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Managing partially protected resources under uncertainty ☆

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ABSTRACT

It is common wisdom that open-access leads to the inefficient use of resources and private ownership of resources improves efficiency. However, the impact of enclosure and efficient management of some resource pools on other open-access resource pools is poorly recognized. The problem is common to many congestion-prone facilities including roads, parks, fisheries, antibiotics, grazing lands and wilderness areas. In this paper, we analyze the optimality of price and quantity instruments in regulating resource use when there is uncertainty about congestion costs. Price instruments are found to be preferable to quantity instruments, and strictly so when demand is less than perfectly elastic. We also explore the effect of market power by resource owners on the relative efficiency of the two instruments.

Introduction

It is widely held that common ownership of natural resource pools leads to over-congestion, and the existence of well-defined and enforceable property rights is a necessary precursor to the optimal use of resources.[1] Although Frank Knight argued that private ownership could achieve optimal congestion, the limited applicability of this argument has long been known [13]. Scott [23] noted and Buchanan [3] was the first to show that private ownership could achieve efficient resource use "only in those cases where the extent of commonality of usage is limited to a relatively small proportion of the total resource supply…" and there was no monopoly power associated with private ownership. However, a second drawback of private ownership; the adverse impact of enclosure and efficient management of some resource pools on other resource pools that are open-access is poorly recognized.

In an important paper, de Meza and Gould [7] showed that if property owners must incur costs to enforce their rights, then the level of enforcement could be more or less than is socially optimal. An example they provide is that of burglar alarms. If no house in the neighborhood has alarms then a single homeowner's decision to install an alarm may reduce that homeowner's risk of being burgled, but could leave everyone else worse off by diverting burglars to unprotected houses. The two socially optimal stable equilibria may be that either all houses have alarms or that none have alarms, and any intermediate solution may be suboptimal to these extrema. This situation also arises in the case of road tolls. Institution of

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[1] An important caveat, as described by Anthony Scott, is that "the property must be allocated on a scale sufficient to insure that one management has complete control of the asset" [23].

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a toll on a highway could reduce the number of commuters on the highway and reduce congestion, but would push some of them onto side roads where there is no toll, thereby inefficiently congesting these other roads. In this case too, the toll may ensure the optimal use of the highway, but may be an inferior solution when the congestion on all roads is considered.

One can see the relevance of this problem of "congestion spillovers" to the optimal management of resources for which some pools are privately owned, while others are open-access. An example discussed by de Meza and Gould is that of the fishery. Regulating any single fishery may displace fisherman who may move to (and congest) other fisheries that are open-access, potentially leaving society worse off compared to the pre-privatization equilibrium. The regulatory problems associated with effort displacement are familiar to those charged with regulating fisheries. For example, concerns that institution of gear restrictions on pelagic fisheries[2] would encourage fishermen to relocate to other sensitive fishing areas, jeopardize sea turtles and dolphins, or increase bottom line fishing of grouper, snapper and tilefish, constituted a significant proportion of all comments sent in response to a NOAA ruling [8].

Partial privatization of grazing lands offers another illustration of congestion spillovers across resources. Efforts to reduce overgrazing and environmental degradation have focused on encouraging pastoralists to confine their animals to fenced enclosures based on the argument that they will be more likely to avoid overgrazing if they owned the land. For instance, a study describes the effect of privatization of rangelands for crop production and private grazing in the Borana rangelands of Southern Ethiopia [12]. However, the impact of private enclosures on the remaining grazing lands that remain open-access has often not been recognized. A possible regulatory response to the cross-resource spillover problem may be to impose a per-animal tax to ensure against overgrazing. Alternatively, one might impose a quota restriction on the number of cattle that can be allowed to graze on a common pasture.

Congestion spillovers across resources are also of contemporary relevance in the case of antibiotic effectiveness, which is a congestible resource in the sense that the evolution of bacterial resistance is directly correlated with the quantity of antibiotics used [16]. Patents permit enclosure of the effectiveness of new antibiotics, but also confer monopoly rights. Other antibiotics have long been in use and are no longer under patent and essentially in an open-access regime. Although patents could give a single firm the incentive to care about resistance to a drug, the patentee is likely to ignore the effect of her pricing decision on exacerbating resistance to antibiotics that may be in the generic domain and may overprice or underuse her antibiotic relative to the socially optimal level.

In this paper, we compare the optimality of price and quantity instruments in regulating for congestion spillovers between resource pools, when there is uncertainty about how congestion costs develop in response to use of the resource pool. Although many common-pool applications have a temporal dimension, the essential feature of cross-resource spillovers is captured adequately by a static consideration of the problem, and we proceed in this vein.[3] We consider optimal policy responses in the face of cost uncertainty in the utilization of resources. Three scenarios are analyzed: no enclosure, partial enclosure with price-taking firms, and the competitive market equilibrium to a market in which enclosure also confers monopoly advantages.

Weitzman's 1974 analysis comparing the optimality of price and quantity instruments is a natural benchmark for our analysis [26]. He found that the relative slopes of the marginal benefits and costs of controlling the externality are critical factors in determining which instrument performs better. Flatter marginal benefits and steeper marginal costs favor prices, while steeper marginal benefits and flatter marginal costs indicate a preference for quantities. One could place the vast literature spawned by Weitzman into two main categories. One set of papers looked at alternatives to taxes and quotas including hybrid instruments [6,15,21,22].[4] A second set of papers focused on modifying assumptions made by Weitzman [10,11,18,24,25,28].[5] Some of these involve tailoring the assumptions to compare price and quantity instruments in specific contexts such as controlling stock externalities in fisheries [14,27] or controlling greenhouse gas emissions [19].[6] Our analysis modifies the Weitzman model in the following way. In Weitzman's analysis, the pollution externality is independent of the marginal abatement cost curve. Here, the users of the open-access resource impose a congestion externality that is equal to the difference between marginal and average costs, thereby linking the production supply curves with the depletion externality.

In our analysis, we identify a superiority of taxes regardless of the relative slopes (and expected positions) of the marginal cost (MC) curves when demand is not perfectly elastic. The intuition arises from the fact that the tax still allows both markets—particularly, the enclosed market—to adjust to the cost shock, while the quota does not. This result differs from the Weitzman case, in which the externality is independent of the marginal abatement cost curve, and the relative

[2] Pelagic or long line gear is the dominant commercial fishing gear used by U.S. fishermen in the Atlantic Ocean to target highly migratory specifics such as Atlantic swordfish and tunas.

[3] See also [4,5,9,20]. Static models have also been used to assess the effect of quotas to reduce fisheries by-catch and optimal menus of antibiotics to reduce depletion of effectiveness [1,17].

[4] For example, Roberts and Spence [22] consider a hybrid of both prices and quotas, such as emissions permits with a price cap, that performs better than either prices or quotas; more recently, Quirion [21] considers additional policy instruments, including intensity-based mechanisms.

[5] For example, Hoel and Karp [11] modify the problem to assume that environmental damage is caused by the stock of pollution (rather than flow); Stavins [24] relaxes the assumption that uncertainty in benefit and cost functions are uncorrelated; Watson and Ridker [25] assume that the error terms on the benefit and cost functions enter multiplicatively and that the benefit and cost functions are linear.

[6] Newell and Pizer consider the problem for long-lived stock externalities, making adjustments for dynamic effects including correlation of cost shocks across time, discounting, stock decay and the rate of benefits growth. They find that in an application to the problem of greenhouse gases and climate change, a price-based instrument generates several times the expected net benefits of a quantity instrument [19].

slopes drive the preference for a tax or quota. Here, since the congestion externality for the open-access supply is defined by the difference between marginal and average costs, a shock shifts that market supply (average cost) curve in the same direction as the social marginal cost curve. Thus, while the tax fixes the price signal for producers in the Weitzman case, here the tax is not the price; rather, it influences the price, as do the cost shocks. A quota, on the other hand, makes supply invariant to shocks, as in the Weitzman case. As a result, the relative tradeoff is not between a too-rigid price and a too-rigid quantity, but a flexible, suboptimal price and a too-rigid quantity. Without the spillovers from partial enclosure however, taxes are equally preferred to quotas.

Perfectly elastic demand represents a special case without enclosure spillovers, since the price does not change according to harvesting behavior in either resource. In this case, both policies have the same expected costs. This differs from the clear superiority of taxes in the Weitzman case, in which the market automatically equalized marginal costs with the marginal benefit (tax). Here, despite the flat marginal benefits of the resource and the policy intervention, behavior in the open-access resource still depends on average, not marginal, costs. With quadratic costs, the losses are symmetric for negative and positive cost shocks, leading to the same expected costs for each policy.

We address these cases, comparing price versus quantity regulation of an open-access resource pool when the competing pool is unenclosed, then enclosed, and finally managed by a private owner with a monopoly on the resource. We develop the intuition by first analyzing the extreme case in which demand for the resource is perfectly inelastic, so that any change in supply from one pool must be made up from the other. We then discuss variations, including perfectly elastic demand and alternative policies, before concluding.[7]

Model

Our model reframes and extends the model of de Meza and Gould [7] in the following ways. First, we focus on the product market equilibrium, rather than the labor market equilibrium. Since congestion arises from use of the product, we prefer to focus on the product price impacts of enclosure, assuming instead that this industry is too small to influence the prevailing wage rates[8]. Second, we consider the scope of the congestion spillover, and whether it applies within or across resource pools. Third, we compare the competitive market equilibrium to a market in which enclosure also confers monopoly advantages. Fourth, we consider the effect of uncertainty in the congestion parameter on the optimal policy response.

We assume two types of resource pools, either enclosed or open-access. The quantity from each pool q_i is produced at cost $C^i(q_i, \theta_i)$, which is convex in q_i and shifted by an uncertain parameter θ_i with mean μ_i and variance σ_i^2. Marginal production costs may be increasing due to diminishing returns to harvesting effort. θ_i denotes ecological uncertainty related to, for example, the impact of cattle on grazing lands or of harvests on fishing stocks. The market price of the product is the inverse demand function $p(Q)$, where Q is total production.

We consider the case of two pools, one that becomes enclosed (denoted by subscript P) and another that remains open-access (denoted by subscript F). Z is the fixed cost of enclosure. We largely abstract from the enclosure decision itself, treated by de Meza and Gould, and focus on the questions of allocative efficiency.

Firms using an open-access pool are price-takers in the product market. Profits for the open-access (“Free”) pool are by definition zero, as effort and extraction occurs until the average marginal product equals the cost:

$$p(Q) = \frac{C^F(q_F, \theta_F)}{q_F}. \tag{1}$$

Prior to enclosure, the “P” pool would also produce until price equals average costs. In a no-enclosure equilibrium, then, market clearing occurs when $Q = q_P + q_F$ and $C^F(q_F, \theta_F)/q_F = C^P(q_P, \theta_P)/q_P$.

When the “P” pool is enclosed and becomes “Private”, the owner maximizes operating profits net of enclosure costs: $\pi_P = p(Q)q_P - C^P(q_P, \theta_P) - Z$. The profit-maximizing extraction for this owner solves

$$MR(Q) = C_q^P(q_P, \theta_P), \tag{2}$$

where $MR(Q) = p(Q) + p'(Q)q_P$ in the monopoly case and $MR(Q) = p(Q)$ in the price-taking case.

In the market equilibrium with partial enclosure, from combining Eqs. (1) and (2), extraction occurs where average costs from the free-access pool are equalized with marginal costs from the private pool, plus any market power effect:

$$\frac{C^F(q_F, \theta_F)}{q_F} = C_q^P(q_P, \theta_P) - p'(Q)q_P. \tag{3}$$

Since C is convex in q, average cost is lower than marginal cost, given any level of extraction; therefore, with equal θ, $q_P < q_F$. To the extent that marginal revenue is lower than the price, this difference is further exacerbated.

A private owner will enclose its resource pool as long as $pq_P - C^P(q_P, \theta_P) \geq Z$, and we assume that this holds. In a model of price-taking firms (i.e., $MR=p$), enclosure of part of the market has two effects on allocative efficiency. On the one

[7] An Appendix available at JEEM's online archive of supplementary material, which can be accessed from a link at http://www.aere.org/journals/, confirms that the results hold more generally for downward-sloping linear demand.

[8] De Meza and Gould assumed product prices were fixed while wages were endogenous; in a sense, we reverse this normalization.

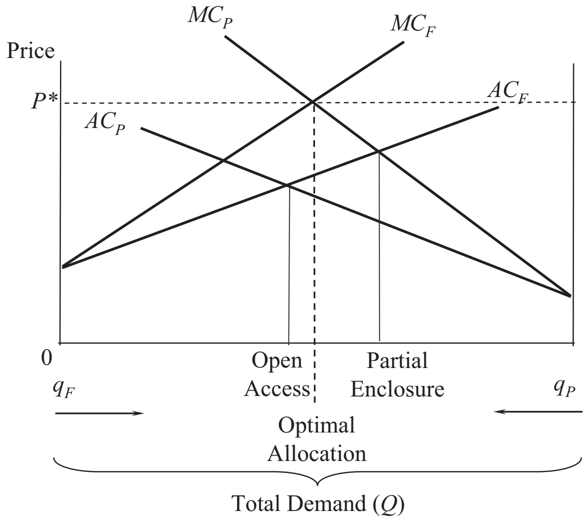

Fig. 1. Market equilibria with fixed demand.

hand, enclosure improves the efficiency of extraction in the private access pool; on the other hand, it exacerbates the over-exploitation of the open-access pool, as the private pool supply contracts. When enclosure also confers monopoly powers, it leads to an under-exploitation of the private access resource, and further over-exploitation of the open-access resource.

Given incomplete enclosure, what policy instruments might best improve welfare, particularly if the production cost function is uncertain? Should we tax open-access extraction, impose a quota on one or the other, or subsidize enclosed extraction?

The problem of partial enclosure offers an important twist on the classic Weitzman "Prices v. Quantities" question. In that model, the externality is independent of the marginal abatement cost curve, and the relative slopes drive the preference for a tax or quota. Here, the congestion externality for the open-access supply is the difference between marginal and average costs; consequently, the production supply curve is correlated with the depletion externality.

The planner problem is to maximize welfare, which calls for price to equal marginal costs, both of which should be equalized: $C_q^P(q_P, \theta_P) = C_q^F(q_F, \theta_F) = p(q_P + q_F)$. In a decentralized program, the planner uses a tax or permit price to achieve this allocation.

Under certainty, both instruments achieve the same outcome. However, a tax or equivalent quota policy set *ex ante*, before the values of θ_i can be resolved, may not have the same effect *ex post*, as the marginal cost curves may shift from their expected values.

To consider how these costs change *ex post*, and following Weitzman (1974) we assume a quadratic cost function:

$$C^i(q_i, \theta_i) = \theta_i q_i + c_i q_i^2, \tag{4}$$

where q_i is the quantity of regulated good, $2c_i$ is the slope of the marginal cost curve and θ_i is a shock to the marginal cost function. As Weitzman shows, the quadratic function in the neighborhood of the optimal quantity is a justifiable second-order approximation following a Taylor's series expansion[9] and reflects the convex cost structure encountered in congestion spillover problems.

With this formulation, we have simple linear supply curves: $MC^i(q_i, \theta_i) = \theta_i + 2c_i q_i$. Marginal cost equalization then implies

$$q_F^* = \left(\frac{1}{2}(\theta_P - \theta_F) + c_P q_P^*\right) \Big/ c_F. \tag{5}$$

Next we consider a series of examples. Most of the intuition behind the general results can be obtained by considering the example of fixed demand, and we begin with this scenario. We first evaluate policy options with no enclosure, then partial enclosure with price-taking firms, and finally partial enclosure by a monopolist. Afterwards, we explore the role of the demand function in these results, considering the other extreme case of perfectly elastic demand. In the Appendix of supplementary material, we discuss how the results hold for downward-sloping demand more generally.

In the case of perfectly inelastic demand for the resource, all agents use one or the other of the resource pools. The case of perfectly inelastic demand can be represented by intersecting marginal and average cost curves, as in Fig. 1. With total

[9] Since the constant term disappears when the approximation is written in terms of deviations from the optimal level, we can omit it from the quadratic form [19].

demand fixed, the residual demand curve for each pool is determined by the supply curve of the other pool. The average cost (AC) curve is the relevant supply curve for an open-access pool. While the optimal allocation is the point where the marginal cost (MC) curves intersect, the open-access equilibrium emerges at the point of intersection of the AC curves, while the partial enclosure equilibrium is represented by the intersection of the AC curve of the free pool and the MC curve of the privately owned pool.

From the society's perspective, the marginal benefit curve for F is downward sloping and represents the benefit from using resource F on averting congestion in resource P. Illustrated in Fig. 1, is the marginal cost of extracting from pool P but drawn in mirror fashion from the right axis.

Fixed demand allows us make some useful mathematical simplifications. Since $q_P = Q - q_F$, we can rewrite (5) to solve for the optimal quantity in the free-access pool:

$$q_F^* = \left(c_P Q + \frac{1}{2}(\theta_P - \theta_F)\right) \Big/ (c_F + c_P). \tag{6}$$

Fixed demand also means that resource payments are transfers between consumers and producers; therefore, maximizing welfare is equivalent to minimizing total production costs.

With our quadratic cost function, total costs are

$$\begin{aligned} TC &= \theta_P(Q - q_F) + c_P(Q - q_F)^2 + \theta_F q_F + c_F q_F^2 \\ &= (c_F + c_P)q_F^2 - (2Qc_P + \theta_P - \theta_F)q_F + \theta_P Q + c_P Q^2. \end{aligned} \tag{7}$$

Consequently, the difference in expected costs between the quota and tax policies is

$$E\{TC_{quota}\} - E\{TC_{tax}\} = (c_F + c_P)E\{\overline{q}_F^2 - (q_F^{tax})^2\} - 2Qc_P E\{\overline{q}_F - q_F^{tax}\} - E\{(\theta_P - \theta_F)(\overline{q}_F - q_F^{tax})\}. \tag{8}$$

Define $\Delta \equiv \overline{q}_F - q_F^{tax}$ as the difference in the *ex post* quantities. Furthermore

$$\overline{q}_F^2 - (q_F^{tax})^2 = (q_F^{tax} + \Delta)^2 - (q_F^{tax})^2 = 2\Delta q_F^{tax} + \Delta^2.$$

Thus, we can rewrite (8) as

$$E\{TC_{quota}\} - E\{TC_{tax}\} = (c_F + c_P)E\{2q_F^{tax}\Delta + \Delta^2\} - E\{2c_P Q\Delta + (\theta_P - \theta_F)\Delta\}. \tag{9}$$

Since policies are set *ex ante*, with this expression, we can focus on how the difference in *ex post* production quantities affects the relative expected total costs of the regulatory policies.

No enclosure

Before considering the effects of partial enclosure on the choice of policy options, it is useful first to study the case of no enclosure. We still allow for two resource pools with potentially different costs, so consider for the moment the P pool to be "Potentially but not yet enclosed." Without intervention, the market produces where the two AC curves intersect, as depicted by the "market equilibrium" point in Fig. 2. Equalizing marginal costs and solving $q_P = Q - q_F$, we find $q_F^{OA} = \left(c_p Q + (\theta_P - \theta_F)\right)/(c_F + c_P)$.

This allocation deviates from the optimum in (5) somewhat, to the extent that the cost curves have different intercepts.

With a decentralized policy, however, each kind of supplier equalizes average cost with its after-tax price. Since overall demand does not respond, only one policy is needed to achieve the cost-minimizing allocation.

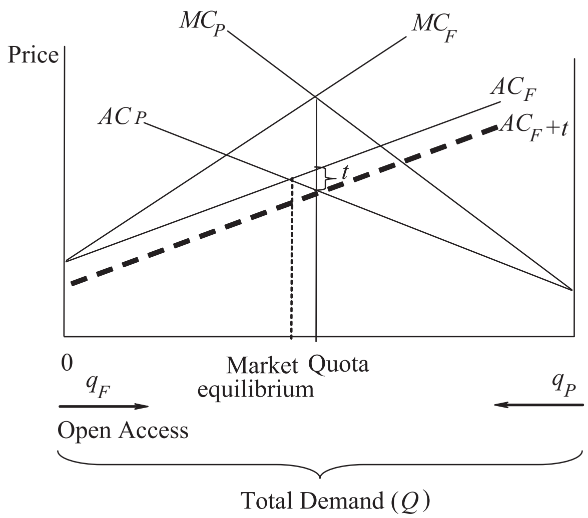

Fig. 2. Open-access equilibrium with fixed demand.

Proposition 1. *With fixed demand, when both resource pools are open access, expected total costs are identical under a tax or quota policy implemented on one pool.*

The proof is shown by solving for the optimal *ex ante* tax and quota, deriving the corresponding allocation of outputs, and comparing the expected total costs.

We impose tax t on pool F. Consequently, the profit-maximizing conditions are

$$p - t = \theta_F + c_F q_F \text{ and } p = \theta_P + c_p q_P. \tag{10}$$

From the above two equations, and from $\sum_i q_i = Q$, we have

$$q_F = \frac{c_P Q + (\theta_P - \theta_F) - t}{c_F + c_P} \text{ and } q_P = \frac{c_F Q - (\theta_P - \theta_F) + t}{c_F + c_P}. \tag{11}$$

Substituting and solving for the optimal *ex post* t^* such that (5) holds, we get $t^* = (\theta_P - \theta_F)/2$. Taking expectations, we simplify the *ex ante* tax rate:

$$t = E\{t^*\} = (1/2)(\mu_P - \mu_F), \tag{12}$$

where μ_i is the mean of each shock term, representing the expected intercept of the MC curve. As drawn in Fig. 2, with $\theta_P < \theta_F$, the tax on pool F is negative and actually a subsidy to counteract overuse of the lower-cost resource. The same equilibrium would result from imposing a positive tax of the same amount on the products of resource pool P.

Substituting the *ex ante* tax into (11) and simplifying, we get

$$q_F^{tax} = \frac{2c_P Q + 2(\theta_P - \theta_F) - (\mu_P - \mu_F)}{2(c_F + c_P)}. \tag{13}$$

Similarly, to solve for the optimal quota, we substitute the *ex post* optimal tax into (11) and find the expected value for output in pool F:

$$\overline{q}_F = E\{q_F^*\} = E\left\{\frac{c_P Q + (1/2)(\theta_P - \theta_F)}{c_F + c_P}\right\} = \frac{2c_P Q + \mu_P - \mu_F}{2(c_F + c_P)}, \tag{14}$$

which is identical to the expected value of q_F^{tax}.

In this case, the *ex post* difference in pool F's production between the quota and tax is

$$\Delta = \frac{(\mu_P - \mu_F) - (\theta_P - \theta_F)}{(c_F + c_P)}.$$

Since $E\{\theta_P - \theta_F\} = \mu_P - \mu_F$, we see that $E\{\Delta\} = 0$, but the other combined terms in the expected cost Eq. (9) may be nonzero.

Note that we can also write

$$2q_F^{tax} = \left(\frac{2c_P Q + (\theta_P - \theta_F)}{(c_F + c_P)} - \Delta\right).$$

Simplifying (9), we have

$$E\{TC_{quota}\} - E\{TC_{tax}\} = E\left\{\left(2c_P Q + (\theta_P - \theta_F)\right)\Delta\right\} - E\left\{\left(2c_P Q + (\theta_P - \theta_F)\right)\Delta\right\} = 0. \tag{15}$$

With no difference in expected costs, we find no preference for the tax or quota when both resource pools are open-access.

Partial enclosure and perfect competition

Now let us turn to the case of partial enclosure. Suppose first that all firms are price-takers, including the representative private resource owner, for whom $MR=p$. Without intervention, the market produces where the AC curve of pool F intersects with the MC curve of pool P, leading to $q_F^{PE} = \left(2c_p Q + (\theta_P - \theta_F)\right)/(c_F + 2c_P)$. In the case depicted in Fig. 1, with the enclosed pool responding efficiently to price signals, this allocation deviates from the optimum by significantly more than when both pools are free-access. Interestingly, this result holds in many cases, and always holds when $\theta_P - \theta_F > 0$ (which we show in the Appendix in Proposition 5 of supplementary material). Essentially, unless a sufficiently large share of the resources are enclosed (which in the two-pool case depends on the relative costs), total costs are higher with partial enclosure than with full open-access.

Indeed, the optimal tax rate in this case is the difference between marginal and average costs in the free-access pool, which with our functional forms is a linear function of the open-access quantity: $t^* = c_F q_F$. However, in practice, it is difficult to implement a tax rate that increases with total quantities sold in the market, as opposed to those sold by a single firm. Therefore, we continue to consider the relative efficiency of a fixed-tax policy.

In the Weitzman problem, setting an optimal *ex ante* tax fixes the price or marginal benefit of supply. Here, in contrast, the optimal tax fixes a wedge between the supply curves, and the price still requires equilibration with the alternative resource's supply curve. A quota policy, on the other hand, fixes the quantity supplied, just as in Weitzman. This different functioning of the tax leads to different relative preferences for instrument choice.

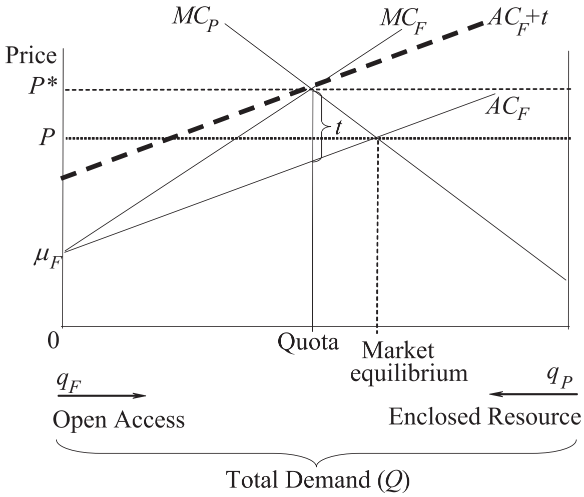

Fig. 3. Optimal tax and quota.

Fig. 3 illustrates the optimal tax and quota, given the expected marginal cost curves, for the case of perfectly inelastic demand.

Solving for the optimal tax and quota for the unenclosed resource, we next compare their expected costs under uncertainty.

Proposition 2. *With fixed demand, when one resource pool is enclosed with a price-taking owner, expected total costs are lower under a tax than under a quota policy for the open-access pool.*

The proof is along the same lines as for Proposition 1. Rewriting the first-order condition for the private resource (Eq. (1)), we get

$$p = \theta_P + 2c_P q_P, \tag{16}$$

while for the open-access resource with a tax t imposed:

$$p - t = \theta_F + c_F q_F. \tag{17}$$

From the above two equations, and from $\sum_i q_i = Q$, we have

$$q_F = \frac{2c_P Q + (\theta_P - \theta_F) - t}{c_F + 2c_P} \text{ and } q_P = \frac{c_F Q - (\theta_P - \theta_F) + t}{c_F + 2c_P}. \tag{18}$$

We can solve for the optimal *ex post* tax and quota by setting expected marginal costs for the two resources equal to each other, so

$$t^* = \frac{(\theta_P - \theta_F)c_F + 2c_F c_P Q}{2(c_F + c_P)} \text{ and } q_F^* = \frac{(\theta_P - \theta_F) + 2Qc_P}{2(c_F + c_P)}. \tag{19}$$

Ex ante, the optimal tax is

$$t = E\{t^*\} = \left(\frac{1}{2}(\mu_P - \mu_F) + c_P Q\right)\frac{c_F}{(c_F + c_P)}. \tag{20}$$

Note that this tax is generally higher than with no enclosure, since the discrepancy between the effective supply curves is larger with partial privatization.

Substituting (20) into (18) and simplifying, the resulting output in the free-access pool is

$$q_F^{tax} = \frac{c_P Q}{(c_F + c_P)} + \frac{2(\theta_P - \theta_F)(c_F + c_P) - c_F(\mu_P - \mu_F)}{2(c_F + 2c_P)(c_F + c_P)}. \tag{21}$$

The optimal quota for the free-access pool, on the other hand, is the same as without partial enclosure—and the same as the expected value of output under the tax with partial enclosure:

$$\overline{q}_F = E\{q_F^*\} = E\{q_F^{tax}\} = \frac{c_P Q}{(c_F + c_P)} + \frac{(\mu_P - \mu_F)}{2(c_F + c_P)}. \tag{22}$$

Expected total costs with the quota are thus also the same as with no enclosure. Since quantities do not change with the quota, these expected total costs also equal the total costs at the expected values of the shock parameters.

With partial enclosure, the difference between *ex post* quantities is

$$\Delta = \overline{q}_F - q_F^{tax} = \frac{(\mu_P - \mu_F) - (\theta_P - \theta_F)}{(c_F + 2c_P)}.$$

Again, $E\{\Delta\} = 0$. Furthermore, with σ_i^2 the variance of θ_i and σ_{PF} the covariance, then

$$E\{(\theta_P - \theta_F)^2\} = (\mu_P - \mu_F)^2 + \Theta, \tag{23}$$

where $\Theta \equiv \sigma_P^2 - 2\sigma_{FP} + \sigma_F^2$.

Simplifying (9), we have

$$\begin{aligned} E\{TC_{quota}\} - E\{TC_{tax}\} &= (c_F + c_P)E\left\{2(\overline{q}_F - \Delta)\Delta + \Delta^2\right\} - 2c_P Q E\{\Delta\} - E\{(\theta_P - \theta_F)\Delta\} \\ &= (c_F + c_P)E\left\{-\Delta^2\right\} - E\{(\theta_P - \theta_F)\Delta\} = \frac{c_P\Theta}{(c_F + 2c_P)^2} \geq 0. \end{aligned} \tag{24}$$

Thus, expected total costs are higher with the quota than the tax as long as $\Theta > 0$. The larger the variances and the smaller the covariance of the uncertain terms, the greater is the superiority of the tax instrument. In the limiting case where the covariance offsets the variances ($(\sigma_P - \sigma_F)^2 = 0$), price and quantity instruments are equally efficient. These results imply a general superiority of taxes—at least when demand is fixed.

The intuition arises in part from the fact that the tax still allows both markets to adjust to the cost shock, while the quota does not. This result differs from the Weitzman case, in which the externality is independent of the marginal abatement cost curve, and the relative slopes drive the preference for a tax or quota. Here, since the congestion externality for the open-access supply is the difference between marginal and average costs, a shock shifts that market supply curve in the same direction as the social marginal cost curve. Thus, while the tax fixes the price signal for producers in the Weitzman case, here the tax is not the price; rather, it influences the price, as do the cost shocks. A quota, on the other hand, makes supply invariant to shocks, as in the Weitzman case. As a result, the relative tradeoff is not between a too-rigid price and a too-rigid quantity, but a flexible, suboptimal price and a too-rigid quantity.

However, another important part is the congestion spillover of partial enclosure. The tax flexibility did not matter when both resource pools were open-access, as the spillovers from two open-access pools netted each other out, in expectations. But when one resource pool responds optimally to a price shift, while the other does not, the scope for market adjustment matters.

Fig. 4 illustrates the market response to an unexpected cost shock in the privately owned resource. Higher costs in the private pool mean that the optimal allocation shifts toward the free pool, but the quota does not allow that, resulting in a larger deadweight loss (DWL) than with the tax, which allows adjustment, even if slightly too much. Of course, the tax preference does not depend on the source of the cost shock; a shift in the before- and after-tax supply curves of the open-access resource would produce the same results.

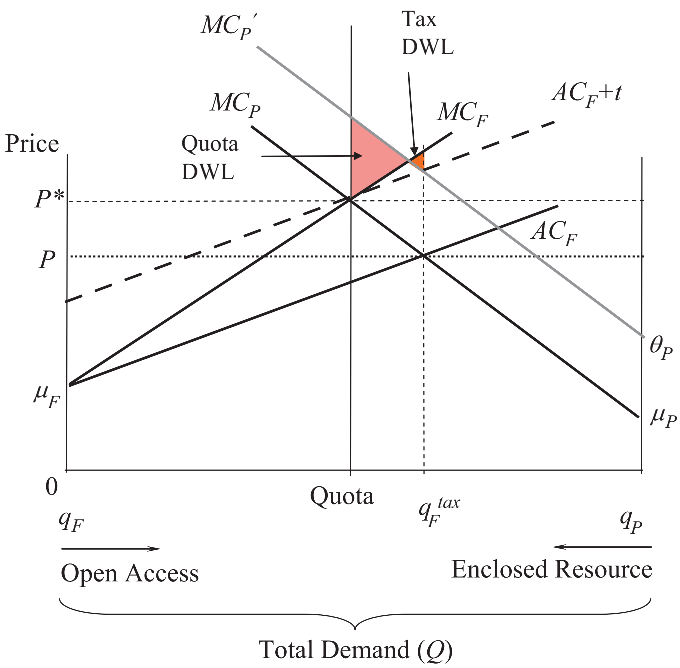

Fig. 4. Response to unexpected cost shock in enclosed resource with tax vs. quota.

Policy options with a monopolist

When the enclosed firm is a monopolist, two problems emerge: underuse of the privatized resource and overuse of the open-access resource. The result is an even more skewed allocation of resource extraction than with partial enclosure with price-taking providers. Thus, partial enclosure is even more likely to raise total costs relative to open-access when the manager behaves as a monopolist (see the Appendix of supplementary material for additional discussion). Consequently, proper regulation of the open-access resource becomes even more valuable.

With fixed demand, the optimal quota does not change; however, the optimal tax must adjust when the private resource owner behaves like a monopolist. Furthermore, marginal revenue is a function not only of demand, but also of the open-access cost—and whether the policy instrument is perceived to be flexible. This begs the question of whether the relative policy preference changes with strategic behavior.

Proposition 3. *With fixed demand, when one resource pool is enclosed with a monopolist owner, a tax policy for the open-access pool is preferred to a quota.*

The proof follows as before. With a quota, the private resource owner faces a fixed residual demand. Theoretically, the monopolist could charge as high a price as desired; however, since that is a transfer, we can focus on the costs, which the monopolist has the same incentive to minimize. Consequently, the results for the quota policy are the same as with price-taking private producers.

However, with the tax, the monopolist's residual demand curve is a function of the open-access behavior. From the open-access response with a tax t imposed (17):

$$p = \theta_F + c_F(Q - q_P) + t. \tag{25}$$

Consequently $MR = p - c_F q_P$, and from the first-order condition in Eq. (1):

$$p - c_F q_P = \theta_P + 2c_P q_P. \tag{26}$$

Solving for output, we have

$$q_F = \frac{(c_F + 2c_P)Q + (\theta_P - \theta_F) - t}{2(c_F + c_P)} \quad \text{and} \quad q_P = \frac{c_F Q - (\theta_P - \theta_F) + t}{2(c_F + c_P)}. \tag{27}$$

We solve for the optimal tax by setting expected marginal costs for the two resources equal to each other, yielding

$$t = t^* = c_F Q. \tag{28}$$

Some important differences arise compared to the case of partial enclosure with price-taking firms. First, the expected cost shocks do not affect the tax. Second, the optimal tax is fixed, not proportional to extraction in the free-access pool. Third, the tax is significantly larger with a monopolist: $c_F Q > c_F q_F^{tax}$.

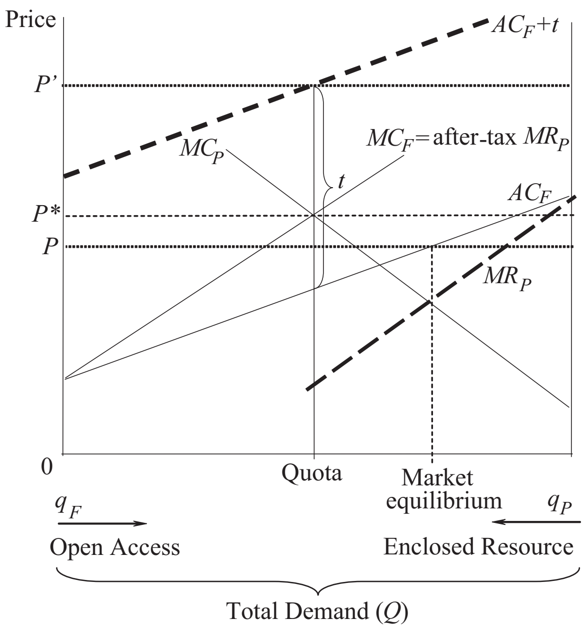

Fig. 5. Monopoly in enclosed resource with fixed demand.

Fig. 5 illustrates the market equilibria when a monopolist is in control of the enclosed pool. The effective marginal revenue (MR) curve for the monopolist derives from the open-access supply curve. The optimal tax shifts the supply curve such that the effective after-tax MR curve equals the MC curve.

Substituting and simplifying, we see that expected total costs are higher with the quota than the tax:

$$E\{TC_{quota} - TC_{tax}\} = \frac{\Theta}{4(c_F + 2c_P)} \geq 0. \tag{29}$$

This result is similar to that with price-taking firms: the superiority of the tax instrument increases the larger the variances and the smaller the covariance of the uncertain terms.

Variations

The preceding section found, at least for the fixed demand case, a general superiority of the tax instrument over the quota, regardless of market structure, although that structure affects the optimal *ex ante* tax rate. In this section, we discuss whether this result holds more broadly for other demand functions and whether other policy options might achieve the same result.

The role of elastic demand

To begin, consider the opposite extreme case from fixed demand: perfectly elastic demand, such as if a perfect substitute is available at constant cost (or perhaps no treatment may be the backstop). With perfectly elastic demand, there is no enclosure congestion spillover between the two resource pools, since any change in production of one is met by the substitute technology, not by putting pressure on the other resource. In this case, the optimal policy for the open-access pool can be implemented with either a quota or tax, while the enclosed pool needs no policy. (Since with perfectly elastic demand, the monopolist cannot exert any market power, that case is not relevant for further consideration.)

With the price fixed, consumer surplus is invariant, so the objective is again to minimize costs. Furthermore, production from each pool is independent of the production (and costs) in the other. Therefore, if both are open-access, then each pool needs its own policy. To determine whether a tax or a quota is preferred, it suffices to look at a single pool; however, total production costs must also include the costs of the available substitute:

$$TC = C^i(q_i, \theta_i) + p(Q - q_i). \tag{30}$$

Solving as before, we get $q_i = (p - t_i - \theta_i)/c_i$. The optimal *ex ante* tax is

$$t_i = \frac{p - \mu_i}{2} \tag{31}$$

leading to

$$q_i = \frac{p + \mu_i - 2\theta_i}{2c_i}. \tag{32}$$

Similarly, we can solve for the optimal quota for each pool:

$$\overline{q}_i = \frac{p - \mu_i}{2c_i}. \tag{33}$$

The expected difference in total costs depends on the difference between production of each open-access resource in the tax and quota scenarios, and any change in use of the available substitute:

$$\begin{aligned} E\{TC_{quota} - TC_{tax}\} &= E\left\{\theta_i(\overline{q}_i - q_i^{tax}) + c_i(\overline{q}_i^2 - q_i^{tax^2}) + p(q_i^{tax} - \overline{q}_i)\right\} \\ &= E\left\{(\theta_i - p)\left(\frac{\theta_i - \mu_i}{c_i}\right) + \frac{(p - \mu_i)^2}{2c_i} - \frac{(p + \mu_i - 2\theta_i)^2}{2c_i}\right\} = 0. \end{aligned} \tag{34}$$

Substituting and simplifying, we find that neither policy outperforms the other in expectations (Fig. 6).

This result is particularly interesting, given that the marginal benefits of the resource are flat in this case. In the Weitzman problem, flat marginal benefits imply that a tax should dominate. The important distinction here is that the marginal damages in this case—the loss from over harvesting the open-access resource—are not flat. Rather, they increase with harvesting. Thus, in both cases, the impacts of cost shocks are roughly symmetric for upward and downward shifts.

This result also runs somewhat counter to Weitzman [27], which notes that a tax allows for better dynamic adjustment over time to optimal escapement in fisheries management, whereas a quota must be fixed prior to the fishing season. A key difference is that, in Weitzman's paper, the fisheries manager knows with certainty the optimal escapement, but ecological uncertainty implies that current escapement, and thereby current optimal harvesting, is unknown. With open-access, a fee set equal to average profits at optimal escapement can automatically induce convergence to that point, while a quota may chase around it. Focusing on the convergence issue, Weitzman ignores the welfare costs along the path. In our case, there is no long-run optimal tax, only an optimal expected tax.

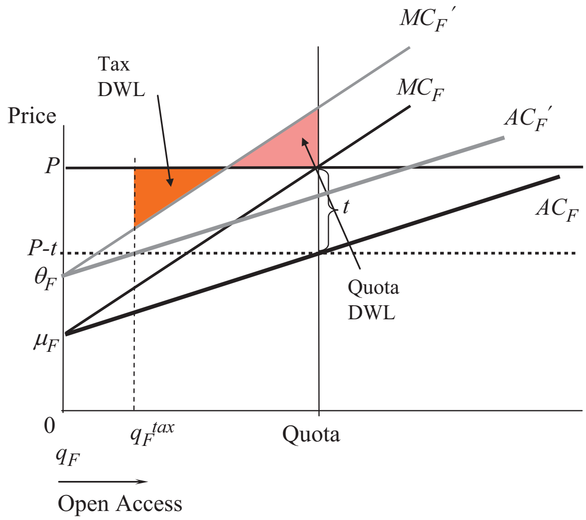

Fig. 6. Responses to a cost shock in an open-access resource with perfectly elastic demand.

Combining the intuition of these two extreme cases, we could expect that the results for downward-sloping demand would lie in between a strict preference for taxes and indifference among the policy options, leaving still a preference for taxes.[10]

Proposition 4. *For any (linear) demand function, a tax policy for the open-access pool is at least weakly preferred to a quota.*

Alternative policies

As noted, with a market failure in each pool, more than one policy instrument is needed when demand is responsive. In the case of the monopoly, the optimal tax policy involves not only a tax on open-access extraction, but also a subsidy to monopoly extraction. (We assume a minimum quota for the monopolist is not possible to enforce.) If one is restricted to a single policy, one would expect that at some point, as demand gets flatter, subsidizing private production would become more important than taxing open-access. Still, we expect one or the other price instrument to dominate the quota.

When demand is fixed, a subsidy to extraction in the (price-taking) enclosed pool is equivalent to taxing the free-access pool, and is therefore a viable option. However, when demand is responsive, a subsidy to the enclosed resource would tend to encourage overproduction there and be less effective at crowding out overproduction in the open-access resource.

An interesting alternative is a tax that is not fixed but rather based on revenues. Such an *ad valorem* tax would not only allow quantities to adjust to cost changes, but it would allow the tax to adjust as well.[11] A cost shock that raises prices would then raise the effective tax. The question is how appropriate this kind of adjustment would be. We simulate the effects of an *ad valorem* tax in the fixed demand case with partial enclosure. We investigate this scenario as the most likely to benefit from a flexible tax, given that the optimal tax was fixed in the monopoly case and the no-enclosure case, although uncertain in the latter. We find that whether the proportional tax dominates the fixed tax depends on the relative values of the cost parameters across the pools. For example, we find that the *ad valorem* tax can lead to lower costs when the free-access MC curve is steeper relative to the MC curve of the enclosed pool, but the fixed tax dominates when the free-access MC curve is relatively flat. In this particular comparison, then, we return to results of the flavor of the original Weitzman study.

Conclusions and further issues

We have described our approach to cross-resource congestion spillovers in the context of grazing lands; however, the insights that emerge from our analysis are broadly applicable to situations where the optimal management and harvesting of any single natural resource pool increases the risk of over-exploitation of other unprotected resource pools. A challenge, of course, is in enforcing policy on an open-access resource. In the case of grazing lands, this would involve a fee per head of cattle or a restriction in the number of cattle that a family could own. And in the case of open-access fisheries, one might consider either a catch quota or a landing tax.

We find that price instruments such as taxes (and in some situations subsidies) are more efficient than quotas when some resources are enclosed and others are not (Table 1). This result holds regardless of whether or not the market for the

[10] These points are verified in an Appendix available at the online archive of supplementary material.
[11] We are grateful to Chris Costello for suggesting this variant.

Table 1
Summary of results comparing price policy (P) to quantity policy (Q).

	Perfectly inelastic demand and downward sloping demand	*Perfectly elastic demand*
No enclosure	$P=Q$	$P=Q$
Partial enclosure with perfect competition	$P>Q$	$P=Q$
Partial enclosure with monopoly	$P>Q$	Not relevant

resource is competitive or monopolistic. When both resource pools are free-access, or when resource demand is perfectly elastic, then both instruments do equally well under uncertainty.

These results point to interesting questions for extensions of the model. First, we have assumed that decisions to enclose are exogenous, but the choice of which resources to enclose and privately manage may be endogenously determined. For instance, a drop in the price of enclosure facilitated by the introduction of barbed wire was posited to be responsible for greater private management of prairie farmers in the American West [2]. A first extension would be to explore the effect of changes in the price of enclosure on the order in which properties are likely to be enclosed and the associated effect on social welfare.

Second, future work should look at whether the cost shocks might shift the slope rather than (or in addition to) the intercept of the marginal cost curve. While our representation may be appropriate for the case of enclosed grazing land, applications to other resource problems may test this assumption. An additional feature that might be incorporated is to examine the effect of correlated shocks about the congestion functions of the two resources.

Third, the issue of optimal regulation of cross-resource congestion spillovers should be examined in a dynamic framework. The static framework that we have adopted offers the advantage of tractability transparency about the underlying intuition, and a sharp focus on the resource pool problem that relates to spillovers. Although it remains suitable in a number of applications, including congestion of infrastructure and other resources, a dynamic framework would permit more biologically realistic modeling of the evolution of renewable resources like fisheries and antibiotic effectiveness.

Fourth, the partial equilibrium model in this paper can be derived from a general equilibrium framework, with an assumption that utility for this product is separable from utility from all other goods, and that those goods exhibit constant returns to scale, which determines the wage rate. Relaxing these assumptions allows some of the incidence of effects in this market to spread to other markets (as through the labor market in de Meza and Gould). The intuition for policy is similar, but additional interactions arise, as is well known in the literature on optimal taxation in the second-best.

Appendix A. Supplementary Material

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.jeem.2009.07.001.

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