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No. 478

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CO₂ TAXATION AND DYNAMICS OF FOSSIL FUEL PRICES

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ABSTRACT: The paper considers nonrenewable resource extraction when resource buyers have formed a government which applies Pigouvian taxation for slowing pollution accumulation and the sellers are competitive or a resource cartel. The evolution of the market equilibrium is studied as a Stackelberg differential game. It is shown that without monopoly power the sellers may lose their resource rent. When a monopolist seller leads a Stackelberg differential game and applies a rent-maximizing price strategy, the resulting market equilibrium is time-inconsistent. At the time-consistent and Markov-perfect equilibrium the seller's monopoly power vanishes asymptotically. The seller's power reduces the buyer's Pigouvian tax at each point in time. If Pigouvian taxation induces the cartelization of resource sellers, the initial level of the producer price under consistent monopoly supply may increase from the efficient level before taxation. However, the price increase is temporary and ultimately pollution taxation reduces energy prices.

KEY WORDS: nonrenewable resources, CO₂ taxation, differential games

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TIIVISTELMÄ: Tutkimuksessa käsitellään fossiilisten polttoaineiden käyttöä kun luonnonvaran ostajamaat ovat tehneet sopimuksen kansainvälisestä Pigoun verosta ympäristöön kasaantuvan saastumisongelman rajoittamiseksi. Luonnonvaran myyjien oletetaan toimivan kilpailullisesti tai muodostavan luonnonvarakartellin. Markkinatasapainon yliajallista kehitystä tarkastellaan Stackelberg-differentiaalipelinä. Jos luonnonvaran omistajat ottavat markkinahinnan annettuna, voi Pigoun vero alentaa resurssin niukkuusvuokran nollaan. Jos taas resurssikartelli kykenee toimimaan Stackelberg - johtajana, ei voitonmaksimoiva hintastrategia ole aikakonsistentti. Jos resurssikartelli ei kykene sitoutumaan tehokkaasti voiton maksimoivaan hintauraan, joutuu se soveltamaan alhaisemman voiton tuottavaa aikakonsistenttia hintastrategiaa. Osoittautuu, että aikakonsistenssissa ja Markov - täydellisessä markkinatasapainossa luonnonvarakartellin monopolivoima katoaa pitkällä aikavälillä. Pigoun verotus voi nostaa tuottajan hintaa tasosta, joka vallitsee ennen verotusta. Hinnannousu on kuitenkin väliaikainen ja pidemmällä aikavälillä saastumisongelma välttämättä alentaa luonnonvaran hintaa.

AVAINSANAT: uusiutuvat luonnonvarat, hiilidioksiidivero, differentiaalipelit

YHTEENVETO

Fossiilisten polttoaineiden käyttö aiheuttaa ympäristöongelmina ilmeneviä haitta-ainepäästöjä. Esimerkkinä tästä on öljyn käyttö ja hiilidioksidin kertyminen ilmakehään. Tämän seurauksena on ehdotettu kansainvälistä hiilidioksidiveroa tai kansainvälisiä markkinoita hiilidioksidin päästöluville. Tärkeä ja kiintoisa kysymys on kuinka tällainen vero vaikuttaa fossiilisten polttoaineiden hintakehitykseen. Usein esitetyn näkemyksen mukaan (esim. The Economist 1993, May 30th) veron aiheuttama mahdollinen öljykriisi on samanlainen kuin aikaisemmatkin: öljyn hinnan odotetaan nousevan.

Tutkimuksessa tarkastellaan optimaalisesti asetetun hiilidioksidiveron (tai päästökaution) vaikutuksia uusiutumattoman luonnonvaran kuten öljyn tai hiilen hintakehitykseen ja luonnonvaran tarjoajan mahdolliseen monopolivoimaan.

Jos luonnonvaran omistajia on useita ja nämä eivät muodosta kartellia, on luonnonvaran omistajien ongelmana ratkaista sellainen myynnin aikaura, joka maksimoi voiton nykyarvon. Vastaavasti kansainvälisestä hiilidioksidiverosta vastaavan päästökseen tekijän ongelmana on löytää sellainen hiilidioksidiveron aikaura, joka maksimoi ostajamaissa kertyvän kuluttajien ylijäämän ja kumulatiivisten saastumishaittojen erotuksen nykyarvon. Ilmenee, että saastumisongelman ollessa palautumaton luonnonvaraa ei välttämättä hyödynnetä loppuun. Luonnonvaraa hyödynnetään hitaammin, kuluttajien maksama hinta kasvaa ja tuottajahinta alenee. Tuottajahinnan aikaura on laskeva ja lähestyy nollaa. Luonnonvaran omistajille ei kerry niukkuusvuokraa.

Tilanne, jossa luonnonvaran omistajia on yksi tai useat omistajat ovat muodostaneet kartellin tutkitaan differentiaalipelinä. Luonnonvaran myyjä on Stackelberg - johtaja ja Pigoun verosta vastaava ostajien organisaatio on seuraaja. Yksinkertaisemmassa tapauksessa myyjän oletetaan voivan sitoutua voiton maksimoivaan hintauraan. Tasapaino ratkaistaan muotoilemalla myyjälle optimiohjausongelma, jossa ostajan välttämättömät ehdot optimaaliselle hiilidioksidiverolle ovat osana optimointia rajoittavia ehtoja (ns. Stackelberg open-loop equilibrium). Näin ratkaistussa markkinatasapainossa luonnonvaran hyödyntäminen on hitaampaa, tuottajan hinta on pysyvästi korkeampi ja hiilidioksidivero on pysyvästi alhaisempi kuin kilpailullisilla markkinoilla. Luonnonvaran omistajan hintastrategia ei kuitenkaan ole aikakonsistentti ja tasapaino ei näinollen ole osapelitäydellinen.

Aikakonsistentti tasapaino (Stackelberg feedback equilibrium) ratkaistaan asettamalla myyjälle ongelma, jossa ostajan Bellman-Jacobi-Hamilton yhtälö on rajoitteena.

Verrattaessa markkinahinnan reagointia Pigoun veroon osoittautuu, että tuottajahinta voi reagoida verotukseen joko kasvamalla tai alenemalla. Mahdollinen hinnannousu on kuitenkin välttämättä väliaikainen. Näinollen teoreettinen tarkastelu ei tue näkemystä, että hiilidioksidipäästöjen aiheuttama mahdollinen "öljykriisi" olisi samanlainen kuin aikaisemmat.

1 INTRODUCTION

A major part of atmospheric CO_2 emissions originates from fossil fuels, i.e. from nonrenewable resources. These emissions accumulate in the atmosphere and pose the threat of climate change with possible adverse effects on productivity and human welfare. Thus, in determining the optimal consumption schedule, users of oil and coal must take into account the long-term consequences of increasing CO_2 concentration. Similarly, owners of nonrenewable resources face the problem of maximization of the present value resource rent. In contrast to the traditional view of nonrenewable resource markets where buyers solve a sequence of static demand decisions, the implication of the pollution problem is that market equilibrium must solve two dynamic optimization problems simultaneously.

Additional complexity follows if the seller of the nonrenewable resource is a monopolist or if the resource owners form a resource cartel which does not take the price of the resource as given. What is the reaction of the resource seller if the buyers adopt Pigouvian taxation or markets for emission permits to slow down CO_2 accumulation? When the monopolist seller tries to exert market power he faces buyers whose demand is influenced not only by the current price but by expectations of future prices as well. A possible consequence is that the rent-maximizing price trajectory is time-inconsistent. This raises the main question studied in this paper: to what extent is a nonrenewable resource monopolist able to maintain his monopoly power when the resource buyers apply Pigouvian taxation for slowing pollution accumulation?

This issue has a counterpart in resource economics. Accumulating pollution may be interpreted as a "durable bad". In contrast, precious metals, gemstones and nonfuel minerals like copper and aluminium are durable goods. Levhari and Pindyck [8] show that Hotelling's rule applies to a durable nonrenewable resource produced in a competitive market but not if the resource is sold in a monopolistic market. They do not, however, consider the question of time-inconsistency. Malueg and Solow [9] show that a monopolist whose costs are convex and who cannot precommit is able to assert his power by delaying resource extraction, although in the long

run his monopoly power will vanish. Recently, Karp [6] studied a model where short-run extraction costs are constant, the resource is exhaustible and the depreciation rate of the durable good is either positive or zero. His results show that the Coase Conjecture [2] holds if the good does not depreciate but fails if depreciation is positive. Thus the durability of the nonrenewable resource may cause the monopolist to lose his power. More generally, Karp argues that the Coase Conjecture fails if the monopolist has reason to spread production over time. When a monopolist maintains part of his power, the market equilibrium is typically different from both the competitive outcome and the equilibrium under a precommitted monopoly.

Together, this background suggests that Pigouvian taxation may have interesting and complex implications for fossil fuel markets. The differential game considered below takes the monopoly resource owner as a Stackelberg leader while the international government choosing the Pigouvian taxation policy is the follower. Thus resource buyers apply emission taxation under international cooperation. The open-loop Stackelberg equilibrium is shown to lead to a higher producer price, lower pollution tax level, higher resource rent and slower pollution accumulation and resource use in comparison with the welfare-maximizing outcome. Furthermore, the total amount of resource extraction is lower. However, the resulting steady state equilibrium depends directly on the initial level of the resource stock. This means that the equilibrium cannot be time-consistent, i.e. the monopolist will have an incentive to deviate from the price trajectory announced at the beginning of the game. If the monopolist is not able to precommit to this profit-maximizing strategy and the buyers notice this, the open-loop market equilibrium is unlikely to be achieved.

To find the time-consistent and Markov-perfect equilibrium, the seller is assumed to solve a dynamic programming problem which includes the dynamic programming equation of the follower as a constraint. It is shown that the resulting equilibrium deviates from the welfare-maximizing path but the seller's monopoly power vanishes asymptotically when the steady state is approached. Ultimately, the consistent monopolist sells the efficient amount but

the steady state is approached too slowly. Along the equilibrium path the producer price is higher but the emission tax lower compared with the efficient levels. This holds even if the marginal extraction costs are linear. The difference between a durable good monopolist and a durable bad monopolist is that, in the case of pollution, demand is a flow relationship. This gives the seller an incentive to spread production over time and thus the market outcome without precommitment deviates from the optimal outcome. By interpreting persistent pollution as a durable bad, this paper extends the durable exhaustible literature to include fossil fuels. If the paper is compared with previous studies, such as Hoel [3], which combine nonrenewable resources and pollution in a social planner's framework, the analysis suggests that market imperfections may play a key role in the interaction between pollution control and nonrenewable resource extraction. Energy pricing and Pigouvian taxation have been studied as a static game by Wirl [15]. His interesting conjecture is that taxation of externalities may raise the world price of energy because taxation encourages cartelization. This paper shows that this is possible, i.e. the producer price under Pigouvian taxation and time-consistent monopoly supply may exceed the efficient price when no taxation exists. However, dynamic analysis reveals that the price increase due to Pigouvian taxation is only temporary and later taxation inevitably leads to a reduction in the producer price.

The paper is organized as follows. Section 2 solves the welfare-maximizing solution as a benchmark. Section 3 presents the equilibrium under precommitted monopoly supply. Section 4 derives the perfect equilibrium and section 5 compares different equilibria. Section 6 summarizes the main results.

2 PARETO EFFICIENT RESOURCE EXTRACTION AND PIGOUVIAN TAXATION

This section specifies the outcome when both buyers and sellers take the resource price as given and buyers apply Pigouvian taxation for emission control. This setup will imply a pareto optimal outcome with which the implications of a monopolistic resource supply can be compared. To solve resource demand it is necessary to specify how the buyers of the nonrenewable resource take the

accumulating pollution problem into account. Bearing in mind global pollution problems such as atmospheric CO₂ accumulation, it is assumed that the buyer countries control emissions in cooperation with each other¹. This means that there exists an international government which sets a tax on emissions so as to induce optimal emission abatement in the cooperating countries.

The buyers' utility² of consuming the resource at the rate $q(t)$ is given by the quadratic function $U[q(t)] \equiv aq(t) - bq(t)^2$. Note that a is the choke price. Let $p(t)$ denote the producer price and $\psi(t)$ the CO₂ tax set by the international organization. $p(t) + \psi(t)$ is thus the consumer price for using the resource. δ is the rate of discount and T is the date when the resource is (perhaps) used up. The pollution damage in the buyer countries is given by the quadratic function $dz(t)^2$, where $z(t)$ is the accumulated pollution stock and $d > 0$ is a parameter. To find the optimal time path for the pollution tax, the government which coordinates the emission abatement must solve the problem:

$$\begin{aligned} \text{maximize } W_b = & \int_0^T [aq - bq^2 - pq - dz^2] e^{-\delta t} dt - \int_T^\infty dz(T)^2 e^{-\delta t} dt \\ \{ q \geq 0, z(T), T \} \end{aligned} \quad (1)$$

$$\text{s.t. } \dot{z} = q, z(0) = \bar{x} - x_0. \quad (2)$$

Note that the bequest function takes into account the present value of damage, which, in the case of an infinite planning horizon, occurs after T . In (2) \bar{x} denotes the total amount of the resource in the ground and x_0 is the amount which is unextracted at moment 0. The equation $\dot{z} = q$ shows an

¹Other alternatives include a case where the buyers control emissions without cooperation or where the pollution problem is more local as perhaps in the case of uranium.

²As is well known, the outcome of non-renewable resource markets is sensitive to functional forms [13, 14]. This study applies linear quadratic functions throughout the analysis in order to obtain closed form solutions. This choice is frequently applied in the literature on a durable goods monopolist [4].

important simplification, i.e. it is assumed that pollution accumulation is irreversible.

The current value Hamiltonian for the buyers is³ $\mathcal{K}_c^b = aq - bq^2 - pq - dz^2 - \psi q$. The necessary conditions for optimal solution are:

$$\partial \mathcal{K}_c^b / \partial q = a - 2bq - p - \psi \leq 0, \quad q \partial \mathcal{K}_c^b / \partial q = 0, \quad q \geq 0, \quad (3)$$

$$\dot{\psi} = -2dz + \delta\psi, \quad (4)$$

and conditions (2). The free horizon and transversality conditions $\mathcal{K}_c^b(T) + dz(T)^2 = 0$ and $-\psi(T) + 2dz(T)/\delta = 0$ are necessary only when $T^* < \infty$.

Let us turn to the resource supply. When sellers are competitive they aim to

$$\begin{aligned} & \text{maximize} \quad W_c^s = \int_0^T [pq - cq^2] e^{-\delta t} dt \\ & \{ q \geq 0, x(T), T \} \end{aligned} \quad (5)$$

$$\text{s.t.} \quad \dot{x} = -q, \quad x(0) = x_0 \leq \bar{x}, \quad (6)$$

$$x(T) \geq 0. \quad (7)$$

Extraction costs depend only on the rate of extraction and in (5) they are given by a convex quadratic function cq^2 . We will, however, also consider the possibility that the marginal extraction costs are constant. In that case it is assumed that $c=0$ without losing generality. The sellers' current value Hamiltonian is $\mathcal{K}_c^s = pq - cq^2 - \varphi q$, where φ denotes rent. The necessary conditions for optimality are:

$$\partial \mathcal{K}_c^s / \partial q = p - 2cq - \varphi \leq 0, \quad q \partial \mathcal{K}_c^s / \partial q = 0, \quad q \geq 0, \quad (8)$$

$$\dot{\varphi} = \delta\varphi, \quad (9)$$

³By changing the sign of ψ in \mathcal{K}_c^b and in (3) and (4), the pollution tax equals the negative costate variable for z . Thus $\psi = -\iota$, $\dot{\psi}_c = -\dot{\iota} = -2dz - \delta\iota = -2dz + \delta\psi$, where $\iota (< 0)$ is the costate variable for z .

including conditions (6), (7) and $\mathcal{K}_c^s(T)=0$, $x(T) \geq 0$, $\varphi(T) \geq 0$, $x(T)\varphi(T)=0$. Again, the transversality and free terminal time conditions are necessary only when the optimal horizon turns out to be finite.

When extraction costs are zero (or linear) the Hamiltonian of competitive sellers is linear in q . However, impulse controls are ruled out by the demand relationship given in (3).

Given that the buyers' cooperation for emission abatement solves (1)→(2), the resource extraction policy is "quasi-competitive" or welfare-maximizing. Social efficiency can be shown by maximizing $W_b + W_c$ subject to (2), (6) and (7). The solution may be called quasi-competitive because the government which represents all the buyers is assumed to act as a price taker.

The analysis will concentrate on the solutions where the resource stock is not depleted in finite time. In this case the properties of the optimal solution can be summarized as follows:

Proposition 1. Given $a - 2d\bar{x}/\delta \leq 0$, the resource stock approaches a steady state level equal to $\bar{x} - a/2d$. Along the optimal path the resource rent is zero. The rate of resource extraction declines, the consumer price increases and the producers price decreases. When $t \rightarrow \infty$ the rate of resource extraction approaches zero, the consumer price and pollution tax increase toward the choke price, and the producer's price towards zero. If $c=0$ the producer price is zero $\forall t$ and the consumer price equals the pollution tax.

Proof: Because $z = \bar{x} - x$ we can define a new shadow price $\mu = \varphi + \psi$ with $\dot{\mu} = 2d(x - \bar{x}) + \delta\mu$. Equations (3) and (8) imply $q = (a - \mu)/(2(b + c))$. Now the equilibrium is defined by the system:

$$\dot{q} = \{2d(\bar{x} - x) + \delta[(2q(b + c) - a)]\}/2(b + c), \quad (10)$$

$$\dot{x} = -q, \quad x(0) = x_0 \leq \bar{x}. \quad (11)$$

The solution for the resource stock is $x(t) = A_1 e^{r_1 t} + A_2 e^{r_2 t} + \bar{x} - \delta a/2d$, where

$$r_1, r_2 = \frac{1}{2} \{ \delta \pm [(\delta^2 + 4d/(b+c))^{\frac{1}{2}}] \}, \quad r_1 > 0, \quad r_2 < 0. \quad (12)$$

The constants A_1 and A_2 are determined using the initial level of the resource stock and the infinite horizon transversality conditions. The solution where $A_1=0$ satisfies the infinite horizon sufficiency theorem ([11] theorem 3.13). Thus by (17):

$$x_c^*(t) = (x_0 - \bar{x} + \delta a / 2d) e^{r_2 t} + \bar{x} - \delta a / 2d, \quad (13)$$

$$q_c^*(t) = -r_2 (x_0 - \bar{x} + \delta a / 2d) e^{r_2 t}, \quad (14)$$

where the subscript c stands for pareto optimal equilibrium. Integrating (4) and (9) yields: $\psi(t) = A_3 e^{\delta t} + \int_t^\infty 2d[\bar{x} - x_c^*(t)] e^{\delta(t-\tau)} d\tau$, $\varphi(t) = \varphi_0 e^{\delta t}$ and $\mu(t) = (\varphi_0 + A_3) e^{\delta t} + \int_t^\infty 2d[\bar{x} - x_c^*(t)] e^{\delta(t-\tau)} d\tau$. By $q = (a - \mu) / a(b+c)$ and (14) it follows that $\mu \rightarrow a$ when $t \rightarrow \infty$. Thus it must hold that $\varphi_0 + A_3 = 0$. Solutions where $\varphi_0 > 0$ and $A_3 < 0$ imply that $\varphi \rightarrow \infty$ and $\psi \rightarrow \infty$ when $t \rightarrow \infty$. In contrast, a solution where $\varphi_0 = 0$ and $A_3 = 0$ implies that $\varphi = 0 \forall t$ and $\psi > 0 \forall t$ and $\psi \rightarrow a$ when $t \rightarrow \infty$. Because the latter type of solution satisfies the sufficient theorem for infinite horizon problems, it must be the optimal solution. Because the problem is strictly concave, the equilibrium is unique. Finally, applying the results that $A_3 = \varphi_0 = 0$ and equations (4), (8) and (14), we obtain

$$\psi_c^*(t) = a + [2d(x_0 - \bar{x}) + \delta a] e^{r_2 t} / (r_2 - \delta), \quad (15)$$

$$p_c^*(t) = -r_2 2c(x_0 - \bar{x} + \delta a / 2d) e^{r_2 t}. \quad (16)$$

From (14) and (15) it follows that as $t \rightarrow \infty$ $x_c^*(t) \rightarrow \bar{x} - \delta a / 2d$ and $q_c^*(t) \rightarrow 0$. Given $c > 0$ equation (16) shows that $p_c^*(t)$ declines monotonically toward zero when $t \rightarrow \infty$, and that $c = 0$ implies $p_c^* = 0 \forall t$. From (4) and $\dot{q}_c^* < 0$ it follows that $\dot{p}_c^* + \dot{\psi}_c^* > 0 \quad \forall t \in [0, \infty)$ i.e. the consumer price is increasing. Equation (15) shows that $\psi_c^* \rightarrow a$ from below. Because p_c^* declines toward zero when $t \rightarrow \infty$ the consumer price will approach the choke price. ■

In the case considered the resource stock is so abundant that the present value marginal damage may exceed the choke price and the stock is not depleted. At the optimal steady state the marginal present value pollution damage equals the pollution tax and the choke price, i.e. $\psi_c^\infty = 2d(\bar{x} - x_\infty)/\delta = a$. This means that the resource demand is finally zero even when the producer price is zero. When part of the resource stock remains in the ground, an increase in the resource stock does not increase the profits of the resource owners. Thus it is natural that the resource rent is zero, which means that the Hotelling rule does not hold. Along the equilibrium path the producer price equals the marginal extraction costs. If marginal extraction costs are zero, the producer price must also be zero.

3 MONOPOLY SUPPLY WITH PRECOMMITMENT

In this and the next section will consider resource market as a Stackelberg game. The leader of the game may be either a monopoly resource seller or the buyers' government. The latter case can be dealt with quickly. When the analysis is restricted to the case where extraction costs are independent of the resource stock, the sellers' resource rent will be zero as in quasi-competitive equilibrium (cf. [5]). The implication is that the buyers' government is solving a standard control problem which includes the sellers' behaviour as a static constraint. If $c=0$ or extraction costs are linear and sellers are price takers the solution will equal the pareto efficient outcome. In general, the solution is time-consistent and by writing the solution in feedback form it can be sustained as a Markov-perfect equilibrium [cf. 5, 7]. Hence in this case the problem of time-inconsistency does not rise. Thus we will focus on the less straightforward case where the resource seller is a monopoly and acts as a leader in a Stackelberg game. The possibility that the resource seller may be able to lead the game is supported by the fact that international negotiations on climate warming have concentrated on the aim of reducing emissions without discussion of a buyers' cartel in fossil fuel markets (cf. [15]).

We first consider the outcome when the monopolist can precommit to a rent-maximizing sales strategy. Let the subscript $_{mp}$ refer to the monopolist with precommitment. The inverse demand function is $p=a-2bq-\psi$ (from 3) and the problem of the precommitted monopolist is to

$$\underset{\{q, x(T), T\}}{\text{maximize}} \quad W_{mp} = \int_0^T [(a-2bq-\psi)q - cq^2] e^{-\delta t} dt \quad (17)$$

$$\text{s.t.} \quad \dot{x} = -q, \quad x(0) = x_0, \quad x_0 \in (\bar{x} - \delta a / 2d, \bar{x}] \equiv \Gamma, \quad (18)$$

$$\dot{\psi} = -2d(\bar{x} - x) + \psi\delta, \quad (19)$$

$$\psi(T) - 2d(\bar{x} - x) / \delta = 0, \quad x(T) \geq 0, \quad (20)$$

$$\mathcal{K}_c^b(T) + d(\bar{x} - x)^2 = 0. \quad (21)$$

Denote the monopolist shadow price for the pollution tax by σ . The current value Hamiltonian is $\mathcal{H}_{mp} = (a-2bq-\psi)q - cq^2 - \varphi q + \sigma[-2d(\bar{x} - x) + \psi\delta]$ and the necessary conditions for optimality are [10]:

$$\partial \mathcal{H}_{mc} / \partial q = a - 2bq - \psi - 2q(b+c) - \varphi \leq 0, \quad q \partial \mathcal{H}_{mc} / \partial q = 0, \quad q \geq 0, \quad (22)$$

$$\dot{\varphi} = -\sigma 2d + \delta \varphi, \quad (23)$$

$$\dot{\sigma} = q, \quad (24)$$

$$\sigma(0) = 0, \quad (25)$$

including conditions (18)–(21). When $T^* < 0$ the transversality and free horizon conditions are $\varphi(T) \geq 0$, $x(T) \geq 0$, $\varphi(T)x(T) = 0$ and $\mathcal{H}_{mc}(T) = 0$.

Equation (24) implies $\sigma(t) = h - x$, where h is a constant. From (25) $\sigma(0) = c - \bar{x} = 0$, which means that $\sigma = x_0 - x$, ($\geq 0 \quad \forall t \in [0, T]$). Now the resource rent satisfies

$$\dot{\varphi} = 2d(x - x_0) + \delta \varphi. \quad (26)$$

The resource stock again has two costate variables φ and ψ . Let us denote the sum of these by μ .

Using (18), (19), (22), and (26) the extremal trajectories of the problem are defined by the equations:

$$\dot{\mu} = 4dx - 2d(\bar{x} + x_0) + \delta\mu, \quad (27)$$

$$\dot{x} = (\mu - a)/2(2b + c). \quad (28)$$

The solution to this linear nonhomogenous system is $\mu(t) = 4dA_1e^{v_1t}/(v_1 - \delta) + 4dA_2e^{v_2t}/(v_2 - \delta) + a$ and

$$x(t) = A_1e^{v_1t} + A_2e^{v_2t} + (\bar{x} + x_0)/2 - \delta a/4d, \quad (29)$$

where

$$v_1, v_2 = \frac{1}{2} \{ \delta \pm [\delta^2 + 8d/(2b + c)]^{\frac{1}{2}} \}, \quad v_1 > 0, \quad v_2 < 0. \quad (30)$$

We again focus on the case where the resource is not depleted in finite time.

Proposition 2. The steady state stock level depends positively on x_0 and equals $\frac{1}{2}(\bar{x} + x_0) - \delta a/4d$. The rate of resource extraction declines monotonically toward zero. The pollution tax and resource rent increase and the producer price decreases along the equilibrium path. The steady state resource rent and producer price levels depend positively and the pollution tax negatively on x_0 . The producer price remains strictly positive as $t \rightarrow \infty$. If $c=0$ the producer price is constant. The consumer price increases asymptotically toward the choke price. The higher is x_0 the smaller is the share of the pollution tax and the larger is the share of the producer price in the consumer price.

Proof: When $\frac{1}{2}(\bar{x} + x_0) - \delta a/4d \geq 0$ a solution with $A_1=0$ approaches a steady state $x_\infty = \frac{1}{2}(\bar{x} + x_0) - \delta a/4d$ (eq. 29). Because this solution satisfies all necessary conditions for optimality and is the unique optimality candidate it must be the optimal solution. Thus

$$x_{mp}^*(t) = [\frac{1}{2}(x_0 - \bar{x}) + \delta a / 4d] e^{v_2 t} + \frac{1}{2}(\bar{x} + x_0) - \delta a / 4d, \quad (31)$$

$$q_{mp}^*(t) = -v_2 [\frac{1}{2}(x_0 - \bar{x}) + \delta a / 4d] e^{v_2 t}. \quad (32)$$

Because $v_2 < 0$ resource extraction declines (exponentially) toward zero when $t \rightarrow \infty$. Next, using (31), (26), (19) and (22) gives

$$\varphi_{mp}^*(t) = [d(x_0 - \bar{x}) + \delta a / 2] e^{v_2 t} / (v_2 - \delta) + a / 2 + d(x_0 - \bar{x}) / \delta, \quad (33)$$

$$\psi_{mp}^*(t) = [d(x_0 - \bar{x}) + \delta a / 2] e^{v_2 t} / (v_2 - \delta) + a / 2 + d(\bar{x} - x_0) / \delta. \quad (34)$$

$$p_{mp}^*(t) = [a(b+c) + b(\varphi_{mp}^* - \psi_{mp}^*) - c\psi_{mp}^*] / (2b+c). \quad (35)$$

Because v_2 is negative, the resource rent and pollution tax increase as time passes. Because $\dot{\varphi}_{mp}^* - \dot{\psi}_{mp}^* = 0$, it follows that $\dot{p}_{mp}^* < 0$. Equations (33) and (34) show directly that the steady state rent depends positively and the steady state pollution tax negatively on x_0 . By (33)–(35), the steady state producer price equals $a(b+c)/(2b+c) + d(x_0 - \bar{x})/\delta > 0 \quad \forall x_0 \in \Gamma$. It clearly depends positively on x_0 . When $c=0$, $p_{mp}^*(t) = a/2 + d(x_0 - \bar{x})/\delta \quad \forall t$, which is constant.

The consumer price equals $a - 2bq_{mp}^*$ (or $p_{mp}^* + \psi_{mp}^*$), which, together with equation (32), shows that the price approaches the choke price from below. Equation (34) shows that the higher is x_0 the lower is the pollution tax $\forall t \in [0, \infty]$. By (33)–(35) a higher x_0 implies higher producer price $\forall t \in [0, \infty]$. Thus the higher is x_0 the lower is the share of the pollution tax in the producer price and consequently the higher must be the share of the producer price. ■

Proposition 2 gives a completely different picture of resource extraction compared with the pareto efficient outcome. The steady state prices and quantities depend directly on the initial resource level, the total amount of the resource extracted is lower, the producer price remains positive and the resource rent is increasing in time compared with the zero level in the efficient outcome. Consequently, the level of pollution accumulation is lower.

However, the solution derived above reveals that the equilibrium is time—inconsistent. This can be seen from the costate variable for the pollution tax, i.e. $\sigma(t)$ (e.q. 24, 25). After $t=0$ its value will be positive, which means that the buyer has an incentive to change the price strategy in a way which increases the pollution tax and resource extraction. By announcing the open-loop price trajectory, the monopolist threatens to use a high price level in the future. From the point of view of buyers' government, there is no need to apply high pollution taxes because pollution accumulation seems to remain slow. As a consequence the share of the producer price in consumer price is high. However, after a period of low pollution taxes, the monopolist cannot lose the gain already received and thus he would like to decrease the price, sell more and let the pollution tax increase. If the government applying Pigouvian taxation has rational expectations, it anticipates these incentives and does not initially apply low pollution taxation. Consequently this description of the pollution tax/resource extraction game is plausible only if the monopolist can efficiently precommit to the rent—maximizing price trajectory.

4 MONOPOLY SUPPLY WITHOUT PRECOMMITMENT

To study the case where the monopoly cannot precommit to profit—maximizing sales strategy, we compute a market equilibrium which solves simultaneously the dynamic programming problems for the resource owner (the leader) and the international organization coordinating the Pigouvian taxation (the follower). This method of computing the equilibrium eliminates all but time—consistent strategies. The resulting outcome is a Stackelberg feedback solution which is a Markov—perfect equilibrium. This means that the information set of the players is restricted to include only variables with direct influence on the current or future pay—offs. In this context this kind of variable is the current stock of the resource. The equilibrium is also subgame perfect because it is based on decision rules which are optimal independently of the resource stock level.

To solve this equilibrium we apply theorem 4.2 in Basar & Haurie [1]. Denote by $V_2(x)$ the

value function of the buyers' government. The Hamilton–Jacobi–Bellman equation is:

$$V_2(x)\delta = \max_{\{q\}} \{aq - bq^2 - pq - d(\bar{x} - x)^2 - V_2'(x)q\}, \quad (36)$$

where, given the linear quadratic functional forms, the value function satisfies the following quadratic form: $V_2(x) = \frac{1}{2}A_2x^2 + B_2x + C_2$. Carrying out the maximization of the RHS of (36) gives the reaction function for the government:

$$q \equiv q(x, p) = (a - p - A_2x - B_2)/2b. \quad (37)$$

Next we can write the Hamilton–Jacobi–Bellman equation for the monopolist resource owner:

$$V_1(x)\delta = \max_{\{p\}} \{p(a - p - A_2x - B_2)/2b - c[a - p - A_2x - B_2]/2b\}^2 - V_1'(x)(a - p - A_2x - B_2)/2b\}, \quad (38)$$

where $V_1(x) = \frac{1}{2}A_1x^2 + B_1x + C_1$. The maximization of the RHS requires:

$$q - p/2b + 2cq/2b + (A_1x + B_1)/2b = 0, \quad (39)$$

which gives the leaders control as a function of the resource stock:

$$p^*(x) = \{x[A_1b - A_2(b+c)] + B_1b - (b+c)(B_2 - a)\}/(2b+c). \quad (40)$$

Next p can be substituted from (39), which then gives the equilibrium resource use as a function of the stock:

$$q^*(x) = -[x(A_1 + A_2) + B_1 + B_2 - a]/2(2b+c). \quad (41)$$

To solve the parameters of the value functions, substitute p^* and q^* into the HJB —equations (36) and (38):

$$\delta(\frac{1}{2}A_2x^2+B_2x+C_2)-[aq^*(x)-bq^*(x)^2-p^*q^*-d(\bar{x}-x)^2-(A_2x-B_2)q^*(x)]=0, \quad (42)$$

$$\delta(\frac{1}{2}A_1x^2+B_1x+C_1)-[p^*(x)q^*(x)-cq^*(x)^2-(A_1x-B_1)q^*(x)]=0. \quad (43)$$

From the fact that equations (42) and (43) must hold $\forall x$, we obtain the following set of equations:

$$\begin{aligned} A_1^2b+2A_1A_2b+A_2^2b-2A^2\delta(2b+c)^2-4d(2b+c)^2 &=0, \\ A_1b(B_1+B_2-a)+A^2b(B_1+B_2-a)-2(2b+c)^2(B_2\delta-2\bar{x}d) &=0, \\ B_1^2b+2B_1b(B_2-a)+B_2^2b-2B_2ab-4C_2\delta(2b+c)^2-4\bar{x}^2d(2b+c)^2+a^2b &=0, \\ A_1^2+2A_1(A_2-\delta(2b+c))+A_2^2 &=0, \\ A_1(B_1+B_2-a)+A^2(B_1+B_2-a)-2B_1\delta(2b+c) &=0, \\ B_1^2+2B_1(B_2-a)+B_2^2-2B_2a-4C_1\delta(2b+c)+a^2 &=0. \end{aligned}$$

The first and fourth equation determine four solution pairs for A_1 and A_2 . Of these, only one pair implies stability and positive levels of resource extraction. Taking this into account, the four main parameters in the value functions are as follows:⁴

$$A_1=4d^2(2b+c)/\left\{\delta[\delta(2b+c)w+4b^2\delta^2+2b(2c\delta^2+3d)+c(c\delta^2+2d)]\right\}>0, \quad (44)$$

⁴ $C_1=[B_1^2+2B_1(B_2-a)+(B_2-a)^2]/4\delta(2b+c)$, $C_2=[B_1^2b+2B_1b(B_2-a)+B_2^2b-2B_2ab-4\bar{x}^2d(4b^2+4bc+c^2)+a^2b]/4\delta(4b^2+4bc+c^2)$.

$$A_2 = -4d(2b+c)(\delta w + 2b\delta^2 + c\delta^2 + 2d) / \delta[w + \delta(2b+c)]^2 < 0, \quad (45)$$

$$B_1 = -2d(2b+c)(2\bar{x}d - \delta a) / \delta\{\delta(2b+c)[w + \delta(2b+c)] + 2d(3b+c)\} > 0, \quad (46)$$

$$B_2 = 2d[\bar{x}(2b+c)(\delta w + 2b\delta^2 + c\delta^2 + 2d) + ab\delta] / \delta\{\delta(2b+c)[w + \delta(2b+c)] + 2d(3b+c)\} > 0, \quad (47)$$

where $w = [4b^2\delta^2 + 4b(c\delta^2 + 3d) + c^2\delta^2 + 4cd]^{\frac{1}{2}}$.

Straightforward algebra reveals that $-(B_1 + B_2 - a)/(A_1 + A_2) = \bar{x} - \delta a/2d$, $A_1(\bar{x} - \delta a/2d) + B_1 = 0$ and $A_2(\bar{x} - \delta a/2d) + B_2 = a$. From (41) it now follows that $q^*(\bar{x} - \delta a/2d) = 0$. The first derivative of the buyer's value function is the pollution tax, i.e. $\psi^*(x) = A_2x + B_2$, and the first derivative of the seller's value function is the resource rent, i.e. $\varphi^*(x) = A_1x + B_1$. Computing reveals $\psi^*(\bar{x} - \delta a/2d) = a$ and $\varphi^*(\bar{x} - \delta a/2d) = 0$. From equation (40) it follows that $p^*(\bar{x} - \delta a/2d) = 0$. Thus at the steady state equilibrium $x^* = \bar{x} - \delta a/2d$, $\varphi^* = 0$, $\psi^* = a$ and $p = 0$. Let us turn to consider the approach paths.

From $\dot{x} = -q$ and equation (41) it follows: $\dot{x} = x(A_1 + A_2)/2(2b+c) + (B_1 + B_2 - a)/2(2b+c)$. Direct integration and the use of the initial condition gives the equilibrium time paths for the resource stock and the rate of extraction:

$$x_{mc}^*(t) = (x_0 - \bar{x} + \delta a/2d)e^{k_1 t} + \bar{x} - \delta a/2d, \quad (48)$$

$$q_{mc}^*(t) = -k_1(x_0 - \bar{x} + \delta a/2d)e^{k_1 t}, \quad (49)$$

$$k_1 = (A_1 + A_2)/2(2b+c) = -2d / \{[4b^2\delta^2 + 4b(c\delta^2 + 3d) + c^2\delta^2 + 4cd]^{\frac{1}{2}} + \delta(2b+c)\} < 0. \quad (50)$$

The subscript $_{mc}$ refers to consistent monopoly supply. Using (37) and (40), we can now express the time derivatives for consumer and producer prices, resource rent and pollution tax as follows: $\dot{p}_{mc}^*(t) + \dot{\psi}_{mc}^*(t) = -2b\dot{q}_{mc}^*(t) > 0$, $\dot{p}_{mc}^*(t) = \dot{x}_{mc}^*(t)[A_1b - A_2(b+c)]/(2b+c) < 0$, $\dot{\psi}_{mc}^*(t) = A_2\dot{x}_{mc}^*(t) > 0$, and $\dot{\varphi}_{mc}^*(t) = A_1\dot{x}_{mc}^*(t) < 0$ and if $c=0$ $\dot{p}_{mc}^*(t) = \dot{x}_{mc}^*(t)(A_1 - A_2)/2 < 0$. We can now summarize the above findings as follows:

Proposition 3. When the resource is supplied by a monopolist who cannot precommit, the market equilibrium approaches a steady state where the resource stock level equals $\bar{x} - \delta a/2d$, the

producer price and resource rent equal zero, and the pollution tax equals the choke price. Along the equilibrium path the rate of extraction decreases, the consumer price and the pollution tax increase, and producer price and the resource rent decrease. The resource rent is strictly positive $\forall t \in [0, \infty)$ and the producer price is nonconstant independently of whether $c \geq 0$.

Comparing propositions 2 and 3 suggests that the market equilibrium under monopoly without precommitment closely resembles the quasi-competitive equilibrium because the long-run steady states as well as the qualitative movements in different variables are equal. The next section compares different outcomes more accurately.

5 COMPARISON OF MONOPOLY AND EFFICIENT OUTCOMES

In addition to the cases studied above it is possible to compare market outcomes with and without the effects of Pigouvian taxation. Thus there are five cases which can be compared. In the following the analysis is focused on comparisons of the pareto optimal outcome and the two monopoly equilibria. In addition, we examine whether Pigouvian taxation may increase the producer price as is argued by Wirl [15].

In the comparison it is necessary to know the relative size of roots in different solutions. These roots are compared by means of the the following lemma:

Lemma 1: $v_2 < r_2 < k_1 < \frac{1}{2}v_2$. Proof, appendix 1.

To compare the optimal and monopoly extraction paths let us depict the paths in $q-x$ state space (Figure 1). Equations (10) and (11) define the efficient solution. The locus of $\dot{q}_c = 0$ intersects the x -axis when $x = \bar{x} - \delta a / 2d$ and is increasing. Accordingly, the locus of $\dot{q}_{mp} \big|_{x_0 = \bar{x}} = \{2d(\bar{x} + x_0) - 4d\bar{x} + \delta[q_{mp}(4b + 2c) - a]\} / (4b + 2c) = 0$ intersects the x -axis when $x = \frac{1}{2}(\bar{x} + x_0) - \delta a / 4d$. Given $x_0 = \bar{x}$, the steady state equals $\bar{x} - \delta a / 4d$. This isocline is denoted in Figure 1. When $x_0 < \bar{x}$ the slopes of the isoclines remain unchanged but they exist on the left side of the isocline $\dot{q}_{mp} = 0 \big|_{x_0 = \bar{x}}$.

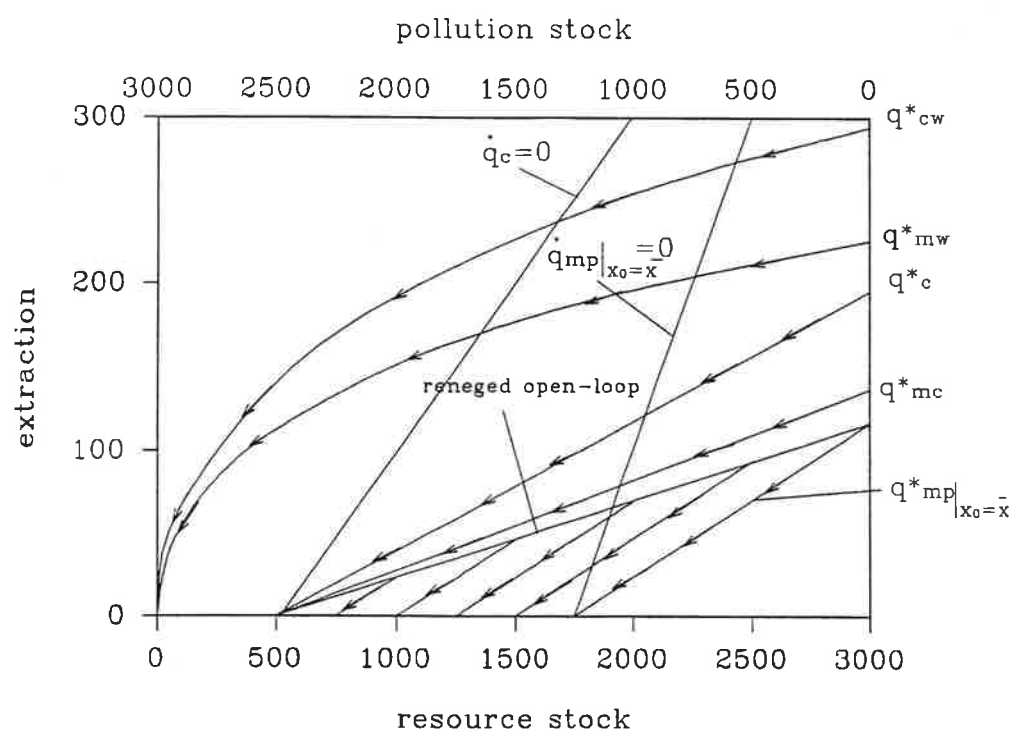


Figure 1. A phase diagram

Note: q_{cw}^* = competitive equilibrium with pollution

q_{mw}^* = monopoly supply without pollution

q_c^* = optimal solution with pollution

q_{mp}^* = monopoly supply with precommitment

q_{mc}^* = monopoly supply without precommitment

Given $t=0$, equation (32) defines the initial level of extraction as a function of the initial stock level, i.e. $q_{mp}^*(0) = -v_2[\frac{1}{2}(x_0 - \bar{x}) + \delta a/4d]$. This yields $\partial q_{mp}^*(0)/\partial x_0 = -v_2/2$ and $q_{mp}^*(0) = 0$, when $x_0 = \bar{x} - \delta a/2d$. By equation (14) the slope of the optimal trajectory is $-r_2$. By lemma 1 $-r_2 > -\frac{1}{2}v_2$, which means that the slopes of the optimal path must exceed the slope of the line $q_{mp}^*(0) = -v_2[\frac{1}{2}(x_0 - \bar{x}) + \delta a/4d]$. Thus $q_c^* > q_{mp}^* \forall x \in \Gamma$. By using lemma 1 it is, in addition, possible to show that the time paths for extraction cannot cross i.e. the optimal time path for extraction is always above the extraction path under monopoly with precommitment.

To compare pollution taxes use (4) and (19) and the fact that both tax levels are approaching steady states to obtain $\psi_{mp}^* = \int_t^\infty 2d[\bar{x} - x_{mp}^*(\tau)]e^{\delta(t-\tau)}d\tau$ and $\psi_c^* = \int_t^\infty 2d[\bar{x} - x_c^*(\tau)]e^{\delta(t-\tau)}d\tau$. Because $x_c^*(\tau) < x_{mp}^*(\tau) \forall \tau > 0, \forall x_0 \in \Gamma$, it follows that $\psi_c^* > \psi_{mp}^* \forall t \in [0, \infty]$, $\forall x \in \Gamma$ i.e. the efficient Pigouvian tax is always higher.

The pareto efficient price is given by $p_c^* = c(a - \psi_c^*)/(b + c)$ [from (3) and (8)]. Comparing this with (35) shows (using $\psi_c^* > \psi_{mp}^*$) that $p_{mp}^*(t) > p_c^*(t) \forall t \in [0, \infty], \forall x \in \Gamma$.

A precommitted monopolist sells less at a higher price than is optimal given any moment of time or any resource stock level. As a consequence the total amount of resource sold and pollution accumulated are lower. It is also clear that under monopoly the producer price accounts for a larger and the pollution tax for a lower proportion of the consumer price than under optimality. The phase diagram in figure 1 demonstrates the time-inconsistency of the open-loop equilibrium. If $x_0 = \bar{x}$, the rent-maximization strategy requires that the path denoted by $q_{mp}^*|_{x_0 = \bar{x}}$ is followed. However, given any $\bar{x} - \delta a/4d < x < x_0$, the monopolist always has an incentive to reoptimize and to start again on the path defined by $-v_2[\frac{1}{2}(x_0 - \bar{x}) + \delta a/4d]$ and denoted "reneged open-loop" [7]. The phase diagram also includes efficient q_{cw}^* and monopoly q_{mw}^* extraction paths without pollution for the sake of comparison.

We next compare the pareto optimal outcome with the case of consistent monopoly.

Proposition 4. The optimal solution and the solution under a consistent monopoly approach the same steady state equilibrium. $\forall x \in \Gamma$ the optimal resource extraction exceeds the rate of resource

extraction under consistent monopoly. However, the time paths for resource extraction cross. Given any $x \in \Gamma$ and any $t \in [0, \infty)$, the pollution tax is lower and the resource price and resource rent are higher under a consistent monopoly than under optimality. Given any x_0 , the consumer price under a consistent monopoly is first above but later below the optimal price level.

Proof: Comparing propositions 1 and 3 shows that the steady states are equal. Thus we turn to compare the equilibrium approach paths. (14) and (49) give the optimal and monopoly resource extraction as functions of the stock level: $q_c^*(x) = -r_1$, $q_{mc}^*(x) = -k_1$. Because $q_c^*(\bar{x} - \delta a / 2d) = q_{mc}^*(\bar{x} - \delta a / 2d) = 0$, Lemma 1 implies that $q_c^*(x) > q_{mc}^*(x) \forall x \in \Gamma$. This means that, given any initial stock level, the rate of resource extraction is first larger under optimal conditions than under consistent monopoly. Because the total level of resource use is the same in both cases, the time trajectories must cross, i.e. the rate of extraction is ultimately smaller. This directly implies that the pareto efficient consumer price is first below but later above the price level under consistent monopoly.

Let us next compare pollution taxes. Recall that $\psi_{mc}^*(x) = A_2 x + B_2$ and that $A_2(\bar{x} - \delta a / 2d) + B_2 = a$. Using (48) it follows that

$$\psi_{mc}^*(t) = a + A_2(x_0 - \bar{x} + \delta a / 2d)e^{k_1 t}. \quad (51)$$

Comparing (51) and (15) shows that $\psi_c^* > \psi_{mc}^* \forall t \in [0, \infty)$, $\forall x \in (\bar{x} - \delta a / 2d, \bar{x}]$ if $1/(r_2 - \delta) > A_2 / 2d$. Using (45) gives $1/(r_2 - \delta) - A_2 / 2d =$

$$-\delta(4b^2\delta^2 + 4bc\delta^2 + 12bd + c^2d^2 + 4cd + 4b^2\delta^2 + 4bc\delta^2 + c^2\delta^2) - \quad (52a)$$

$$\delta^2(2b+c)[4b^2\delta^2 + 4bc\delta^2 + 12bd + c^2\delta^2 + 4cd]^{\frac{1}{2}} \quad (52b)$$

$$+ 4b^2\delta^3 + 2bc\delta^3 + 4bd\delta + 2b\delta^3c + c^2\delta^3 + 2d\delta c + \quad (52c)$$

$$[(b\delta^2 + c\delta^2 + 4d)(4b^2\delta^2 + 4b^2\delta^2 + 4bc\delta^2 + 12bd + c^2\delta^2 + 4cd)(2b\delta + \delta c)^2 / (b+c)]^{\frac{1}{2}} + \quad (52d)$$

$$\{(b\delta^2 + c\delta^2 + 4d)[(2b+c)(2b\delta^2 + c\delta^2 + 2d)]^2 / (b+c)\}^{\frac{1}{2}} \quad (52e)$$

Computation shows that $(53a)+(53c)+(53d)>0$ and $(53b)+(53e)>0$. Thus $1/(r_2-\delta)-A/2d>0$ and furthermore, given any resource stock level or point in time, the optimal pollution tax level exceeds the tax level under consistent monopoly. The resource rent under monopoly is strictly positive and thus exceeds the zero level which occurs in optimal solution.

Finally, we can compare the pareto efficient producer price with the price under consistent monopoly. Equations (37) and (39) give $p_{mc}^*=[a(b+c)+b(\varphi_{mc}^*-\psi_{mc}^*)-c\psi_{mc}^*]/(2b+c)$. Comparing this with the efficient price which equals $p_c^*=c(a-\psi_c^*)/(b+c)$ [from (3) and (8)] shows that the fact $\psi_c^*>\psi_{mc}^*$ implies $p_{mc}^*>p_c^*$ for $\forall t\in[0,\infty)$, $\forall x\in\Gamma$. ■

The steady state stock is approached sooner in optimal solution than under consistent monopoly. At any point in time the monopolist has sold a smaller proportion of his resource compared with the optimal level. The last units will be sold at a producer price near zero and at zero rent as in the optimal solution. Thus, without precommitment monopoly power is limited to delaying extraction. One aspect that should be emphasized is that, in contrast to the Coase Conjecture and durable non-renewable resource models [5], the monopoly power does not completely vanish even if marginal extraction costs are constant. The reason for this difference is that in the case of durable bads demand is a flow relationship whilst with durable goods the inverse demand function gives price as a function of the cumulative quantity sold [7]. With durable bads the cumulative quantity sold affects demand via Pigouvian tax, not directly as in the case of durable goods. The consequence is that the monopoly seller has an additional incentive to spread production over time, which does not arise when demand is a stock relationship.

Next, we compare the outcomes of consistent and inconsistent monopoly supply.

Proposition 5. $\forall x_0\in\Gamma$, $\forall t\in[0,\infty)$ the level of resource extraction is higher and the consumer price lower if the monopolist cannot precommit. $\forall x_0\in\Gamma$ the initial level of pollution tax is lower without precommitment. However, the time paths cross. Given $c=0$ and any $x_0\in\Gamma$ the initial levels of the resource rent and the producer price are higher without precommitment but the time paths cross.

Proof: In figure 1 the path q_c^* has been drawn above the path of the "reneged open-loop Stackelberg equilibrium", i.e. it is contended that $q_{mc}^* > q_{mp}^* \forall x \in \Gamma$ independently of x_0 . This can be proved by showing that the slope of the consistent path exceeds the slope of the path for the reneged Stackelberg equilibrium, which gives the initial extraction levels under precommitment. The slopes of these paths are $-k_1$ and $-\frac{1}{2}v_2$ [equations (32) and (49)]. By lemma 1 $-k_1 > -\frac{1}{2}v_2$, which means that $q_{mc}^* > q_{mp}^* \forall x \in \Gamma$.

The intersection of the time paths requires that $\dot{q}_{mc}^* < \dot{q}_{mp}^*$ at the moment of intersection, i.e. that $k_1 < v_2$, which contradicts lemma 1. Thus the time paths cannot cross. This also means that the consumer price is lower under monopoly without precommitment.

Pollution taxes can be compared by studying equations (34) and (52). Let us first compare pollution taxes when $t=0$ and $x_0=\bar{x}$. $\psi_{mp}^*(0)|_{x_0=\bar{x}} > \psi_{mc}^*(0)|_{x_0=\bar{x}}$ if $\delta a/2(v_2-\delta)+a/2 > A_2\delta a/2d + a$. Equations (45) and (30) and some algebra reveals that this equality holds. When $x_0=\bar{x}-\delta a/2d$, equations (34) and (52) show directly that both pollution tax levels equal the choke price. Because the initial levels of pollution taxes depend linearly on the initial resource level, it follows that $\psi_{mc}^* < \psi_{mp}^* \forall x_0 \in \Gamma$. Consider next the time paths for pollution taxes. In proposition 2 it is shown that the pollution tax always remains below the choke price if the monopolist is able to precommit while proposition 3 shows that the time-consistent pollution tax always approaches the choke price. This means that the time paths for pollution taxes must cross.

If the monopoly cannot precommit, the resource rent is $A_1x+B_1=A_1(x_0-\bar{x}+\delta a/2d)e^{k_1t}$. Comparing this with equation (33) shows that $\varphi_{mp}^*(0)|_{x_0=\bar{x}} < \varphi_{mc}^*(0)|_{x_0=\bar{x}}$, if $A_1\delta a/2d > \delta a/2(v_2-\delta)+a/2$. Given $c=0$, this follows using equations (30) and (44). Because both rents are zero when $x_0=\bar{x}-\delta a/2d$ and depend linearly on x_0 , it follows that $\varphi_{mp}^*(0) < \varphi_{mc}^*(0) \forall x \in \Gamma$. However, because $\dot{\varphi}_{mp}^* > 0$ and $\dot{\varphi}_{mc}^* < 0$ the time paths must cross.

Finally, comparing $p_{mc}^* = [a(b+c) + b(\varphi_{mc}^* - \psi_{mc}^*) - c\psi_{mc}^*] / (2b+c)$ with equation (35) and using the results that $\psi_{mc}^*(0) < \psi_{mp}^*(0)$, $\varphi_{mp}^*(0) < \varphi_{mc}^*(0) \forall x \in \Gamma$ reveals that $p_{mc}^*(0) > p_{mp}^*(0) \forall x_0 \in \Gamma$. Since the consistent producer price approaches zero while the inconsistent one remains strictly positive, the

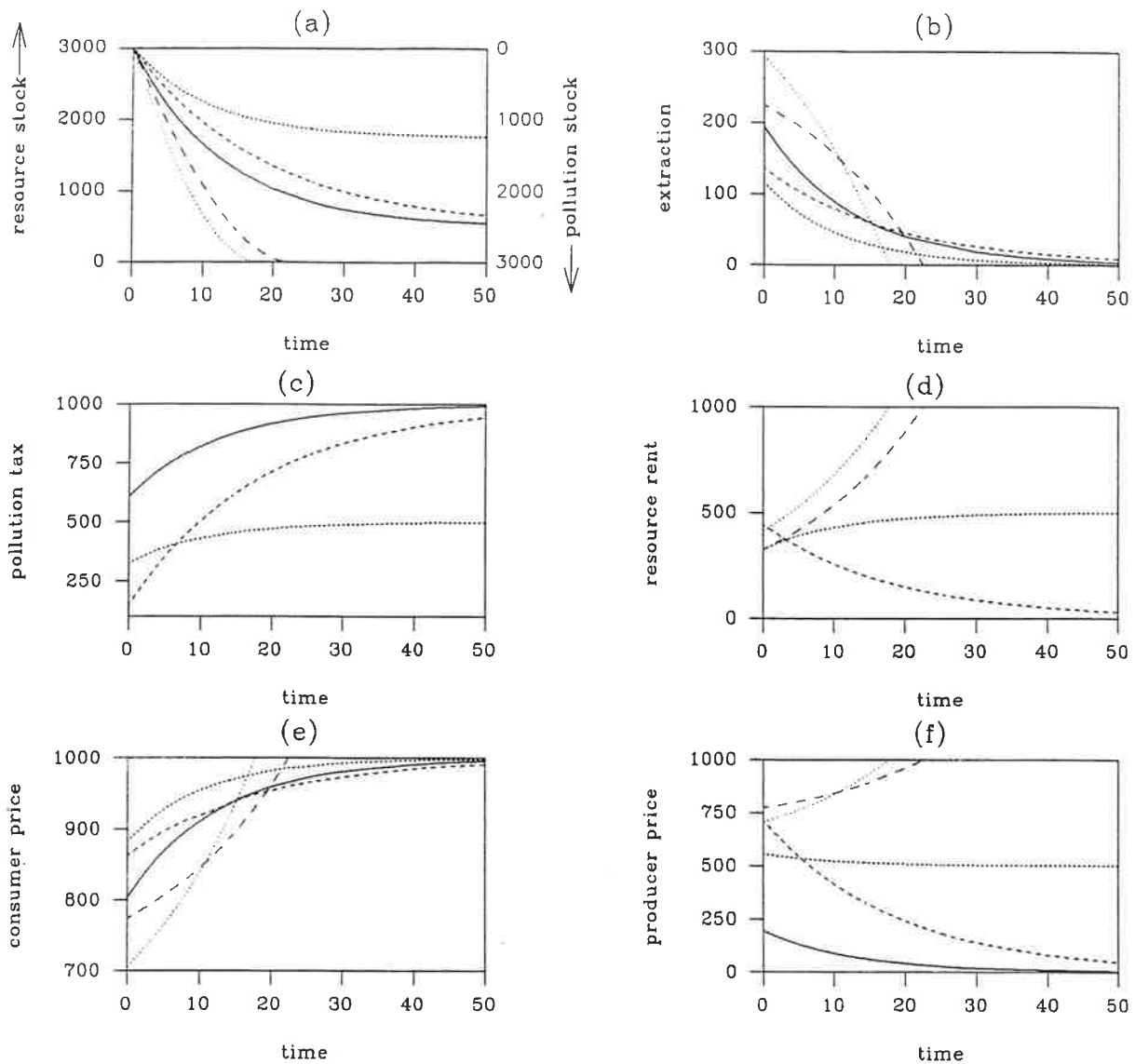


Figure 2. Comparison of time paths

Note: — = Competitive equilibrium without pollution
 - - - = Monopoly supply without pollution
 — = Optimal solution with pollution
 = Precommitted monopoly with pollution
 = Consistent monopoly with pollution

time paths must cross. ■

Together propositions 4 and 5 indicate that, given any resource stock level the rate of extraction by the consistent monopolist lies between the efficient rate and the rate of extraction by the precommitted monopolist (see figure 1). This result is in line with the durable goods monopolist literature [4]. The comparison of prices, taxes and rents is more complicated. It is noticeable that under a consistent monopoly the initial level of pollution tax is lower and the rent and producer price are higher than under a precommitted monopoly⁵. However, in the long run the consistent monopolist does not maintain monopoly power.

Figure 2 gives a general view of the evolution of market equilibrium in various cases.⁶ The example depicted confirms the results presented in propositions (1)–(5). In addition to the three cases considered above, it shows the competitive equilibrium and monopoly supply without pollution. We will finally consider the interesting conjecture by Wirl [15], i.e. the claim that by inducing cartelization Pigouvian taxation may raise the producer price for fossil fuels. Note that in figure 2f the initial level of the producer price under consistent monopoly and Pigouvian taxation approximately equals the efficient price without taxation. However, after some units of time the efficient price without taxation is higher. More generally, it is possible to prove the following:

Proposition 6. Pigouvian taxation reduces the efficient producer price but may raise the initial level of the producer price (competitive or monopoly) if the resource is supplied by a time-consistent monopolist who acts as a Stackelberg leader. However, there always exists a moment of time after which the producer price without Pigouvian taxation is higher than the price

⁵In proposition 6 the comparison of rents and producer prices is carried out in the case where $c=0$. However, it seems to be impossible to find parameter values where the same result does not hold also in the case where $c>0$.

⁶The example is computed by assuming the same numerical values as in figure 1. In addition, it is assumed that $x_0=3000$.

level under Pigouvian taxation and consistent monopoly supply.

Proof: Note that the competitive solution without Pigouvian taxation solves (1)–(2) and (5)–(6) and the equilibrium under monopoly but without taxation solves (17)–(21) given $d=0$ in both cases. In the example depicted in figure 1, the path without Pigouvian taxation q_{cw}^* is located above the efficient path $q_c^* \forall x \in [\bar{x}, 0]$. If this does not hold with some parameter values the paths must intersect. Without Pigouvian taxation $d=0$ in (10) and given any point in the q – x state space the slope of any trajectory (\dot{q}/\dot{x}) is higher compared with the slope in the Pigouvian case where $d>0$. Thus $q_{cw}^* > q_c^* \forall x \in [\bar{x}, 0]$. With and without Pigouvian taxation the producer price equals $2cq + \varphi$. Because $q_{cw}^* > q_c^*$ and $\varphi_{cw}^* > \varphi_c^* \forall x \in (0, \bar{x})$ pollution reduces the efficient producer price at all resource stock levels.

We next show that there are cases where the producer price under Pigouvian taxation and consistent monopoly may exceed the price without Pigouvian taxation. To find such a case, increase the initial resource level by assuming that the initial level of pollution stock remains constant, i.e. $\Delta x_0 = \Delta \bar{x} > 0$. Without Pigouvian taxation the initial level of resource rent equals $ae^{-\delta T_i^*}$, where T^* is the moment when the resource is used up and $i=mw$ refers to monopoly and $i=cw$ to competitive supply without taxation. T_i^* depends positively on x_0 . When $x_0 \rightarrow \infty$ it follows that $ae^{-\delta T^*} \rightarrow 0$. By (3), (8), $d=\psi=0$ and $\varphi \rightarrow 0$ it follows that $p_{mw}^*(0) \rightarrow ca/2(b+c)$ and by (3), (22), $d=\psi=0$ and $\varphi \rightarrow 0$ that $p_{mw}^*(0) \rightarrow a-ab/(2b+c)$. When $c=0$ the price under Pigouvian taxation and consistent monopoly equals $p_{mc}^*(t) = (x_0 - \bar{x} + \delta a/2d)e^{k_1 t} (A_1 - A_2)/2 + p(\bar{x} - \delta a/2d)$ (by 40 and 48). By proposition 3, $p(\bar{x} - \delta a/2d) = 0$ and thus $p_{mc}^*(0) = (x_0 - \bar{x} + \delta a/2d)(A_1 - A_2)/2$. Using (44), (45) and $c=0$, $p_{cm}^*(0)$ equals $-b^{\frac{1}{2}} \delta [(b\delta^2 + 3d)^{\frac{1}{2}} + b\delta^2 + 2d] [2d(\bar{x} - x_0) - a\delta] / \delta [(b\delta^2 + 3d) + b^{\frac{1}{2}} \delta]^{\frac{1}{2}}$. $p_{cm}^*(0)$ is independent of the initial resource level given $x_0 - \bar{x}$ is constant. In addition, $p_{cm}^*(0)$ is strictly positive given $x_0 > \bar{x} - \delta a/2d$. By decreasing the level of c , the initial price level $p_{cw}^*(0)$ can be made arbitrarily small. Thus it is possible that $p_{cm}^*(0) < p_{cw}^*(0)$. When $c=0$ and $x_0 \rightarrow \infty$ $p_{mw}^*(0) \rightarrow a/2$. Given $x_0 > \bar{x} - \delta a/2d$ simple algebra shows that $p_{cw}^*(0) > a/2$. Thus it is possible that $p_{mc}^*(0) > p_{cw}^*(0)$. We have established that when \bar{x} and x_0 are high enough and c is small enough it must follow that

$p_{mc}^*(0) > p_{iw}^*(0)$. Because p_{mc}^* approaches zero and p_{cw}^* and p_{mw}^* approach the choke price there always exists a moment of time after which $p_{mc}^*(t) < p_{iw}^*(t)$. ■

Taxation reduces the efficient price because consumers are willing to buy less given any level of the producer price. If taxation induces the cartelization of the resource suppliers this in turn causes a price increase which may outweigh the initial price decrease. The above proposition shows that this is possible if the initial resource level is "large", the initial pollution level is "low" and the resource is not exhausted in finite time. This supports the conjecture by Wirl [15] that Pigouvian taxation may raise the imported price of energy. However, the dynamic analysis shows that this kind of price increase is only temporary. In the long run Pigouvian taxation reduces the imported price of fossil fuels.

Proposition 6 shows that producer price under Pigouvian taxation and consistent monopoly supply may exceed monopoly price without taxation. To interpret this note that in contrast to efficient outcome Pigouvian taxation may increase the initial level of resource rent under monopoly supply (figure 2d). This follows because the resource rent gives the marginal value of the amount of the resource the monopolist can sell over the planning horizon. This equals the amount of resource at each point of time minus the amount which will be left in the ground, i.e. $x_0 - \int_0^t q(\tau) d\tau$ in the case without pollution and $x_0 - \int_0^t q(\tau) d\tau - \bar{x} + \delta a/2d$ when pollution exists and the monopoly cannot precommit. At $t=0$ $\varphi_{mw}^*(0)$ is the shadow price for x_0 while $\varphi_{mp}^*(0)$ is the shadow price for the amount of the resource equal to $(x_0 - \bar{x}) + \delta a/2d$. The latter can be considerably smaller than x_0 and thus its shadow price may be higher (as shown in the proof of proposition 6). This implies that also the initial price level may be higher under Pigouvian taxation. Note that this result may be conditional on the assumption that some resource remains in the ground and that pollution accumulation is irreversible. If in the numerical example used in figures 1 and 2 the level of $d=0.0833$, the resource is exhausted asymptotically given extraction is efficient or the monopolist cannot precommit. In this case $p_{cw}^*(0)=705$, $p_{mc}^*(0)=713$ and $p_{mw}^*(0)=774$. In other words Pigouvian taxation may raise the initial level of the producer price if

it induces cartelization but lower the price level if the cartel already exists.

6 CONCLUSIONS

This paper has analyzed the effects of Pigouvian taxation and an accumulating pollution problem on nonrenewable resource markets. The important simplifications of the analysis were the use of quadratic linear functional forms, the independence of extraction costs from the stock level, a zero rate of decay of pollution and the restriction of the analysis to cases where the stock is not depleted in finite time. Pareto optimal and monopoly outcomes were solved in closed form. In the absence of monopoly power the resource owners lose their resource rent. A monopoly resource owner (or cartel) maximizes its resource rent by applying an open-loop price strategy as a Stackelberg leader. This strategy implies that a less-than-pareto-optimal proportion of the resource stock will be used. The problem with this strategy was, however, that it was time-inconsistent. A time-consistent and Markov-perfect equilibrium was solved by dynamic programming. It turns out that, along a time-consistent equilibrium path the seller's monopoly power vanishes asymptotically. The total amount of resource sold and the related pollution ultimately equal the pareto optimal levels. Along the Markov-perfect equilibrium path the producer price is higher and the Pigouvian tax lower than in the case of the pareto optimal outcome.

Pigouvian taxation may cause the competitive sellers to lose their resource rent. Thus it may also encourage cartelization. The implication is that taxation may increase the resource price. The price increase is, however, temporary, and ultimately pollution control will reduce the producer price.

From the Coase Conjecture and durable exhaustible resource literature it is known that the monopolist loses his power if he cannot precommit, if the good does not depreciate and if marginal extraction costs are constant. It was shown that this is not the outcome in the case of a durable bads monopolist. The reason for this is that, in the case of durable bads monopolist demand is a

flow relationship. This gives the monopolist an additional incentive to spread production over time, which means that his power vanishes asymptotically. This result may be carried over to durable exhaustible resources like copper and aluminium where demand is predominantly a flow relationship because scrap must be transformed before secondary use [11, 4].

APPENDIX

Proof of lemma 1 (i.e. $v_2 < r_2 < k_1 < \frac{1}{2}v_2$).

From (12) $r_2 = \frac{1}{2}\{\delta - [(\delta^2 + 4d)/(b+c)]^{\frac{1}{2}}\}$ and from (30) $v_2 = \frac{1}{2}\{\delta - [\delta^2 + 8d/(2b+c)]^{\frac{1}{2}}\}$. Because $[(\delta^2 + 4d)/(b+c)] < [\delta^2 + 8d/(2b+c)]^{\frac{1}{2}}$ it follows that $v_2 < r_2$. From (50) $k_1 = -2d/\{[4b^2\delta^2 + 4b(c\delta^2 + 3d) + c^2\delta^2 + 4cd]^{\frac{1}{2}} + \delta(2b+c)\}$. $r_2 < k_1$ if $\frac{1}{2}\{[\delta^2 + 8d/(2b+c)]^{\frac{1}{2}} - \delta\} - 2d/\{[4b^2\delta^2 + 4b(c\delta^2 + 3d) + c^2\delta^2 + 4cd]^{\frac{1}{2}} + \delta(2b+c)\}$ is positive. This holds if $\{[\delta^2 + 8d/(2b+c)]^{\frac{1}{2}} - \delta\}\{[4b^2\delta^2 + 4b(c\delta^2 + 3d) + c^2\delta^2 + 4cd]^{\frac{1}{2}} + \delta(2b+c)\} - 4d =$

$$[4b^2\delta^4 + 4bc\delta^4 + 12bd\delta^2 + c^2\delta^2 + 4cd\delta^2 + (16db^2\delta^2 + 16bdc\delta^2 + 48d^2b + 4dc^2\delta^2 + 16cd^2)/(b+c)]^{\frac{1}{2}} \quad (A1)$$

$$+ \{[\delta^2 + 4d/(b+c)](4b^2\delta^2 + 4bc\delta^2 + c^2\delta^2)\}^{\frac{1}{2}} \quad (A2)$$

$$- (4b^2\delta^4 + 4bc\delta^4 + 12bd\delta^2 + c^2\delta^4 + 4cd\delta^2)^{\frac{1}{2}} \quad (A3)$$

$$- \delta^2 2b - \delta^2 c - 4d \quad (A4)$$

is positive. (A2) equals $(4b^2\delta^4 + 4bc\delta^4 + c^2\delta^4 + 12b\delta^2d + 4b^2\delta^2d/(b+c) + 4c\delta^2d)^{\frac{1}{2}}$. Comparing this with (A3) shows that (A2) + (A3) > 0. (A1) equals $[4b^2\delta^2 + \delta^4c^2 + 4\delta^4bc + 16d^2 + 8bd\delta^2 + 4cd\delta^2 + 4cd\delta^2 + (4b^2d\delta^2 + 32d^2b + 16bdc\delta^2 + 16b^2d\delta^2)/(b+c)]^{\frac{1}{2}}$. Comparing this with (A4) gives (A1) + A(4) > 0. This shows that $r_2 < k_1$.

$$\begin{aligned} &\text{Compare next } k_1 \text{ and } v_2/2. \quad k_1 < v_2/2 \text{ if } -k_1 + [\delta(2b+c)^{\frac{1}{2}} - (2b\delta^2 + c\delta^2 + 8d)^{\frac{1}{2}}]/4(2b+c)^{\frac{1}{2}} = \\ &\frac{[\delta(2b+c)^{\frac{1}{2}} - (2b\delta^2 + c\delta^2 + 8d)^{\frac{1}{2}}] \{ (4b^2\delta^2 + 4bc\delta^2 + 12bd + c^2\delta^2 + 4cd)^{\frac{1}{2}} \delta(2b+c) + 8d(2b+c) \}}{(4b^2\delta^2 + 4bv\delta^2 + 12bd + c^2\delta^2 + 4cd)^{\frac{1}{2}} 4(2b+c)^{\frac{1}{2}}} \quad (A5) \end{aligned}$$

is positive. The denominator of (A5) is clearly positive. The numerator can be developed in the form $[(2b\delta^2 + c\delta^2 + 8d)^{\frac{1}{2}} - (2b\delta^2 + c\delta^2)^{\frac{1}{2}}][(4b\delta^2 + 4bc\delta^2 + 16db + c^2\delta^2 + 8dc)^{\frac{1}{2}} - (4b^2\delta^2 + 4b\delta^2c + 12bd + c^2\delta^2 + 4cd)^{\frac{1}{2}}]$, which is positive. Thus $k_1 < v_2/2$. ■

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