R) = R^{-1/\alpha}$, where $\alpha > 1$ is the price-elasticity of demand, supposed to be greater than unity to ensure existence of the monopolist's solution. The cost of extraction is linear: $C(R) = cR$, where $c \geq 0$ is the per unit extraction cost.

Let us characterize the optimal extraction path. From condition (2.2), the first-best extraction path is the solution of the differential equation[5]:

$$g_R^*(t) = -\alpha r\big(1 - cR^*(t)^{1/\alpha}\big), \tag{3.1}$$

[5]The derivative with respect to time of any variable X is denoted by $\dot{X}$. Its rate of growth is denoted by $g_X = \dot{X}/X$.

which satisfies the boundary condition (2.4), i.e.:

$$R^*(t) = e^{-\alpha rt}\big(R_0^*(S_0)^{-1/\alpha} + c(e^{-rt} - 1)\big)^{-\alpha}, \tag{3.2}$$

where $R^*(0) = R_0^*(S_0)$ is increasing.

3.1 Set of optimal linear tax/subsidy paths

Differentiating condition (2.5) and substituting $\dot{R}^*$ from equation (3.1), one finds that the efficiency-inducing tax schemes are the solutions to the differential equation:

$$\dot{\tau}^*(t) = rcR^*(t)^{1/\alpha}\big(\tau^*(t) - \frac{\alpha}{\alpha - 1}\big), \tag{3.3}$$

which ensure $\lambda^M > 0$, i.e. the set, denoted Θ^*, of positive functions:

$$\tau^*(t) = \big(\tau^*(0) - \frac{\alpha}{\alpha - 1}\big)e^{rc\int_0^t R^*(s)^{1/\alpha}\,ds} + \frac{\alpha}{\alpha - 1}, \tag{3.4}$$

which satisfy:

$$\lambda^M = \frac{\alpha - 1}{\alpha}\tau^*(0)R_0^*(S_0)^{-1/\alpha} - c > 0. \tag{3.5}$$

Proposition 1 *There exists an infinite family of efficiency-inducing producer tax/subsidy paths:* $\Theta^* = \big\{\{\tau^*(t)\}_{t\geq 0} : (3.4),\ \tau^*(0) > \frac{\alpha}{\alpha-1}\max\{cR_0^*(S_0)^{1/\alpha}, 1 - e^{-rc\int_0^{+\infty} R^*(t)^{1/\alpha}\,dt}\}\big\}$.

Proof of proposition 1 □ *Among the set of functions (3.4), one has to select the optimal ones by eliminating* ı) *those being negative or zero at some* $t \geq 0$ *(for taxes to be well-defined) and* ıı) *those not satisfying condition (3.5) (for the participation constraint to hold).*

(3.5) is equivalent to $\tau(0) > \tau_{PC} \equiv cR_0^*(S_0)^{1/\alpha}\alpha/(\alpha - 1)$.

Positivity is ensured for tax schemes (3.4) such that $\tau(0) \geq \alpha/(\alpha - 1)$ *since, from*

(3.3), they are increasing or constant and initially positive. Tax schemes (3.4) such that $\tau(0) < \alpha/(\alpha-1)$ *are decreasing. Ensuring positivity everywhere is thus equivalent to ensuring positivity asymptotically, i.e.:* $\min_{t\geq 0}\{\tau(t) : (3.4), \tau(0) < \alpha/(\alpha-1)\} = \lim_{t\mapsto+\infty}\tau(t) = \big(\tau(0)-\alpha/(\alpha-1)\big)\exp\{rc\int_0^{+\infty} R^*(t)^{1/\alpha}\,dt\}+\alpha/(\alpha-1) > 0$*. This condition amounts to* $\tau(0) > \tau_{WD} \equiv \big(1-\exp\{-rc\int_0^{+\infty} R^*(t)^{1/\alpha}\,dt\}\big)\alpha/(\alpha-1)$*.*

Optimality then requires $\tau^*(0) > \tau_{PC}$ *and* $\tau^*(0) > \tau_{WD}$*, that is* $\tau^*(0) > \bar{\tau} \equiv \max\{\tau_{PC}, \tau_{WD}\}$ $= \frac{\alpha}{\alpha-1}\max\{cR_0^*(S_0)^{1/\alpha}, 1-e^{-rc\int_0^{+\infty} R^*(t)^{1/\alpha}\,dt}\}$*.*

One can see that $\tau_{WD} < \alpha/(\alpha-1)$*. From (2.2) at date* 0*, and* $\lambda^* > 0$*, one knows that* $cR_0^*(S_0)^{1/\alpha} < 1$*. Hence,* $\frac{\alpha}{\alpha-1}\max\{cR_0^*(S_0)^{1/\alpha}, 1-e^{-rc\int_0^{+\infty} R^*(t)^{1/\alpha}\,dt}\} < \alpha/(\alpha-1)$*.* ■

From Karp and Livernois (1992), these taxation schemes have the nice property of being identical to the optimal linear Markov perfect (and subgame perfect) taxation schemes obtained without the assumption of precommitment ability.

The multiplicity of optimal taxes may seem surprising. This feature relies on the exhaustibility constraint. Under this constraint, the choice of the extractor is more about when to supply the resource than how much to supply. Hence, the relevant tool to influence her decision must affect the profitability to extract at each date relative to the profitability to extract at other dates. This can be achieved through different tax schedules. The explicit expressions of these schedules allow us to examine their levels and their dynamic properties.

The examination of Θ^* reveals that some of its functions are rising strict subsidies, one is a constant one, other tax/subsidy profiles may be falling, and there may also exist falling strict taxes (See figure 1).

In particular, there is the constant ad valorem subsidy proposed by Im (2002) in a similar model. However, this scheme appears to be one element of an infinite set of taxation policies. One notes from (2.2) and (2.3) that this instrument equalizes the marginal revenue to the price so that these conditions become equivalent. In the same

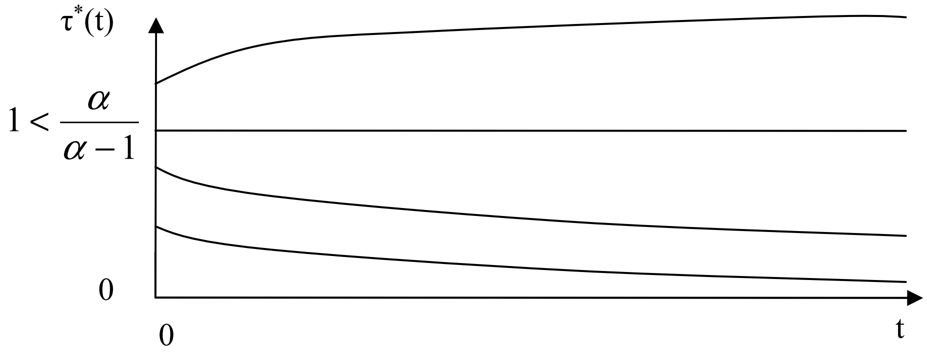

Figure 1: Optimal tax/subsidy time-profiles

model without the exhaustibility constraint, this subsidy would actually be the unique linear optimal tax (See for instance Tirole, 1988). This illustrates that the exhaustibility of the resource offers other ways of regulating the monopolistic producer.

Some other optimal policies can seem counter-intuitive. From Stiglitz (1976), in this model, the monopoly under laissez-faire is more conservative than a competitive extractor. Hence, every optimal policy aims to induce the monopoly to extract faster. Surprisingly, some of these policies are unit subsidies rising over time.

Potential optimal taxes are more intuitive since they are all rising, thus providing the extractor with clear incentives to supply the resource faster. Besides the distributional reasons for taxing monopolist extractors, the consistency in the time-profiles of potential optimal strict taxes may offer another argument: optimal subsidies can be rising or falling so that it is easier to be wrong in designing optimal subsidies than optimal taxes.

3.2 Existence of optimal strict tax profiles

This subsection shows that the boundary condition restricting Θ^*, $\tau^*(0) > \frac{\alpha}{\alpha-1}\max\{cR_0^*(S_0)^{1/\alpha}, 1 - e^{-rc\int_0^{+\infty} R^*(t)^{1/\alpha}\,dt}\}$, is all the more relaxed as the per unit cost of extraction is low, so that below a certain threshold cost, the set of efficiency-inducing tax schemes includes strict taxes: $\{\tau(t)\}_{t\geq 0}$ such that $\tau(t) \leq 1$, $\forall t$.

We shall see that this result is technically not trivial because a change in the extraction cost alters the whole first-best extraction path, as well as the reaction of the monopoly to a certain taxation scheme. Let us write the critical variables as functions of the per unit extraction cost, c.

Proposition 2 *ı) The lower the per unit extraction cost, the larger the set of efficiency-inducing taxation schemes in the sense that:* $\forall\, c, c' \geq 0,\ c < c' \Rightarrow \Theta^*(c) \supset \Theta^*(c')$.
ıı) There exists a threshold cost of extraction below which market power can be corrected through strict taxes: $\exists\, \bar{c} > 0 :$ *if* $0 \leq c < \bar{c}$ *then* $\exists\, \{\tau^*(t)\}_{t \geq 0} \in \Theta^*(c) : \tau^*(t) \leq 1,\ \forall t \geq 0$.

Proof of proposition 2 $\square$ *Let us use the notations $\bar{\tau}$, τ_{WD} and τ_{PC} introduced in the proof of proposition 1.*

ı) From condition (2.2) under my specifications, $R^*(t, c)^{-1/\alpha} = \lambda^*(c)e^{rt} + c$, *which leads to* $g_R^*(t, c) = -\alpha r \big(1 + e^{-rt} c \lambda^*(c)^{-1}\big)^{-1}$. *Comparing this expression with (3.1), one obtains:* $\big(1 + e^{-rt} c \lambda^*(c)^{-1}\big)^{-1} = 1 - cR^*(t, c)^{1/\alpha}, \forall t \geq 0$. *Note that if* $c\lambda^*(c)^{-1}$ *is increasing in c, then* $cR^*(t, c)^{1/\alpha}$ *is also increasing in c.*

Again from (2.2), one has $R^*(t, c) = \big(c + \lambda^*(c)e^{rt}\big)^{-\alpha}$. *Using the binding constraint (3.4), one obtains:* $S_0 = \int_0^{+\infty} \big(c + \lambda^*(c)e^{rt}\big)^{-\alpha} dt$, *from which* $\lambda^*(c)$ *is decreasing in c, thus proving, from above, that* $cR^*(t, c)^{1/\alpha}$ *is increasing in c for all* $t \geq 0$.

It follows that $cR^*(0, c)^{1/\alpha}$ *and* $\int_0^{+\infty} cR^*(t, c)^{1/\alpha} dt$ *are increasing in c, implying that* $\tau_{PC}(c)$, $\tau_{WD}(c)$ *and thus* $\bar{\tau}(c)$ *are increasing in c. This proves the first part of proposition 2.*

ıı) Note moreover that $\bar{\tau}(c)$ *is continuous in c since c continuously affects all the variables. Due to the finiteness of* S_0, *if* $c = 0$, *one can easily see that* $\tau_{PC} = \tau_{WD} = \bar{\tau} = 0$. *Hence, by continuity,* $\exists \bar{c} > 0 : \bar{\tau}(c) < 1, \forall c \leq \bar{c}$. *Since, from (3.3), all paths* $\{\tau^*(t)\}_{t \geq 0}$ *in* Θ^* *such that* $\tau^*(0) \leq 1 < \alpha/(\alpha - 1)$ *are decreasing over time: if* $c \leq \bar{c}$, *then* $\exists \{\tau^*(t)\}_{t \geq 0} \in \Theta^*(c) : \tau^*(t) \leq 1, \forall t \geq 0$. *This is the second part of proposition 2.* $\blacksquare$

The cost of extraction appears as a critical parameter when designing and evaluating the cost of the cheapest regulation. This is because it affects the marginal rent whose positivity constrains the regulator in raising tax revenues from (or saving subsidies to) the mining sector while inducing efficiency. If it is low enough, some strict taxes are in the set of optimal tax/subsidy schemes.

4 Conclusion

A standard single-product monopolist can be induced to behave efficiently with a unique taxation policy which is a subsidy. When the same monopoly is subject to an exhaustibility constraint, the possibilities to regulate her are somewhat broader. This is what this paper illustrated in a standard model of resource depletion.

More formally, the results are as follows:

i) The subsidy which is optimal without the exhaustibility constraint is still efficiency-inducing when the monopolist is an extractor.

ii) In this case, a continuum of other tax/subsidy schemes is optimal.

iii) Among these schemes, some may be strict taxes.

The extension of this work to the case of oligopoly should shed light on how market structure affects the set of optimal taxes and the possibility for the regulator to capture rents. Moreover, other economic distortions of the extraction should be considered simultaneously. For example, when the exhaustible resource is polluting, a single tax on the resource may correct pollution and market power. Sophisticating the market structure and considering other distortions of the extraction path could thus lead to more practical results. This should be the next step of this research.

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