PRICING RESOURCE EXTRACTION WITH STOCK

EXTERNALITIES

Sittidaj Pongkijvorasin
Department of Economics, University of Hawaii, HI, USA; sittidaj@hawaii.edu

Basharat Pitafi
*Department of Economics, University of Southern Illinois, Carbondale, USA;
pitafi@siu.edu*

James Roumasset
Department of Economics, University of Hawaii, HI, USA; jimr@hawaii.edu

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Pricing resource extraction has drawn substantial attention by economists. According to the "Washington Consensus" on sustainable development, resource owner should be required to pay extraction fees accordance with the condition that the efficiency price of resource equals the sum of its marginal extraction cost, marginal user cost (MUC), and marginal externality cost (MEC) (Pearce and Markandya, 1989). Failing to take into account of these components will result in underpricing natural resources and lead to overharvesting. For example, there is an evidence that, in developing countries, resources are generally underpriced, failing to account for its scarcity rent, even not include externality cost (World Bank, 1992). Extensive deforestation in developing countries is one of the most severe environmental problems in the world (Repetto 1988).

Forest is one of the resources that have multiple functions. Its direct use values can draw from timber harvesting. Moreover, it has many other indirect values, for example, on ground water recharge, or biodiversity, which may even turn out to be more significant than the timber value. In this article, we focus on forest's role in watershed conservation. Forest cover is a critical factor for the soil erosion and water runoff leading to the downstream sedimentation. In case of sedimentation in stream, lakes, and reservoirs, it can harm aquatic life, decrease water quality, increase the risk of flooding, and reduce reservoir storage capacity (Dixon 1997, Barbier 1995). For forest near coastal area, the sedimentation may affect the nearshore resources including fish and other aquatic lives, and coral reef (Hodgson and Dixon 1988, Hodgson 1989, and Kaiser et al. 1999).

As forests confer positive stock externalities through the effects on other pollution stocks (i.e. sediment), marginal external cost of forest harvesting should be taken into account in pricing the harvest. There arises policy challenges how a regulatory authority should tax resource extraction in order to internalize the externalities. The predominant position is the resource owner should be required to pay the "marginal externality cost." However, that cost has not been well defined for the case of stock externalities, inasmuch as accumulation today has welfare implications for the future. This article shows that, in this case (i.e. forest-sediment), the marginal opportunity cost concept suggested in the literature is not applicable as MEC contains as a part of MUC. For private resource owner, unlike famous climate change model, taxing resource extraction according to the shadow price of pollution will not yield an optimal outcome because externality is associated with the resource stock, not its extraction *per se*. Public concessionaire should be taxed equal to MUC.

The optimal management of resource where resource stock has amenity services is also considered in this article. For example, forest has scientific, recreational, and aesthetic values for its existence. Unlike forest-sediment case, these externalities arise directly from resource stock, not via other pollution stocks. In this case, as will be shown in the article, marginal externality cost is also embedded in user cost. Optimal pricing policies for public concessionaire and private owner are shown.

In the literature, some issues about MUC remain unclear and need to be clarified. Leaving aside externalities, terms royalty and MUC of resource are often used interchangeably in resource economics. There are, at least, two problems with this usage. First, marginal user cost is usually defined as the change in present value of a resource with unit change in stock. This article shows that, however, the MUC

that equals royalty at the first-best is the current value or inflated to time t one (MUC'

hereafter in this article), not the present value as its definition. Second, royalty and

MUC' are two separate variables that obtain equal values only at the first-best. If the

resource is being overharvested, royalty may be smaller than MUC'. Repetto (1988)

and Gillis (1988) suggestion that royalty should be used to price a public forest would

work only if the observed royalty was the result of optimal extraction. If the forest

was being overharvested, charging observed royalty will be too low and will not result

in optimal harvesting.

Next section reviews the previous literature on the related topics. The

discussion of marginal user cost concept and royalty is in section 2.3. In section 2.4,

the optimal condition for forest-sediment, as an example of extracting resource with

stock externality, will be shown. Optimal taxes for public concessionaire and private

owner are derived. The results are compared to the traditional marginal opportunity

cost concept. In section 2.5, the model is adapted to present the case where resource

stock itself has an amenity value. The conclusion is in section 2.6.

Review of Literature

Reppetto (1988) and Gillis (1988) are among those who study the forest policies in

developing countries. Both suggest that stumpage value – the difference between

price and extraction cost – is the economic rent of forest resource. Forest policies

should be such that transfer this rent back into government revenue (i.e. by royalties,

land rents, license fee, or harvest taxes). Thus, their suggestions imply that

government should charge stumpage value of forest. This will be discussed in next

section.

Pearce and Markandya (1989) suggest using marginal concept for measuring

resource value. Marginal cost of using resource consists of three components:

marginal direct cost, marginal external cost, and marginal user cost. Direct cost deals with cost associating with the resource extraction. Second component, marginal external cost, refers to the cost of externalities resulted from resource usage. Marginal user cost, raised from intertemporal considerations, is the cost from incapability of using the resource in the future. The efficient level of resource use can be specified by equating the marginal cost and marginal benefit of its use. However, the article neither specifies the expressions for MUC and MEC explicitly nor discusses the corrective policy dealing with externalities that may occur from resource use.

Stock characteristic of externality has drawn economists' consideration since the pioneer works by Keeler et al. (1972), and Plourde (1972). This group of studies, including Nordhaus (1991), however, emphasizes its scope on dynamic framework of externalities and ignores the linkage between externalities and the resource use. This type of models applies to the case where resource use is of a sufficiently small scale and its scarcity is unimportant, for example, waste accumulation and disposal, the build-up of chemical from pesticides in agricultural land. In many cases, however, limited natural resource plays an important role in determining how much to use. In these situations, ignoring the linkage between resources and externalities will fail to capture the essences of the problem. This relationship has been incorporated into the consideration in 1990s, mostly in climate change studies.

Since climate change problem becomes more popular, there have been many studies modeling fossil fuel use and greenhouse gases accumulation. This group of models emphasizes the linkage between resource use and accumulated pollution, as fossil fuels are limited. The beginning attempts to integrate resource use with stock externality issue can be found in Sinclair (1994) and Ulph and Ulph (1994). Both studies analyze the evolution of optimal carbon tax rate. Sinclair (1994) calls for

declining fossil fuel tax over time. Ulph and Ulph (1994), however, show that there are different factors causing a rise or a fall in tax rate. Under some circumstances (e.g. quadratic benefit and damage function, constant extraction cost), optimal tax can be such that it rises first and then falls later. The model is extended in many ways. For example, Hoel and Kverndokk (1996) consider also the case where damages depend on rate of change in stock of carbon. They also allow non-polluting backstop technology in the model. Farzin (1996) considers threshold effects of stock externalities and finds that optimal tax is required even in the initial period where there is no damage. Farzin and Tahvonen (1996) study the model by relaxing the assumption on constant rate of decay of carbon. Lately, Perman et al. (2003) provide a article on stock externality in their book. A comprehensive model on stock externality arise from nonrenewable resource use is discussed. Three-part taxes including utility damage tax, pollution flow damage tax, and stock damage tax are suggested in order to internalize the externality problem. In the climate change case, as private resource owner ignores environmental external effect, corrective tax equal to shadow price of pollution stock must be taxed. Nevertheless, this article will show that this is not the general rule and it is not applicable to forest-sediment case.

Downstream sediment can be considered a stock pollution arises from forest degradation. There are some studies exploring the effects of forest removal on downstream sedimentation. Logging often causes soil erosion, resulting in the transfer of soil from one location where it has positive benefits to another where it imposes cost (Clark 1985, Hodgson 1997, Magrath and Doolette 1990). Water-borne runoff and sedimentation are off-site result from soil erosion. Runoff and sedimentation, if occurred in stream, lakes, and reservoir, can create many negative impacts including: reducing reservoir storage capacity, losses to navigation, negative effects on aquatic

life, increase in risk of flooding, adverse effects on agricultural and industrial production in lowlands, and decrease in water quality (Barbier 1995, Dixon 1997). Magrath and Aren (1989) (cited in Barbier 1995) estimate the off-site cost of reservoir sedimentation in Java, Indonesia. The combined cost of annual hydropower and irrigation losses is range from $1.62 to 7.48 million. Kaiser et al. (1999) estimate that significant forest disturbance on Ko'olau forest, located in Hawaii, will increase runoff and cause damage (estimated from dredging cost alone) ranges from $0.75-1.2 million per year. In case of costal forest, the runoff and sedimentation may affect the nearshore resources including fish and other aquatic life, and coral reef (Hodgson and Dixon 1988, Hodgson 1989, Kaiser et al. 1999). For example, a study of coral reefs in Indonesia indicates that sediment from logging may cause present value net losses from fisheries and tourism damages of $273,000 per square kilometer of reef (Cesar 1996, cited in Kaiser et al. 1999). This group of studies, however, pays attention more to monetary estimation of one-time damage and ignores the dynamic accumulation of sedimentation. Dynamic corrective tax and pricing rules for forest-sediment case have not been studied in the literature. By comparing to climate change model, one might suggest optimal tax equal to shadow price of pollution. Unfortunately, this article shows that it is not true for forest-sediment case.

For the amenity values of forest, there are many studies in this area. Hartman (1976), Berck (1981), and Krautkraemer (1985) are among the pioneers in the topic. Hartman (1976) studies the effect of standing value of forest on the optimal harvesting age under Faustmann framework. He finds that amenity values postpone the optimal age of forest harvesting. Krautkraemer (1985) shows that resource amenity values will increase the initial price and decrease rate of growth in resource price. Englin and Khan (1990) solves for Pigouvian tax when forest has amenity values. Most of the

studies in this field models the forest in Faustmann framework (optimal rotation age), which is not adaptable to other resources. In term of biomass model, Berck (1981) gets similar results – with amenity value, steady state of forest stock is higher. However, there is no study involving Pigouvian tax under biomass model.

MUC vs. Royalty

Before talking about pricing resource with externality, I would like to discuss the use of term MUC in capital theory and in resource economics. As will be shown, there is inconsistency in MUC terms used in these two fields. This needs to be clarified. The appropriateness of interchangeable use of "royalty" and "MUC" will also be discussed later in this section.

A resource stock at time t is $X(t)$ and is extracted at rate $x(t)$ at a cost of $c(X(t))$[1] per unit to obtain benefits (consumer surplus) of $\int_0^{x(t)} p(z)dz$, where $p(z)$ is the inverse demand function or price of resource. The stock increases with natural growth, $f(X(t))$[2], and decreases with harvest, $x(t)$. Over time, the rate of change in stock is, therefore, $\dot{X}(t) = f(X(t)) - x(t)$. A hypothetical social planner chooses the resource extraction path, $x(t)$, to maximize the stream of present value of net social benefits, $V = \int_0^\infty e^{-rt} \left[\int_0^{x(t)} p(z)dz - c(X(t))x(t) \right] dt$ where r is the discount rate, i.e.,

$$\max_{x(t)} \quad V$$
$$s.t. \quad \dot{X}(t) = f(X(t)) - x(t)$$

...(1)

The present-value Hamiltonian[3] for this optimal control problem is:

$$H = e^{-rt} [\int_0^{x(t)} p(z)dz - c(X(t))x(t)] + \lambda(t)[f(X(t)) - x(t)]$$

Here, following Dorfman (1969, p. 820), $\lambda(t) = \dfrac{\partial V^*}{\partial X(t)}$, i.e., $\lambda(t)$ is the increase in the

maximized value of the objective function (V) due to a unit increase in the stock (X) at

time t. This is the definition of marginal user cost. First-order conditions according to

the Maximum Principle are:[4]

$$\frac{\partial H}{\partial x} = e^{-rt}\left[p(x) - c(X)\right] - \lambda = 0 \qquad\qquad ...(2)$$

$$\frac{\partial H}{\partial X} = e^{-rt}\left[-c'(X)x\right] + \lambda f'(X) = -\dot{\lambda} \qquad\qquad ...(3)$$

From (2), we see that, at the optimum,

$$\lambda = e^{-rt}\left[p(x) - c(X)\right] \qquad\qquad ...(4)$$

That is, optimality requires that Dorfman's MUC (or the one used in capital theory)

on the left-hand side equals the discounted present value of royalty on the right-hand

side. Alternatively,

$$\lambda e^{rt} = p(x) - c(X) \qquad\qquad ...(5)$$

current value of royalty equals the value of MUC inflated to time t (MUC'). This

inflated MUC is used in Pearce and Markandya (1989) (and in resource economics) as

MUC. Two points are worth noting here. First, Dorfman's MUC is not equal to

royalty itself but instead to the present value of royalty. In other words, MUC that is

used by resource economics is not Dorfman's MUC, but it is current value of

Dorfman's MUC (MUC'), which is equal to royalty at the first-best.

Second, the equality in equation (5) does not always hold; it is only guaranteed

at the first-best. Therefore, a public concessionaire who ignores the effect of own

extraction on future benefits will need to be taxed equal to the MUC' (the left-hand

side of equation (5) above), not equal to royalty as suggested by Repetto (1988) and Gillis (1988). If the resource is, for example, being overused (i.e. not on the optimal path currently), the observed royalty would be less than the MUC' and a tax equal to the royalty will not serve to obtain an efficient outcome, whereas a tax equal to the MUC' will. For example, the resource will be overharvested under short-term concessionaire system. One can imagine that, as concessionaire has only short-term rights to harvest the resource, his problem is to harvest now or never. The problem can be viewed as an open-access resource over time. As will be shown later in section 2.5.1, short-term concessionaire, who ignores the user cost in the future, will harvest resource until price is equal to extraction cost ($p=c$), or at point x_1 in figure 2.1. Charging observed royalty, which equals to zero, would not improve the efficiency. The corrective policy is a tax equal to MUC'.

(Insert figure 1 here)

Combining (2) and (3) and rearranging, we get:

$$p(x) = c(X) + \frac{\dot{p} - c_X f}{r - f_X} \qquad\qquad ...(6)^5$$

The left-hand side in equation (6) is the inverse demand function, which represents the marginal benefit of resource consumption. The right-hand side is the marginal opportunity cost, which includes unit harvest cost as the first term and MUC' as the second term. The two sides are equated at the optimum.

Rearranging (6) further, we get a Hotelling-like equation:

$$\dot{p} = c_X f + (p - c)(r - f_X) \qquad\qquad ...(7)$$

The first term on the right-hand side is negative since $c_X < 0$, and the second term is positive as long as $r > f_X$. Their relative magnitude determines whether price, p, is increasing or decreasing at any time. The price is increasing if:

$$p - c > -\frac{c_X f}{r - f_X}$$

Next, we extend the above model to include stock externality for a downstream environment.

Resource extraction with stock externality (forest-sediment)

Thinking of resource in term of forest, I will follow the same setup as previous section. With externalities, the forest stock, $X(t)$, is inversely related to the flow of sediment, $h(X(t))$, from upland watersheds to nearshore resources, i.e., $h_X<0$. The sediment stock, $S(t)$, at time t, in nearshore waters grows with input $h(X(t))$, and decreases with natural decay and wave action as a constant fraction, δ, of stock $S(t)$, i.e., $\dot{S}(t) = h(X) - \delta S(t)$. The pollution stock causes damage $E(S(t))$, at time t, with $E_S>0$. The present value of the net social benefit, therefore, now becomes:

$$W = \int_0^\infty e^{-rt}\left[\int_0^{x(t)} p(z)dz - c(X(t))x(t) - E(S(t))\right]dt .$$ A hypothetical social planner

chooses the forest harvest path, $x(t)$, to maximize W, i.e.,

$$\max_{x \geq 0} \quad W$$
$$s.t. \quad \dot{X}(t) = f(X(t)) - x(t) \qquad\qquad ...(8)$$
$$\dot{S}(t) = h(X(t)) - \delta S(t)$$

The current-value Hamiltonian for this optimal control problem can be written as:

$$\tilde{H} = \int_0^{x(t)} p(z)dz - c(X(t))x(t) - E(S(t)) + \lambda(t)[f(X(t)) - x(t)] + \alpha(t)[h(X(t)) - \delta S(t)]$$

where λ is the shadow price of resource stock, X, and α is the shadow price of pollution stock. First-order conditions according to the Maximum Principle are:[6]

$$\frac{\partial \tilde{H}}{\partial x} = p - c - \lambda = 0 \qquad\qquad\qquad ...(9)$$
$$p = c + \lambda$$

$$\frac{\partial \tilde{H}}{\partial X} = -xc_X + \lambda f_X + \alpha h_X = r\lambda - \dot{\lambda} \qquad\qquad ...(10)$$

$$\frac{\partial \tilde{H}}{\partial S} = -E_S - \delta\alpha = r\alpha - \dot{\alpha} \qquad\qquad\qquad ...(11)$$

Manipulating and rearranging (9) – (11), we get:

$$p = c + \frac{\dot{p} - c_X f}{r - f_X} + \frac{\alpha h_X}{r - f_X} \qquad\qquad\qquad ...(12)$$

Comparing equation (12) to equation (9), the combination of second and third term on the right-hand side of equation (12) is MUC'. Even extracting forest creates downstream sedimentation, however in this case, we cannot write pricing equation in term of $p = c + MUC' + MEC$, as suggested in the literature. In this case, externality cost is embedded in user cost term. The interesting question is how government should price the resource in order to achieve the social optimal outcomes.

Pricing policy for public concessionaire

Public concessionaire usually has short-term rights to harvest the forest. As a result, public concessionaire normally fails to take into account both externality and user costs (the future effects of extracting resource now, i.e. higher extraction cost in the

future and forgone benefit from increased price). Many instruments can be implemented in order to internalize the externalities. The most direct one, in this case, is to subsidize forest stock, as it creates the externalities. Forest stock subsidies are, however, difficult to administer. The difficulties in measuring forest stock in every period and the budget limitation are the main problems. From these reasons, harvest tax, which is the easiest and most practical tax, will be the major concern in this article. To achieve optimal outcomes, a public concessionaire need to be charged a unit tax, $T(t)$, equal to the MUC'. This is because the concessionaire chooses $x(t)$ to maximize the present value of net after tax benefits:

$$Y = \int_0^\infty e^{-rt} \left[\int_0^{x(t)} (p(z) - T(t))dz - c(X(t))x(t) \right] dt \qquad \ldots(13)$$

Without having to consider change in forest stock (an equation of motion of resource stock), the maximization will imply: $p = c + T$. Comparing this with (12), we get:

$$T = \lambda = \frac{\dot{p} - c_X f}{r - f_X} + \frac{\alpha h_X}{r - f_X} \qquad \ldots(14)$$

Solving differential equation in (10) with transversality condition:

$\lim_{t \to \infty} e^{-rt} \lambda(t) X(t) = 0$, we can solve for λ or optimal tax:

$$T = \lambda(t) = \int_t^\infty e^{-\int_t^\tau (r - f_X)dv} [\alpha h_X - x c_X] d\tau, \qquad \ldots(15)$$

     In conclusion, public concessionaire should be taxed at MUC' level in order to internalize user cost and externality cost. This contrasts to the thinking that public concessionaire should be taxed both MUC' and MEC because, under this situation, externality cost is included in user cost.

Pricing policy for private owner

This subsection examines the optimal tax when the resource is owned by a private owner. Private owner should be taxed because he ignores the environmental damage, $E(S(t))$; however, he takes into account the effect of resource stock on extraction cost in the future. Suppose the tax rate is $T(t)$ per unit of harvest, $x(t)$. The owner chooses $x(t)$ to maximize the present value of net after tax benefits:

$$Z = \int_0^\infty e^{-rt}\left[\int_0^{x(t)} (p(z) - T(t))dz - c(X(t))x(t)\right]dt \text{ , i.e.,}$$

$$\max_{x \geq 0} \quad Z$$
$$\text{s.t.} \quad \dot{X}(t) = f(X(t)) - x(t) \qquad \qquad \ldots(16)$$

The current-value Hamiltonian for this optimal control problem can be written as:

$$\tilde{H} = \int_0^{x(t)} (p(z) - T(t))dz - c(X(t))x(t) + \lambda(t)[f(X(t)) - x(t)],$$

where $\lambda(t)$ is the shadow price of the resource stock[7], $X(t)$. First-order conditions are:[8]

$$\frac{\partial \tilde{H}}{\partial x} = p - T - c - \lambda = 0 \qquad \qquad \ldots(17)$$

$$\frac{\partial \tilde{H}}{\partial X} = -xc_X + \lambda f_X = r\lambda - \dot{\lambda} \qquad \qquad \ldots(18)$$

Manipulating and rearranging (17) – (18), we get:

$$p = c + \frac{\dot{p} - c_X f}{r - f_X} + \left(T - \frac{\dot{T}}{r - f_X}\right) \qquad \qquad \ldots(19)$$

Comparing (12) and (18), we see that the tax must be chosen such that

$$T - \frac{\dot{T}}{r - f_X} = \frac{\alpha h_X}{r - f_X} \qquad \qquad \ldots(20)$$

$$T(t) = \int\limits_{t}^{\infty} \alpha(\tau) h_X(X(\tau)) e^{-\int\limits_{t}^{\tau}(r - f_X(X(\upsilon)))d\upsilon} \, d\tau \qquad \qquad \text{...(21)}$$

Equation (20) and (21) specify optimal tax for private owner. Unlike concessionaire, private owner already takes into account user cost, therefore should be taxed only the externality part. Nevertheless, optimal tax is not equal to the shadow price of pollution (α), as it is in climate change case. Intuitively, this is because the externality is determined by the stock of forest, whereas the tax is imposed on the harvest. If the externality were being caused by harvest and not by the stock, taxing shadow price of pollution will restore the optimum. The last term in (19) represents the fact that tax will also affect the future producer price. Designing optimal tax also has to consider effect of tax in the future price. Next section shows that this logic applies for the case where stock of resource has amenity values.

Resource with amenity values

In many cases, resource stock has its own amenity values. The obvious example is a forest, which has many values for its appearance, for example, biodiversity, scientific, recreational, or aesthetic values. Without considering these external benefits, forest will be overexploited.

Instead of externality damage from sediment stock, we assume that there is externality benefit derived directly from forest stock, $B(X)$, where $B_X>0$. The present value of the net social benefit, therefore, now becomes:

$$V = \int\limits_{0}^{\infty} e^{-rt} \left[\int\limits_{0}^{x(t)} p(z)dz - c(X(t))x(t) + B(X(t)) \right] dt$$. A hypothetical social planner

chooses the forest harvesting path, $x(t)$, to maximize V, i.e.,

$$\max_{x \geq 0} \quad V$$

$$\text{s.t.} \quad \dot{X}(t) = f(X(t)) - x(t) \qquad \qquad \ldots(22)$$

The current-value Hamiltonian for this optimal control problem can be written as:

$$\tilde{H} = \int_0^{x(t)} p(z)dz - c(X(t))x(t) + B(X(t)) + \lambda(t)[f(X(t)) - x(t)]$$

where λ is the shadow price of resource stock, X, for this case. First-order conditions according to the Maximum Principle for interior solution are:[9]

$$\frac{\partial \tilde{H}}{\partial x} = p - c - \lambda = 0 \qquad \qquad \ldots(23)$$

$$\frac{\partial \tilde{H}}{\partial X} = -c_X x + B_X + \lambda f_X = r\lambda - \dot{\lambda} \qquad \qquad \ldots(24)$$

$$\lim_{t \to \infty} e^{-rt} \lambda X = 0 \qquad \qquad \ldots(25)$$

Manipulating (23) and (25), we can get

$$p = c + \frac{\dot{p} - c_X f}{r - f_X} + \frac{B_X}{r - f_X} \qquad \qquad \ldots(26)$$

From equation (23) and (26), we can arrange optimal condition as $p = c + MUC'$, where MUC' is the second and third term on the right-hand side of equation (26). Even extracting resource effects externalities, marginal externality cost does not explicitly appear. The intuition is similar to forest-sediment case; externalities are not explained directly by the resource extraction, but the remaining forest stock. Like the previous case (forest-sediment), MEC is embedded in MUC'. If government can impose tax/subsidy base on resource stock, static Pigouvian tax equal to damage cost occur at each period will yield the optimum. However, government can practically

impose tax on amount of timber harvested. From this reason, dynamic aspect of resource must be taken into account.

Pricing policies for public concessionaire

In order to find the optimal tax for public concessionaire, this section will follow section 4.2. A public concessionaire will maximize his benefit, without considering external benefit or scarcity of resource, i.e. maximize;

$$V = \int_0^\infty e^{-rt} \left[\int_0^{x(t)} (p(z) - T)dz - c(X(t))x(t) \right] dt \qquad \ldots(27)$$

This maximization problem will give first-order condition;

$$p - T - c = 0 \qquad \ldots(28)$$

Comparing (28) with (23), optimal tax for public concessionaire is expressed by

$$T = \lambda = \frac{\dot{p} - c_X f}{r - f_X} + \frac{B_X}{r - f_X} \qquad \ldots(29)$$

In other words, the optimal tax equal to MUC' should be imposed in order to internalize resource scarcity and externality. In this case, externality effects are included in user cost.

Private Owner

Private owner, who takes into account resource scarcity, but not externality, will maximize

$$\max_{x \geq 0} \quad \int_0^\infty e^{-rt} \left[\int_0^{x(t)} (p(z) - T)dz - c(X(t))x(t) \right] dt \qquad \ldots(30)$$

$$s.t. \quad \dot{X}(t) = f(X(t)) - x(t)$$

The current-value Hamiltonian for this optimal control problem is written as:

$$\widetilde{H} = \int_0^{x(t)} (p(z) - T(t))dz - c(X(t))x(t) + \lambda(t)[f(X(t)) - x(t)]$$

where $\lambda(t)$ is the shadow price of the resource stock[10], $X(t)$. First-order conditions are:[11]

$$\frac{\partial \widetilde{H}}{\partial x} = p - T - c - \lambda = 0 \qquad \text{...(31)}$$

$$\frac{\partial \widetilde{H}}{\partial X} = -c_X x + \lambda f_X = r\lambda - \dot{\lambda} \qquad \text{...(32)}$$

Manipulating and rearranging (31) – (32), we get:

$$p = c + \frac{\dot{p} - c_X f}{r - f_X} + (T - \frac{\dot{T}}{r - f_X}) \qquad \text{...(33)}$$

Comparing (26) and (33), we see that the tax must be imposed such that

$$T - \frac{\dot{T}}{r - f_X} = \frac{B_X}{r - f_X} \qquad \text{...(34)}$$

Solving the differential equation (34), we get:

$$T(t) = \int_t^\infty B_X e^{-\int_t^\tau (r - f_X) dv} d\tau \qquad \text{...(24)}$$

For private owner, as he takes into account the user cost, government only needs to internalize externalities. Like forest-sediment case, the optimal tax for a private owner is only a part of MUC'. The effect of tax on future producer price is considered in designing optimal tax.

Conclusion

When resource extraction creates environmental externalities, market equilibrium is not socially optimal. In case of climate change, where fossil fuel extraction causes greenhouse gas accumulation in the atmosphere, charging resource owner for his extraction equal to the shadow price of pollution will restore the optimum. This,

however, does not hold generally for all case. Considering the case where forest determines growth in sediment accumulation, optimal tax for forest owner is not equal to the shadow price of pollution. The differences arise because in forest-sediment case, pollution stock is determined by the forest stock, not forest extraction. However, practical policy is to impose taxes on timber harvested, not subsidies on remaining forest area. This causes the complexity in tax formula. From the same reason, externality cost from resource extraction is embedded in the user cost. Marginal opportunity cost concept may be not well applicable in this case. This logic also applies to the case where resource has amenity values, for example, forest has amenity values including biodiversity, recreational, aesthetic values. While private owner is taxed only externality part from user cost; public concessionaire must be taxed the whole user cost (including externality cost). This is because public concessionaire fails to take into account both externality and future effects of current extraction.

The marginal opportunity cost concept suggested in the literature is still a powerful concept. In some cases, nonetheless, externality cost may not appear explicitly, but as a part of user cost. When externalities arise from resource stock, not resource extraction, user cost consists of foregone benefits of increase in price, higher extraction cost in the future, and externality cost.

Another interesting issue is to find the time path of optimal taxes and compare it with the other cases, for example, carbon taxes in climate change model. Dynamic solution of the problem of interacting resources has never been studied in the literature. The model setup discussed in this article can serves as a good beginning for the problem.

This article shows at the beginning that the interchangeable use of term "MUC" and "royalty" in resource economics is not exactly correct; it is true only with

some underlying understands. There are two things need to be clarified. First, MUC that equal to royalty at first-best is a current value MUC (MUC'); while MUC that used in capital theory is a present value one, by definition. Second, the equality holds only at the first-best. So, at first-best, optimal tax can be set at either MUC' or royalty. However, if the resource is being over-harvested or under-harvested, charging royalty will not restore the optimum, while charging MUC' will.

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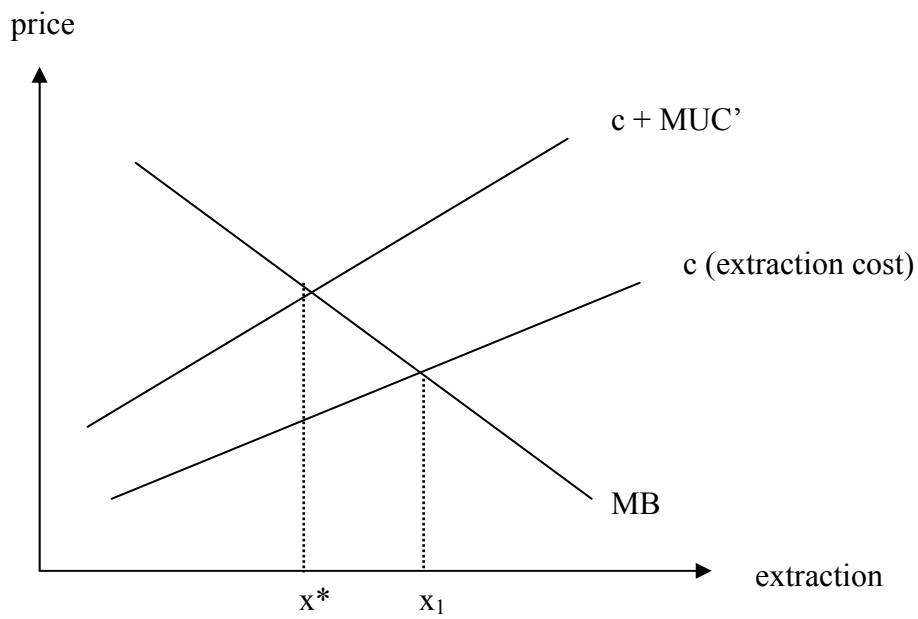
price

c + MUC'

c (extraction cost)

MB

x*   x₁

extraction

Figure1. Charging observed royalty is not always an optimal policy

Footnote:

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[1] c(X) is assumed to be a decreasing function in X. Rising cost given lower resource stock may be explained by difficulties in finding the resource when its stock is low, the use of farer resource, or the use of lower quality resource.

[2] *f(X)* is assumed to have the tradition properties; strictly concave that attain a maxima at a finite value of X

[3] Please note that we use present-value Hamiltonian, not current-value Hamiltonian as the definition of MUC is in present-value term. This may be the source of confusion.

[4] Time as function argument has been ignored to avoid notational clutter.

[5] Function arguments have been ignored to avoid notational clutter.

[6] Function arguments have been ignored to avoid notational clutter.

[7] Note that λ here is different from the one in social planner case.

[8] Function arguments have been ignored to avoid notational clutter.

[9] Function arguments have been ignored to avoid notational clutter.

[10] Again, this λ is different from the one in social optimal case.

[11] Function arguments have been ignored to avoid notational clutter.