When is Increasing Consumption of Common Property Optimal? Sorting, Congestion and Entry in the Commons

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Abstract

First-best pricing or assignment of property rights for rival and non-excludable goods is often infeasible. In a setting where the social planner cannot limit total use, we show common-property resources can be over or under-consumed. This depends on whether the external benefits of reallocating users to less congested resources outweigh the additional costs imposed by new entrants. Importantly, we show it may be optimal to *encourage* consumption of some common property resources. Our results have important implications for settings ranging from fisheries and forestry to recreational demand and transportation.

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1 Introduction

Achieving first-best consumption of common property resources is challenging in many settings. Open access management of common property resources is generally expected to lead to inefficient over-consumption, *i.e.* the "tragedy of the commons" (Gordon, 1954; Hardin, 1968; Smith, 1968; Brown, 1974; Stavins, 2011). While in some cases users have constructed formal or informal institutions to more efficiently manage the commons (Acheson, 1988; Ostrom, 1990; Kaffine, 2009; Anderson and Parker, 2013), economists have generally advocated pricing or assignment of property rights as a remedy to over-consumption. Unfortunately, in many or perhaps even most contexts, these first-best solutions are infeasible due to coordination costs, opposition to pricing mechanisms, or the public trust doctrine. Management can be further complicated if users sort amongst many substitute common property resources, altering consumption levels across the commons.

In this paper, we consider the allocation of consumption across substitute common-property resources. Importantly, we focus on cases where first-best instruments to limit entry and thus total consumption are unavailable, but a regulator can manage an individual resource and thereby indirectly affect consumption across substitute resources. These policies are important in a number of contexts ranging from fisheries to recreation and transportation. For example, a fisheries manager who cannot implement an ITQ system to manage total fishing effort, but may influence the allocation of effort through fishermen relocation programs. Similarly, consider a park manager who cannot limit total usage with an access fee, but can influence visitation patterns across park sites, or a transportation planner who cannot limit total driving with a congestion toll but can adopt policies to increase the number of carpoolers.

We use the term "linked common-property resources" to describe substitute resources that are rival and non-excludable with heterogenous access costs and congestion externalities. Here, the term "linked" refers not to a physical connection, but to the fact users substitute across resources such that the congestion level of one resource influences congestion across the other resources. Congestion externalities are broadly defined to include any external costs arising from the intensity of use that affect the production or consumption costs of other users. Surprisingly, we find common property resources may be *over* or *under*-consumed in the decentralized equilibrium. In other words, a regulator may want to *increase* consumption of some common-property resources.

To illustrate the type of problem we study here, consider the example of recreation demand. Imagine two recreation sites, a nearby low access cost (LAC) site and a more distant high access cost site (HAC), which are otherwise identical. Because of the difference in access costs, the LAC site will be more heavily utilized than the HAC site. Further, imagine users of either site impose congestion costs on other users, for instance due to crowding. Given that users at both sites fail to account for the costs they impose on others, one may conclude that each site is *over*-consumed under open-access. This view, taken by much of literature in natural resource economics, implies a regulator should *discourage* consumption of both resources.[1]

On the other hand, because of the difference in access costs, the LAC site is more congested than the HAC site. As such, shifting users from the more congested LAC site to the less congested HAC site could lower total congestion costs. Intuitively, equating marginal external congestion costs across sites would minimize total congestion.[2] In this case, one would conclude the HAC resource is *under*-consumed and policy makers would want to *encourage* consumption.

How is it these competing viewpoints lead to such different policy recommendations? We show the correct policy prescription depends on the extent to which entry of new users from alternative outside options mitigates the benefits from reallocating users across resources. For instance, in the example above, users may also choose to stay at home instead of visiting either site. Reducing congestion could entice some who would have otherwise stayed home

[1] For an excellent review see Stavins (2011).

[2] Equating marginal costs minimizes total costs, and is analogous to the cost-effectiveness of pollution taxes and emissions permits in environmental economics (Baumol and Oates, 1988).

to visit one of the sites. In this case, the benefits of encouraging users to reallocate from the more congested to the less congested site would be eroded by entry from new users. We use the term "induced demand" to describe the entry of new users in response to lower congestion costs. Many resource models assume these entry effects are large.[3] If entry effects are large, there is little to no congestion benefit of reallocating users across resources and both sites are over-consumed. However, if there is little to no entry, the equimarginal principle implies the high access cost resource is under-consumed.

Here, we propose a consistent framework for evaluating the allocation of users across substitute common property resources with congestion, entry, and differences in access costs in the case where the social planner cannot limit entry. We begin by developing a simple analytical model consisting of two rival and non-excludable goods, a LAC resource and a HAC resource. Users also have uncongestible outside alternatives, and thus can elect to not consume either resource if congestion costs are too large. Reductions in congestion levels may therefore lead to entry via induced demand. We compare outcomes under competition, where users weigh access and congestion costs and independently choose which resource to consume, against the allocations of a constrained social planner.

Under these assumptions we derive the following results analytically and graphically. First, because higher access costs imply the HAC resource is less congested in the decentralized equilibrium, in the case of no induced demand the HAC resource is *under*-consumed. This is because there is a net "congestion relief" benefit if some users are shifted from the LAC to the less congested HAC resource. Second, in the case of full induced demand, the HAC resource is *over*-consumed as new entrants negate any congestion relief benefits for the LAC resource. Third, for intermediate levels of induced demand, the decentralized equilibrium may be identical to the constrained social optimum. Finally, we derive a simple expression that can be used to test whether HAC resources are over or under-consumed for a given level of induced demand depending on the equilibrium number of users and the

[3]For instance, Gordon (1954) assumes perfectly elastic entry from an outside alternative.

marginal congestion cost of each resource. The greater the difference in equilibrium usage levels, the more likely it is the HAC resource is under-consumed, providing a rationale for a regulator to increase HAC use.

We illustrate the implications of our analytical results with a simple numerical application. We adapt our model to a California fishery with thirteen distinct patches. The patches differ by growth rate and carrying capacity, factors that affect productivity. The distance between each patch and the nearest harbor creates differences in access costs across patches. Consistent with our analytical results, we show that for patches with higher access costs, the optimal policy would often increase consumption. Decreasing the magnitude of induced demand increases the likelihood high access cost patches are under-consumed.

Our analysis contributes to several literatures. The model is similar in spirit to the recent work by Fischer and Laxminarayan (2010) which considers price versus quantity instruments for managing common-property resources under uncertainty. In particular, they focus on cases where some resources are privately managed and some are open-access. Costello, Quérou, and Tomini (2015) similarly examine a partial enclosure of the commons, with an emphasis on spatial externalities and resource heterogeneity. In contrast to these papers, we focus on partial incentive-based management as opposed to partial privatization or enclosure. Further, we model differences in access costs, which drive differences in consumption and congestion levels across resources. We also incorporate induced demand effects, which we show to be crucial for calculating the social costs from changes in consumption. Our analytical model is most similar to Verhoef, Nijkamp, and Rietveld (1996) who study second-best highway pricing. However, by incorporating differences in access costs, we explicitly explain differences in congestion across substitute resources.[4] Further, we explore implications of a more general model with multiple common property resources.

The linked common-property problem appears to have implications in a broad and diverse set of markets. For example, grazing on public lands where both low-elevation (LAC) and

[4]Given that access costs across resources differ, consumption and marginal external congestion costs will vary across resources even in the special case where congestion cost functions are identical.

high-elevation (HAC) pastures exists, or in fisheries, where the proximity to shore or the harvest technology used create differences in access costs and congestion. In recreational demand, users may weigh congestion and travel costs when choosing between near (LAC) and distant (HAC) locations. In each of these examples, a regulator may pursue policies to shift some consumers from the LAC good to the HAC good. However if induced demand effects are large, the reduction in congestion may be eroded by new entrants. We explore potential applications of our model in more detail following our analytical and simulation results.

2 Analytical model of linked common-property resources

We define a "linked common-property resource" as a good with the following characteristics. Consumption is rival and non-excludable, such that congestion arising from the intensity of use raises a user's cost of consumption and serves to ration demand. There exists one or more substitute goods with similar characteristics but different access costs. As noted in the introduction, resources may be spatially distinct where, for example, access costs represent different travel costs depending on distance. Changes in the level of consumption of one of these substitute goods affects congestion, and in turn consumption and congestion levels of the other goods in equilibrium, forming a *link* between the costs of consuming each good. A reduction in the level of congestion may entice users who had previously consumed none of these goods to enter the market via an "induced demand" effect. Finally, we assume policy makers cannot limit total consumption but can influence the allocation across substitute resources. This assumption reflects the political realities in many common-property markets where there may be public resistance to "closing the commons."[5]

To illustrate the properties of these goods, we begin by building a simple analytical model

[5] Public opposition to access fees, in particular, is quite common. Recent examples include user fees for highways (McFadden, 2016; Whaley, 2015), beaches (Hewitt, 2015; Meagher, 2012; Moore, 2012) and recreation on Federal public lands (Burns, 2004).

that highlights the essential features of the linked common property resource problem.[6] More formally, we consider $\bar{N}$ total cost-minimizing users. Users make discrete choices, selecting between a HAC good and a LAC good, where n_h is the number of HAC users and n_l is the number of LAC users. Because both goods are congestible, users may also choose to not consumer either good, and instead pursue some uncongestible alternative outside option, where n_a is the number of outside option users. The outside option captures users' next best alternative to consuming the common property goods. For example, an alternate leisure activity that offers an equivalent recreation benefit. Everyone must be allocated, such that $\bar{N} - n_h - n_l - n_a = 0$. Finally, because users of the common-property resources and alternative option receive the same benefit from consumption, cost minimization implies utility maximization.

Users who choose the LAC good face only the congestion cost of use, given by $T_l(n_l)$. Users who choose the HAC good face both a congestion cost of use $T_h(n_h)$ as well as an access cost $\tau(n_h)$.[7] Users who choose the outside option face heterogenous costs given by $A(n_a)$. The function $A(n_a)$ is an ordering of users from lowest to highest outside option costs. Because the alternative outside option is uncongestible, each user pays her cost (*i.e* there are no inframarginal users). Thus, the outside option user with the lowest cost pays $A(0)$ and the highest cost user faces a cost $A(n_a)$. As a result, changes in n_a generate no rents for users of the alternative option.[8] Similarly, access costs $\tau(n_h)$ may also vary by user. Ordering subsequent users based on their access costs generates the function $\tau(n_h)$, whereby each user pays their individual cost. Finally, congestion cost functions are assumed to be increasing and strictly convex.

[6]Section 4.1 develops a model variant that recasts our model in a production framework where congestion affects users' productivity instead of costs.

[7]If both goods are costly to access, this can represent the difference in access costs between the HAC and LAC goods. Further, the resources could be spatially distinct areas indexed by i as in our application. Here, we focus on two resources and drop the i subscript for ease of notation.

[8]Because the HAC resource is congestible, HAC users with low access costs do receive some rents, which are accounted for in our analysis below.

2.1 Decentralized equilibrium

We begin by analyzing a decentralized equilibrium, where users minimize costs by sorting across their three options (LAC, HAC, alternative option).[9] In the decentralized equilibrium, no user can improve their welfare by choosing another option, *i.e.* users achieve a Nash Equilibrium, such that:

$$
\begin{aligned}
T_l(n_l) - T_h(n_h) &= \tau(n_h) \qquad (1)\\
T_l(n_l) &= A(n_a)\\
\bar{N} &= n_h + n_l + n_a.
\end{aligned}
$$

The first condition says that the marginal user equates the private benefit of using the HAC good (congestion savings) with the private cost of the HAC good (the access cost). The second condition describes entry from the outside option. It requires the marginal user of the LAC good be indifferent between the congestion cost in the LAC and the cost of the outside option. In other words, users will consume the LAC good until the congestion cost equals the cost of the next best alternative.

2.2 Constrained social planner

Next, we consider the allocation of users by a cost-minimizing social planner. We use the term "constrained social planner" to denote the fact the planner cannot limit total consumption of the resources. The constrained social planner chooses n_h, n_l, n_a to minimize total costs, subject to the constraints that all users must be allocated, and the fact that congestion relief for the LAC good will induce users from the outside option until congestion costs in the LAC

[9] Given our interest in substitution and entry, we focus on interior solutions. However, corner solutions where the set of users of a particular resource is empty are possible. For instance, if access costs τ are prohibitively large, we would find no users of the HAC resource.

are equal to the cost of the outside option:

$$\min_{n_h, n_l, n_a} \quad T_h(n_h)n_h + \int_0^{n_h} \tau(n)dn + T_l(n_l)n_l + \int_0^{n_a} A(n)dn \tag{2}$$

$$s.t. \quad \bar{N} - n_h - n_l - n_a = 0$$

$$T_l(n_l) = A(n_a)$$

with the corresponding Lagrangian:

$$\begin{aligned} T_h(n_h)n_h + \int_0^{n_h} \tau(n)dn + T_l(n_l)n_l + \int_0^{n_a} A(n)dn \\ + \lambda_1(\bar{N} - n_h - n_l - n_a) + \lambda_2(T_l(n_l) - A(n_a)) \end{aligned} \tag{3}$$

and first-order conditions:

$$T_h + n_h T_h' + \tau - \lambda_1 = 0 \tag{4}$$

$$T_l + n_l T_l' - \lambda_1 + \lambda_2 T_l' = 0 \tag{5}$$

$$A - \lambda_1 - \lambda_2 A' = 0, \tag{6}$$

which define the constrained socially optimal allocation of users n_h, n_l, and n_a across the three options.[10,11] The arguments in (4)-(6) are suppressed for simplicity.

With some iterative substitution, the first FOC can be written as:

$$T_l - T_h = \tau + n_h T_h' - n_l T_l' \frac{A'}{A' + T_l'} \tag{7}$$

which states the marginal private benefit of an additional HAC user equals the marginal

[10]This allocation satisfies the second-order sufficient conditions for a local constrained minimization.

[11]For the purposes of comparison, the FOC's for the first-best (unconstrained) social planner's problem can be written as $T_l + n_l T_l' = T_h + n_h T_h' + \tau = A$, which yields the familiar result that the first-best consumption of each resource should reflect the marginal external costs, here $n_l T_l'$ and $n_h T_h'$. The key difference in our setting comes from the fact the constrained social planner is unable to restrict entry, and thus must be mindful of induced demand when allocating users to the HAC resource.

private cost plus the marginal net external cost.[12] Alternatively, Equation 7 can be written as:

$$T_l + n_l T_l' \frac{A'}{A' + T_l'} = T_h + \tau + n_h T_h' \tag{8}$$

which makes it clear that the constrained social optimum equilibrates marginal social costs across the resources.

The term $\frac{A'}{A'+T_l'}$ represents the effect of induced demand on the marginal external cost for the LAC good. If $A' = \infty$, this represents a case of no induced demand (vertical supply curve for users of the outside option), and in the limit $\frac{A'}{A'+T_l'} = 1$. Similarly, if $A' = 0$, this represents a case of full induced demand (horizontal supply curve for users of the outside option), and $\frac{A'}{A'+T_l'} = 0$. To simplify exposition, let $\alpha = 1 - \frac{A'}{A'+T_l'}$ where $\alpha = 0$ represents no induced demand and $\alpha = 1$ represents full induced demand. In addition to simplifying exposition, the induced demand term α has an intuitive economic interpretation. For each additional user allocated to the HAC resource, α users enter the LAC from the alternative outside option. With this notation the above constrained social planner's FOC can then be written as:

$$T_l - T_h = \tau + n_h T_h' - n_l T_l'(1 - \alpha) \tag{9}$$

Ultimately we are interested in comparing the distribution of users under the decentralized equilibrium with that under the constrained social planner. Comparing the decentralized equilibrium equation $T_h - T_l = \tau$ with the constrained social planner's condition in Equation 9, we see the last two terms of (9) drive a wedge between the decentralized equilibrium and the constrained social planner's solution. The first term reflects the costs an additional HAC user imposes on all other HAC users by increasing congestion. The second term reflects the benefits an additional HAC user creates for the LAC users by relieving congestion, taking

[12] Alternatively, one could frame the constrained social planner's problem in terms of the costs and benefits of resource consumption where demand, $D(n_l + n_h)$, takes the place of the outside option. The constrained social planner maximizes total benefits of consumption net of congestion and access costs subject to the constraint the marginal user's benefits of consumption equal her costs. In that case, the optimal allocation of users is simply $T_l - T_h = \tau + n_h T_h' - n_l T_l' \frac{D_N'}{D_N' - T_l'}$. While this framing is equivalent to our setup, we adopt the outside option framework in order to more clearly emphasize the important role of entry.

into account induced demand. Together, the terms are the marginal net external costs of increasing HAC use:

$$n_h T_h' - n_l T_l'(1-\alpha) \tag{10}$$

Because users do not internalize either the external congestion costs or benefits, then intuitively the question of whether or not the constrained social planner would want to increase or decrease HAC good use hinges on whether the external costs to HAC users are larger or smaller than the external benefits to LAC users.

3 Analysis and results

We now formally compare the allocation of users in the decentralized equilibrium with the allocation selected by the constrained social planner. We focus on the role of access costs and entry of new users via induced demand in determining the efficiency of the decentralized allocation.

3.1 Comparison of decentralized equilibrium with constrained social planner

We begin by constructing a simple example where the total number of users of the two goods is fixed and access costs are equal. Then, we investigate more realistic cases where access costs differ across resources and entry occurs from the outside option via induced demand. Throughout, we assume the congestion cost functions for each good are identical functions of the number of *users*, such that if $n_h = n_l$, then $T_h(n_h) = T_l(n_l)$.[13] While the symmetry assumption simplifies the proofs of Propositions 1, 2 and 4 below, the intuition developed here also applies when functions are similar but not symmetric.

Proposition 1. *If access costs are equal, such that* $\tau(n_h) = 0 \quad \forall n_h$ *and the number of*

[13]In our numerical example, the number of users is readily extended to the amount of fishing effort.

users of the two common-property resources is fixed, such that $\alpha = 0$, then the decentralized equilibrium is equivalent to the allocation of the constrained social planner.

Proof. If $\tau(n_h) = 0$, the decentralized equilibrium requires $T_h = T_l$. For symmetric cost functions this means $n_h = n_l$, and therefore $T_h' = T_l'$. Since $\alpha = 0$, the marginal net external costs are given by $n_h T_h' - n_l T_l'$, which equals zero. Finally, comparing Equation 1 against Equation 9, the allocation of users in the decentralized equilibrium will equal the constrained social optimum when the marginal net external costs are equal to zero. □

The intuition is that if access costs are the same, congestion costs and thus the numbers of users are equilibrated. Therefore, the congestion cost of an additional user of the HAC good exactly balances the congestion relief benefit for the LAC good. As such, there is no need to increase or decrease HAC use relative to the decentralized equilibrium allocation. Moreover, the decentralized allocation is also first-best, as it is equivalent to that chosen by an (unconstrained) social planner. While this is a useful starting point for analysis, it assumes away any difference in access costs. Including differences in access costs will drive a wedge between congestion costs for the two goods, which leads to our second proposition.

Proposition 2. *If access costs differ such that $\tau(n_h) > 0$ and if there is no entry via induced demand, $\alpha = 0$, then the HAC good is under-consumed in the decentralized equilibrium.*

Proof. The decentralized equilibrium requires $T_h + \tau = T_l$, which by symmetry requires that $n_h < n_l$, and therefore $T_h' < T_l'$. If $\alpha = 0$, the marginal net external costs are $n_h T_h' - n_l T_l' < 0$. Thus, the marginal external benefits to LAC users exceed the marginal external costs to HAC good users. Finally, comparing Equation 1 against Equation 9, the constrained social planner would increase the number of HAC users relative to the decentralized equilibrium. □

In this case, potential users of the HAC good do not internalize the fact that the congestion relief they will provide to the LAC users is larger than the congestion cost they would impose on existing HAC users, leading to too few HAC users in the decentralized equilibrium. Policies that move users from the more congested LAC good to the less congested HAC good would increase welfare, assuming the number of resource users is fixed (no induced demand from the outside option).[14]

The assumption that the number of resource users is fixed is one extreme case. At the other extreme, induced demand may be near 1; that is, for every user leaving the LAC good, another user will ultimately replace her.[15] This leads to our third proposition, considering the efficiency of HAC use under full induced demand.

Proposition 3. *If $\alpha = 1$ such that there is full induced demand, then the HAC good is over-consumed in the decentralized equilibrium.*

Proof. If $\alpha = 1$, the marginal net external costs are simply $n_h T_h' > 0$. Comparing 1 against 9, the constrained social planner would decrease the number of HAC users relative to the decentralized equilibrium. □

The intuition for this proof is that with full induced demand, additional HAC users provide no congestion relief for the LAC good. Furthermore, HAC users do not internalize the congestion cost they impose on other HAC users, leading to too many HAC users in the decentralized equilibrium. In this case, policies to increase HAC use would reduce welfare, as the HAC good is over-consumed, despite the lower level of congestion relative to the LAC good. Note that Proposition 3 holds even when congestion cost functions are not symmetric as full induced demand always increases HAC costs without reducing costs for LAC users.

In many cases, induced demand likely falls somewhere between the extremes of no induced demand ($\alpha = 0$) and full induced demand ($\alpha = 1$).[16] This leads to our fourth proposition.

[14]Here we focus on the effects that come from moving the marginal LAC user to the HAC resource. We note that moving the marginal user from the LAC to HAC resource imposes a real resource cost τ on the user. However, given the decentralized equilibrium, that user is exactly compensated by the difference in congestion cost $(T_l - T_h)$. In Section 3.3, we explicitly consider how a policy could achieve such a reallocation.

[15]This is a common assumption in resource models that consider open access issues (e.g. Kaffine (2009) and Costello, Quérou, and Tomini (2015)).

[16]Section 3.2 provides graphical intuition for the relationship between the alternative option cost function and induced demand α. Thus, we can think of changes in α as arising from changes in the outside option cost function (*e.g.* steeper or flatter slope).

Proposition 4. *There exists a critical level of induced demand $0 < \alpha^\star < 1$ such that the decentralized equilibrium is equivalent to the constrained social optimum.*

Proof. From Equation 9, marginal net external costs will be zero when $\frac{n_h T_h'}{n_l T_l'} = (1 - \alpha^\star)$ for some $\alpha^\star$. By the decentralized equilibrium condition in Equation 1, $n_h T_h' < n_l T_l'$, and thus $(1 - \alpha^\star)$ and therefore $\alpha^\star$ is bounded between zero and one. □

At the critical level of induced demand $\alpha^\star$, the marginal external costs imposed on HAC users in the decentralized equilibrium are exactly equal to the marginal external benefits provided to LAC users. Thus, at this critical level of induced demand, the decentralized equilibrium is equivalent to the constrained social planner's allocation despite the fact that users fail to internalize their congestion externalities in the decentralized equilibrium.[17] Two corollaries follow from Proposition 4.

Corollary 1. *For levels of induced demand below the critical level $\alpha < \alpha^\star$, the HAC good is under-consumed. For levels of induced demand above the critical level $\alpha > \alpha^\star$, the HAC good is over-consumed.*

Proof. The proof follows intuitively from Proposition 4. If $\alpha < \alpha^\star$, then marginal external costs are less than net marginal external benefits ($n_h T_h' - n_l T_l'(1 - \alpha) < 0$) and the HAC good is under-consumed. If $\alpha > \alpha^\star$, then net marginal external costs are $n_h T_h' - n_l T_l'(1 - \alpha) > 0$ and the HAC good is over-consumed. □

Corollary 1 provides a useful criterion for determining whether the HAC resource is over or under-consumed for intermediate values of induced demand $0 < \alpha < 1$. If the equilibrium usage levels (n_h and n_l) and marginal congestion costs (T_h' and T_l') can be determined, one can simply compare the critical level of induced demand $\alpha^\star$ with the actual level of

[17]Recall that we have assumed that changes in the number of outside users do not generate any rents in the outside option. This strikes us as a reasonable assumption in many settings. However, one may wonder how our results might change in other contexts if rents are generated in the outside option. For the extreme cases of induced demand, Propositions 2 and 3 hold exactly. However, for intermediate levels of induced demand, as in Proposition 4, the additional rents in the outside option will increase the likelihood that the HAC good is under consumed for a given α, effectively increasing $\alpha^\star$.

induced demand α. Note that because τ influences the equilibrium usage levels (n_h and n_l), determining $\alpha^\star$ does not require knowledge of τ, which may be difficult to measure in practice. However, this is not to say τ has no impact on the critical level of induced demand, as the following corollary demonstrates.

Corollary 2. *Let $\tau^\star$ be the level of access cost at the decentralized equilibrium. The critical level of induced demand is increasing in access cost τ, $\frac{\partial \alpha^\star}{\partial \tau^\star} > 0$.*

Proof. From the decentralized equilibrium condition 1, $\frac{\partial n_l}{\partial \tau} > 0$ and $\frac{\partial n_h}{\partial \tau} < 0$. From Proposition 4, the critical level $\alpha^\star$ satisfies $n_h T_h' - (1-\alpha^\star) n_l T_l' = 0$. By the implicit function theorem, $\frac{\partial \alpha^\star}{\partial \tau^\star} = -\frac{\frac{\partial n_h}{\partial \tau^\star}(T_h' + n_h T_h'') - (1-\alpha)\frac{\partial n_l}{\partial \tau^\star}(T_l' + n_l T_l'')}{n_l T_l'} > 0$ $\square$

The implication of Corollary 2 is that the greater the difference in access costs between the different resources, the more likely it is the HAC good is under-consumed for a given level of induced demand. In other words, more induced demand is required before the costs of entry outweigh the benefits of reallocating users from the high congestion LAC good to the low congestion HAC good. By contrast, if the difference in access costs is small, then even a small amount of induced demand may outweigh the benefits of reallocating users.

In the previous results, the only externality created by decentralized consumption decisions arose from changes in congestion levels. In many contexts however, users may generate additional use-externalities. For example, loss of existence value from overconsumption of fisheries or forests, or air pollution from vehicles. If E represents an additional external cost-per-user, then $E \times (n_h + n_l)$ represents the additional external costs. In this case, it is easy to show that:

$$T_l - T_h = \tau + n_h T_h' - n_l T_l'(1-\alpha) + \alpha E \tag{11}$$

Because the total number of users is increasing in HAC use for any positive α, the critical level of induced demand identified in Proposition 4 will decrease (increase) as external user costs (benefits) increase.[18]

[18]Specifically, $\alpha^\star = \frac{n_l T_l' - n_h T_h'}{n_l T_l' + E}$ such that $\alpha^\star$ is decreasing in the external cost per user E.

3.2 Graphical illustration of the analytical model

Much of the intuition behind our analytical results can be obtained from the graphical illustration of our model in Figure 1. As before, if congestion costs are symmetric, then the presence of access costs $\tau > 0$ means the LAC is more heavily consumed. Therefore, the marginal private benefit (MPB) of HAC consumption is the reduction in congestion cost relative to the more congested LAC resource, $T(n_l) - T(n_h)$, as shown in Panel a. In the decentralized equilibrium, the marginal consumer sets $T(n_l) - T(n_h) = \tau$ resulting in consumption level $n_{h,D.E.}$. Because the constrained social planner considers the external costs imposed on other users, the optimal level of consumption may be larger or smaller than $n_{h,D.E.}$. The HAC resource is *over-consumed* in equilibrium if marginal social cost (MSC) is greater than marginal private cost (MPC) and $n^*_{h,1} < n_{h,D.E.}$. The HAC resource is *under-consumed* in equilibrium if $n^*_{h,2} > n_{h,D.E.}$. Intuitively, whether MSC is higher or lower than MPC depends on whether congestion relief in the LAC resource outweighs additional congestion from increased consumption of the HAC resource.

Figure 1 Panel b, illustrates the relationships between the alternative option, the LAC good and induced demand. Congestion costs for the LAC good and costs for the alternative option are shown as $T(n_l)$ and $A(n_a)$, respectively. The total resource supply is the horizontal sum of $T(n_l)$ and $A(n_a)$.[19] Since all users are allocated, the sum of outside option and LAC consumption is $D_1 = \bar{N} - n_h$ with corresponding cost P_1 and consumption levels $n_{l,1}$ and $n_{a,1}$. Shifting ϵ_h consumers to the HAC resource lowers costs from P_1 to P_2 and results in consumption levels $n_{l,2}$ and $n_{a,2}$. Increasing HAC consumption lowers LAC congestion and reduces the number of consumers who choose the alternative outside option. Here, there is induced demand since $n_{l,1} - n_{l,2} < \epsilon_h$. Moreover, note that if $A(n_a)$ is perfectly elastic, ϵ_h leave the alternative option and there is full induced demand. However If $A(n_a)$ is perfectly inelastic, ϵ_h consumers to leave the LAC resource and induced demand is zero.

[19]Note that the slope of $T(n_l + n_a)$ defines the induced demand effect. For example, in the case where $T(c_l)$ and $A(c_a)$ are simple linear functions, it is straightforward to show that the slope of $T(n_l + n_a)$ is $T'_l \frac{A'}{A' + T'_l} = T'_l(1 - \alpha)$.

3.3 Policy interventions

Here, we consider policy interventions in the setting where price and quantity instruments to limit total consumption are unavailable. Recall from Section 3.1, a regulator may want to increase consumption of some common property resources depending on the relative levels of congestion and induced demand effects. These policy interventions are readily incorporated into the framework developed above.

Consider a regulator who enacts a policy that provides an incentive θ to encourage HAC use, such that the decentralized equilibrium in Equation 1 becomes $T_l = T_h + \tau - \theta$. This incentive could represent a variety of potential pecuniary or non-pecuniary policies that influence how users choose amongst resources. For example, providing preferential parking for carpoolers, improving the road to more distant campsites or subsidizing fuel cost for users of more distant fishing grounds. Users will respond to these incentives by reallocating consumption across the HAC and LAC goods and the alternative option. The incentive θ decentralizes the constrained social optimum since like the constrained social planner, the regulator can only influence the allocation of users across resources and cannot limit total consumption.

Taking the total derivatives of the decentralized equilibrium conditions and substituting, we can express the effect of a change in the incentive θ on consumption of each good and the alternative option as:

$$\frac{dn_h}{d\theta} = \frac{1}{T_h' + \tau' + T_l'(1-\alpha)} \tag{12}$$

$$\frac{dn_l}{d\theta} = -\frac{(1-\alpha)}{T_h' + \tau' + T_l'(1-\alpha)} \tag{13}$$

$$\frac{dn_a}{d\theta} = -\frac{\alpha}{T_h' + \tau' + T_l'(1-\alpha)}. \tag{14}$$

Note that if there is no induced demand ($\alpha = 0$), $\frac{dn_h}{d\theta} = -\frac{dn_l}{d\theta}$ such that increased HAC consumption leads to an equal decrease in LAC consumption. However, if there is full induced demand ($\alpha = 1$), increasing θ has no effect on LAC consumption as every new

HAC user is replaced by a new entrant from the alternative option, $\frac{dn_h}{d\theta} = -\frac{dn_a}{d\theta}$. Further, neither the above nor the derivations that follow require $T_h(n_h) = T_l(n_l)$ when $n_h = n_l$, *i.e.* symmetry of the congestion cost functions is not necessary.

Faced with the problem of how best to allocate users across resources, the regulator can consider the optimal θ that minimizes total costs (C).[20] Differentiating (2) with respect to θ yields:

$$\frac{dC}{d\theta} = (T_h + n_h T_h')\frac{dn_h}{d\theta} + \tau\frac{dn_h}{d\theta} + (T_l + n_l T_l')\frac{dn_l}{d\theta} + A\frac{dn_a}{d\theta}. \tag{15}$$

Substituting (12), (13) and (14) from above into (15) we obtain an expression for the optimal θ^* that decentralizes the constrained social optimum:

$$\theta^* = -[n_h T_h' - n_l T_l'(1-\alpha)] \tag{16}$$

Intuitively, θ^* can be thought of as equivalent to the subsidy (tax) on HAC use that achieves the constrained social optimum, if such a pricing instrument were available. Thus, it depends on congestion costs in the HAC and LAC goods, accounting for the effects of induced demand α.[21] Notice the term in brackets on righthand side of Equation 16 is the marginal net external cost of congestion, Equation 10, as discussed in Propositions 1 through 4.

Further examination of Equation 16 yields several interesting comparative statics. Specifically, $\frac{\partial\theta^*}{\partial\alpha} < 0$, $\frac{\partial\theta^*}{\partial T_h'} < 0$ and $\frac{\partial\theta^*}{\partial T_l'} > 0$. The first condition comes from the fact that greater induced demand leads to less congestion relief when LAC users are shifted to the HAC resource. The second and third conditions reflect how the steepness of the congestion cost functions affect the marginal net external costs. For instance, a relatively steeper LAC congestion cost function increases the net benefits of reallocating users from the LAC to the HAC resource, implying a larger optimal incentive. In general, Equation 16 describes the

[20]For simplicity, we assume the cost of providing the incentive θ is exactly equal to the direct benefit to HAC users, such that they disappear from the total cost expression.

[21]For comparison, an unconstrained regulator could decentralize the first-best with $\theta^*_{FB} = \{-n_l T_l, -n_h T_h\}$ for the LAC and HAC resources, *i.e.* the familiar Pigouvian prescription.

optimal incentive or disincentive for HAC good consumption when the regulator is unable to limit total consumption.

4 A model variant and application

The analysis in the preceding sections shows linked common property resources can be over or under-consumed depending on congestion costs and entry of new users from the outside option. Furthermore, even in the case where total consumption cannot be limited, a regulator can improve upon the decentralized allocation by offering an appropriate incentive that changes the allocation of users across resources. While the preceding analysis illustrates the economic forces at work in the linked common property setting, here we show how the model in Section 2 can be adapted to more complex settings. To do this we introduce a "model variant" tailored to the features of a specific resource problem. In particular, we consider the allocation of fishing effort across a fishery that consists of many different fishery resources or "patches."

While economists have long argued for first-best price or quantity-based instruments to remedy over-exploitation in fisheries, these approaches remain relatively rare. For example, Costello, Gaines, and Lynham (2008) study 11,135 commercial fisheries and find only 121 use some sort of individual transferable quota (ITQ) to limit total consumption. In light of this, regulators may be able to improve welfare by reallocating fishing effort across patches.

The fishery example has much in common with the analytical model, as well as some important differences. In terms of similarities, fishermen are making discrete choices regarding the allocation of effort (use) across patches and these choices are influenced by the total amount of effort allocated to individual patches (i.e. they are common property resources). Fishermen also have outside options, namely non-fishing wages, such that fishermen can enter or exit the fishery. The patches also vary in distance from the nearest harbor, which creates differences in access costs.[22] However, there are some important differences that need

[22]For example, increased fuel or labor costs spent traveling to more distant patches. If fishermen consider

to be considered when adapting our model to this specific context. First, in the analytical model, users face a common benefit across their choices and thus decide which choice minimizes their costs. Here, fishermen face a common cost (a day's effort), but the returns from that effort (fishing earnings or wage earnings) vary across choices. Second, the fishery in our application below contains thirteen distinct patches rather than two as in our analytical model, as shown in Figure 2.

4.1 Model variant - fisheries

To see more clearly how our model can be adapted to the fishery example, first consider the production relationship. Fishermen create production externalities for other users as productivity, or catch per unit of effort, depends on the total fish stock. Intuitively, when one fisherman increases fishing effort, this decreases the stock and lowers productivity for other fishermen.[23] Thus, the returns from allocating effort in any particular patch is downward-sloping in total effort in that patch. The magnitude of this effect depends on oceanographic and biological parameters such as the growth rate and carrying capacity, which vary across patches. Depending on the returns from fishing effort, fishermen may also choose to allocate their effort to the non-fishing sector (outside option), where wages may vary across fishermen.

To draw clear parallels with our previous model, we begin with a fishery consisting of only two patches and an outside option whereby a fixed amount of effort $\bar{E}$ is applied across a HAC resource, a LAC resource and an outside option. For example, the LAC resource and HAC resource could represent near and distant fishing patches. In this context, the outside option can be thought of as non-fishing wages. All effort is allocated such that $\bar{E} - E_h - E_l - E_w$, where E_h, E_l and E_w are effort applied to the HAC, LAC and outside option. Adopting standard fisheries notation, total earnings in patch i equal $pH_i = pqX_i(E_i)E_i$, where H_i is harvest in patch i, q is the catchability coefficient (subsequently normalized to one), $X_i(E_i)$

these access costs in deciding where to fish, we expect closer locations to be more heavily used and therefore less productive, all else equal.

[23]Fishing "effort" refers to the intensity of fishing activity. For instance, the number of fishermen in a patch, the number of boat days spent fishing or the level of investment in equipment.

is the population or stock with $X_i' < 0$, and p is the (constant) price of harvest. As before, users of the HAC resource face heterogenous access costs $\tau(E_h)$, such that the return on effort in the HAC resource is given by $pX_h(E_h) - \tau(E_h)$ while the return on effort in the LAC resource is given by $pX_l(E_l)$. Finally, users of the alternative outside option earn a return from heterogenous wages $W(E_w)$ with $W' \leq 0$.

In the decentralized equilibrium, fishermen compare earnings from a day's effort across patches and the outside option. Users sort across the three options until no user can improve her earnings by allocating their effort to another option, such that:

$$
\begin{aligned}
pX_h(E_h) - pX_l(E_l) &= \tau(E_h) \\
pX_l(E_l) &= W(E_w) \\
\bar{E} &= E_h + E_l + E_w.
\end{aligned}
\tag{17}
$$

Next, consider the allocation of effort by a constrained social planner who cannot limit total entry into the fishery from the outside (wage) option. The constrained social planner chooses E_h, E_l and E_w to maximize total earnings, subject to the constraints that all effort is allocated and that earnings in the low access cost resource equals the wage in the non-fishing outside option, *i.e.* due to entry. The Lagrangian for this problem is given by:

$$
\begin{aligned}
pX_l(E_l)E_l + pX_h(E_h)E_h - \int_0^{E_h} \tau(E)dE + \int_0^{E_w} W(E)dE \\
+\lambda_1(\bar{E} - E_h - E_l - E_w) + \lambda_2(pX_l(E_l) - W(E_w))
\end{aligned}
\tag{18}
$$

and first-order conditions:

$$pX_h + pX_h'E_h - \tau - \lambda_1 = 0 \tag{19}$$

$$pX_l + pX_l'E_l - \lambda_1 + \lambda_2 pX_l' = 0 \tag{20}$$

$$W - \lambda_1 - \lambda_2 W' = 0, \tag{21}$$

where the arguments in (19)-(21) are suppressed for simplicity.[24] With some iterative substitution, the first FOC can be written as:

$$pX_h(E_h) - pX_l(E_l) = \tau - pX_h'(E_h)E_h + pX_l'(E_l)E_l \frac{W'(E_w)}{W'(E_w) + pX_l'(E_l)} \tag{22}$$

Equation 22 is the production analog to Equation 7 in Section 2. Note that positive access costs imply productivity and earnings are relatively higher in the HAC resource compared with the LAC resource. Increasing HAC consumption lowers productivity in the HAC by $pX_h'(E_h)E_h$ but increases earnings in the LAC resource by $pX_l'(E_l)E_l \frac{W'(E_w)}{W'(E_w)+pX_l'(E_l)}$. As before, the final term captures entry from the non-fishing outside option such that the total effect on fishing earnings depends on the level of induced demand. In this production framework, the earnings and externality terms are the negative analogs of the congestion cost relationships in Section 2. Otherwise, the insights developed in the preceding sections are identical in a production setting.

A final issue in adapting our model relates to the fact the fishery application consists of many distinct patches. In Appendix A, the two resource model above is extended to multiple resources in order to illustrate how to accommodate a multi-patch fishery. From an examination of the first-order conditions, it turns out that the intuitions developed above also apply to the case of multiple resources; however, analytical solutions are intractable due to the complicated changes in productivity that arise from re-sorting effort across resources and entry from the outside option. Given this complexity, we turn to numerical methods to examine the effects of policies to reallocate effort across the fishery.

4.2 Numerical example: Southern Californian fishery

We apply the model variant in the previous section to a California fishery consisting of thirteen distinct patches. The patches, indexed by j, vary by biological factors that affect

[24] Similar to footnote 11, the FOC's of the first-best (unconstrained) solution for this model variant can be written as $pX_l + pX_l'E_l = pX_h + pX_h'E_h - \tau = W$.

productivity and by distance from the nearest port (access cost τ_j). We consider how policies, such as those in Section 3.3, can improve upon the decentralized equilibrium. The term θ_i corresponds to the incentives considered in Section 3.3 for a particular patch i, whereby a regulator can influence the allocation of effort across resources as a means of improving total earnings. Specifically, we consider cases where $\theta_i \neq 0$ for some patch i, but where $\theta_j = 0 \ \forall j \neq i$. In other words, effort in one particular patch receives a subsidy while all other patches are unsubsidized (though earnings in other patches may be affected via reallocation of effort).[25]

From the decentralized equilibrium conditions (17) and given $\theta_i \neq 0$ for patch i, effort enters each patch and will be distributed across resources such that no user of patch j could improve her earnings by substituting to any other patch or by choosing the outside (wage) option such that:

$$
\begin{aligned}
pX_i(E_i) - pX_j(E_j) &= (\tau_i - \theta_i) - \tau_j \quad \forall j \neq i, \\
pX_j(E_j) - \tau_j &= W(E_w) \quad \forall j \neq i, \\
\bar{E} &= \sum_j E_j + E_w,
\end{aligned}
\tag{23}
$$

or noting that $\theta_j = 0 \ \forall j \neq i$, more simply:

$$
pX_j(E_j) - W(E_w) - (\tau_j - \theta_j) = 0 \quad \forall j. \tag{24}
$$

For a given incentive θ_i applied to patch i, one can then determine total earnings, given by the sum of returns to fishing across all patches plus wages earned in the non-fishing outside option. The optimal θ_i maximizes total earnings and can be positive or negative depending on whether the regulator wishes to encourage or discourage effort in patch i.

[25] While we focus on the constrained social optimum for a single patch, the model can readily be solved for the case where the regulator instead jointly incentivizes several resources. While such cases do not provide much additional insight beyond what is presented here, of course the more instruments available to the regulator, the closer the constrained social optimum is to first-best.

We adopt functional forms and parameterize the model above with values from Costello, Quérou, and Tomini (2015). While Costello, Quérou, and Tomini (2015) allow for between-patch dispersal, to be consistent with the analytical model, we assume zero between-patch dispersal. We assume logistic growth, such that the steady-state fish stock in patch j, X_j depends on carrying capacity K_j, the intrinsic growth rate r_j and total fishing effort E_j according to: $X_j(E_j) = K_j(1 - \frac{E_j}{r_j})$. Access costs τ_j vary linearly with the distance between the patch and the nearest harbor, Santa Barbara. We model the outside option as follows. Wages are assumed to be linearly downward sloping in E_w such that $W(E_w) = w_0 - a_1 E_w$. Denoting total fishing effort E_f as the sum of fishing effort across all patches ($E_f = \sum_j E_j$), then $W(E_w) = w_0 - a_1(\bar{E} - E_f) = w_0 + w_1 E_f$, yielding an upward sloping wage curve in terms of total fishing effort.[26] Substituting these functional forms and parameterizations into Equation 24 yields the following equilibrium equation as a function of the incentive θ_i, which we take to our numerical simulation:

$$pK_j(1 - \frac{E_j}{r_j}) - (w_0 + w_1 E_f) - (\tau_j - \theta_j) = 0 \quad \forall j. \tag{25}$$

The numerical algorithm is as follows: For a given patch i, the optimal θ_i^* that maximizes total earnings is calculated. This procedure is repeated for a given patch but with different levels of induced demand via varying the slope of the wage curve, w_1. We then move on to the next patch and repeat the above procedures for determining θ_i^* in new patch i for varying levels of induced demand. Figure 3 shows optimal policies θ_i^* across the thirteen patches as a function of induced demand. Darker shaded areas indicate cases where the optimal policy is to discourage effort in a particular patch, while lighter shaded areas indicate cases where effort should be encouraged in that patch. The patches are sorted by access cost from low to high along the y-axis. Consistent with our analytical model, the optimal policy tends

[26]The intuition is straightforward - fishermen with poor outside options (low wages) will enter the fishery first, with increasingly higher returns from fishing required to coax higher wage fishermen out of their outside option. A flat slope parameter (w_1) indicates a flat wage profile, while a steep slope parameter implies greater heterogeneity in outside options for fishermen. Thus, increasing the slope of the wage curve w_1 will effectively decrease induced demand/entry.

to encourage effort in high access cost patches and to discourage effort in low access cost patches. Similarly, encouraging effort in a particular patch is more likely to increase total earnings when induced demand is low relative to when induced demand effects are large. Based on our parameterization, the regulator would want to increase effort in the two most distant patches, twelve and thirteen, for moderate levels of induced demand.

Our application has two notable exceptions to the trends above. In our example, patches six and seven are always over-consumed (the darkest lines in Figure 3). Both patches have high carrying capacity (K) and growth (r) parameters, but near-average access costs (see Figure 2). Intuitively, these are very high productivity patches and most likely to have relatively high consumption levels and congestion externalities. Nonetheless, the optimal policy in these patches does respond to entry concerns, as effort is discouraged less for lower levels of induced demand. More formally, we investigate the relationships between optimal fishery policies and patch characteristics by regressing the values in Figure 3 on growth rate, carrying capacity, access costs and the slope of the wage curve. Patches are more likely over-consumed (should discourage effort) when growth rate, carrying capacity and induced demand are large. They are more likely under-consumed (should encourage effort) when access costs are large.[27]

Finally, we consider the differences between the constrained social optimum and the unconstrained first-best. Table 1 presents simulation results for various slopes of the wage curve, where $w_1 = 0$ implies full induced demand and $w_1 = 25$ implies low induced demand. In the results below we report the range of values across patches for each level of induced demand. The first-best policies shown are the maximum and minimum incentives (θ^*_{FB}) across patches that decentralize the first-best, normalized by the mean access cost (τ) across the thirteen patches. We note that all values are positive, *i.e.* effort is taxed, and vary from about 5 percent to about 94 percent of mean access costs.[28]

[27] All parameters are statistically significant with $p < 0.05$. Regression results available upon request.

[28] While not presented here, the relative levels of patch-specific taxes follow the general pattern shown in Figure 3.

Policies that achieve the constrained social optimum are smaller in magnitude than the first-best, and can be negative, i.e effort is subsidized for low levels of induced demand. The constrained policies are always smaller because the marginal costs of reallocated effort are greater compared to the first-best.[29] Next, we see the percent deadweight loss, defined as social welfare under the decentralized (unregulated) equilibrium divided by social welfare under the first-best, can be quite substantial, up to 52 percent. Intuitively, the percent deadweight loss decreases with a steeper wage curve due to lower effort levels across patches. Interestingly, despite intervening in only a single patch, policies that achieve the constrained social optimum can reduce deadweight loss by approximately one quarter. Note also, across the thirteen patches the minimum reduction in deadweight loss is small, suggesting that in some patches the regulator would not wish to increase or decrease effort, consistent with Proposition 4.

We view this example as a good illustration of the economic forces at work in our model rather than a detailed analysis of a particular set of resources. In particular, we have made several simplifying assumptions that likely affect the specific earnings and optimal effort values we estimate. For instance, we assume fish in this location do not move across patches. If this is not the case, policy recommendations may be somewhat different.[30] Further to maintain consistency with our analytical model, we collapse the dynamic aspects of the fishery problem to steady-state outcomes. This may ignore important temporal aspects of fisheries management. Therefore, while this example is not intended to provide specific policy recommendations, it serves to illustrate how our model can be applied to a real world resource problem.

[29]It may seem surprising that the constrained policies are less aggressive at reallocating effort. However, the intuition is that reducing effort in one patch leads to greater effort and thus lower productivity in substitute patches. Moreover, note that with full induced demand the constrained optimal policies are identical to the first-best policies since there is no benefit from reallocating effort across resources, consistent with Proposition 3.

[30]Of course, one could find other examples where dispersal is almost certainly zero and our model applies directly without this assumption.

5 Potential applications

In this section we discuss potential applications to other markets. Like the fisheries example, each application may require tailoring to suit the features of the specific resource problem. However, each example exhibits economic forces consistent with the linked common property resource problem and the models we develop above.

Recreational demand has many features of the linked common property resource problem. Congestion likely plays an important role in recreational site choice via crowding effects and can lead to degradation of protected resources. Differences in travel costs across sites can lead to differences in access costs. Gramann (2002) shows crowding contributes to spatial and temporal displacement of visitors to Mount Rainier and Olympic National Parks. The author finds 20.3 percent of Rainier visitors surveyed and 24.7 percent of Olympic visitors used less popular locations within the parks to avoid crowds. Of users who visited during off-peak seasons, over 50 percent of respondents in each park visited off-peak to avoid crowds. In our model, both effects represent substitution between linked common-property resources. At the extreme, some visitors may choose not to recreate at either park, *i.e.*, chose the alternative option. Gramann (2002) finds 5.6 percent of Rainier visitors surveyed and 4.1 percent of Olympic visitors stated they would not return because of crowded conditions.

We note in many cases, for example the recently announced management plan for the Merced River in Yosemite National Park, limiting total consumption has not been a viable option (National Park Service, 2014). Instead, park managers seeking to improve users' experience have pursued a variety of non-price strategies to reduce crowding at specify locations. In a recent survey of 93 national park unit managers, 38 percent report encouraging use of less popular access points and backcountry areas (Leung and Marion, 1999). Similarly, 13 percent report encouraging or requiring camping on sites with no evidence of use. Whether these policies reduce congestion depends on the entry of users from alternative recreational options via induced demand.

In commercial fisheries, empirical studies of location choice and capital allocation suggest fisherman do substitute effort across resources based on expected profits.[31] Further, more distant locations with higher access costs are less likely to be fished (Smith, 2002; Holland and Sutinen, 2000). There is also evidence of induced demand. For example, Smith (2002) shows the intensity of fishing in the California sea urchin fishery depends in part on the state unemployment rate, which suggests substitution to alternative options consistent with our model. A policy for changing effort across fisheries similar to the type we imagine is the Faeroe Island licensing program. The program limited commercial fishermen to a set number of fishing days and distinguished between "inner" and "outer" fisheries. A license for a fishing day in the inner territory could be exchanged for a three days in the outer territory, thus lowering access costs in the more distant fishery. Importantly, the system was designed to encourage Faeroese vessels to "target deep-water species rather than the traditional demersal stocks" (Gezelius and Raakjaer, 2008).

In subsistence fisheries, programs such as the "Fishermen Relocation Programme in Peninsular Malaysia" (Hotta and Wang, 1985; Omar et al., 1992; Mohamed, 1991) have been developed to reduce poverty and the negative effects of overfishing.[32] The program used fishing vessel buy-backs, credit schemes, vocational programs and aquaculture to move users out of congested inshore fisheries and into offshore fisheries or alternative employment (Hotta and Wang, 1985).[33] The success of these policies depends on the extent to which relocated fishermen are replaced by new entrants. The possibility of induced demand effects was recognized by program designers who noted "limiting or reducing the new entry to fishing... could be effective in achieving improvement in individual catches (for remaining fishermen)" (Hotta and Wang, 1985). While we are not aware of a detailed assessment of the program, Teh and Teh (2014) suggest overexploitation of Malaysia's inshore fisheries continues today.

Our model also has implications beyond traditional natural resource settings. For in-

[31] In some cases, habits or other sources of behavioral "inertia" may limit this response (Boyce, 1993; Holland and Sutinen, 2000; Abbott and Wilen, 2011)

[32] A similar program existed in Thailand.

[33] For instance, the "Special Fisheries Loan Scheme" operated by the national Agriculture Bank aimed to modernize and develop the off-shore fishing industry in Malaysia easing overfishing in the inshore resource (Mohamed, 1991).

stance in transportation, resistance to congestion pricing in the U.S. has led policy makers to pursue alternatives such as high occupancy vehicle (HOV) lanes as a way to reduce traffic congestion.[34] During peak periods, both mainline and HOV lane use are rationed by congestion (Bento et al., 2014). Transaction costs of carpool formation lead to differences in access costs across the mainline and HOV lanes. As a result, mainline lines are generally more heavily used and therefore more congested. Finally, travelers have outside alternatives such as telecommuting, public transit or forgoing discretionary trips. Evaluation of programs to promote carpooling, such as informational campaigns, preferential parking and guaranteed ride home programs, should account for the substitution and entry effects modeled above.

6 Conclusions

We show that in the linked common-property resource setting high access cost resources can be *over* or *under*-consumed. Because differences in access costs lead to higher congestion costs for low access cost resources, a reallocation of users may reduce overall costs. Crucially, whether increasing consumption of the high access cost resource improves welfare depends on the amount of entry from induced demand. The finding that increasing consumption of some common-property resources may be desirable is novel in light of models which consider individual resources in isolation or assume full induced demand. On the other hand, because positive induced demand negates some or all of the congestion relief benefit from reallocating users from LAC to HAC resources, equating marginal congestion costs across resources may not always be optimal.

We highlight the implications of our model with a simple application to a Southern California fishery with multiple distinct patches. Specifically, we show how our approach could be applied to a real world resource problem. Consistent with our analytical model, the optimal policy tends to encourage effort in high access cost patches and to discourage effort

[34] While congestion pricing has found support in some parts of the world, the vast majority of U.S. roadways are un-priced. A handful of exceptions include high occupancy toll (HOT) lanes in California, Colorado, Florida, Georgia, Minnesota, Washington, Utah and Texas.

in low access cost patches. Similarly, encouraging effort in a particular patch is more likely to increase total earnings when induced demand is low relative to when induced demand effects are large.

Taken together, our results suggest policy makers need to carefully consider relative congestion levels and the potential for induced demand when designing policies in a linked common-property resource setting. Further empirical research into fisheries, forestry, recreation, traffic and other similar markets would provide additional insight into the importance of the mechanisms outlined in this paper.

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7 Tables

Table 1: Comparison of the constrained social optimum with first-best fishery policies.

w_1	First-Best Policies (θ^*_{FB})			Constrained Optimal Policies (θ^*)			Percent Deadweight Loss	Percent Reduction in Deadweight Loss at the Constrained Optimum		
0	0.16	-	0.94	0.16	-	0.94	52%	0.7%	-	23.7%
5	0.13	-	0.92	0.06	-	0.86	19%	0.1%	-	24.4%
10	0.11	-	0.89	-0.01	-	0.79	10%	0.0%	-	25.2%
15	0.08	-	0.87	-0.06	-	0.74	6%	0.0%	-	26.1%
20	0.07	-	0.85	-0.10	-	0.71	4%	0.0%	-	27.1%
25	0.05	-	0.83	-0.14	-	0.67	3%	0.0%	-	28.0%

Notes: First-best policies are the taxes on each patch that achieve the first-best allocation. The constrained socially optimal policy is the incentive, on a single patch, that decentralizes the constrained social optimum. The maximum and minimum values are presented across patches. All policies are normalized by the average access cost (τ) across patches. Percent deadweight loss is calculated as deadweight loss at the decentralized equilibrium divided by first-best welfare. Percent reduction in deadweight loss is calculated as one minus the ratio of deadweight loss under the policy to deadweight loss under the decentralized equilibrium; the maximum and minimum values are presented.

8 Figures

Figure 1: Panel a.) Private benefits, costs and social costs for the HAC resource. Panel b.) Congestion costs, alternative option costs and induced demand effects.

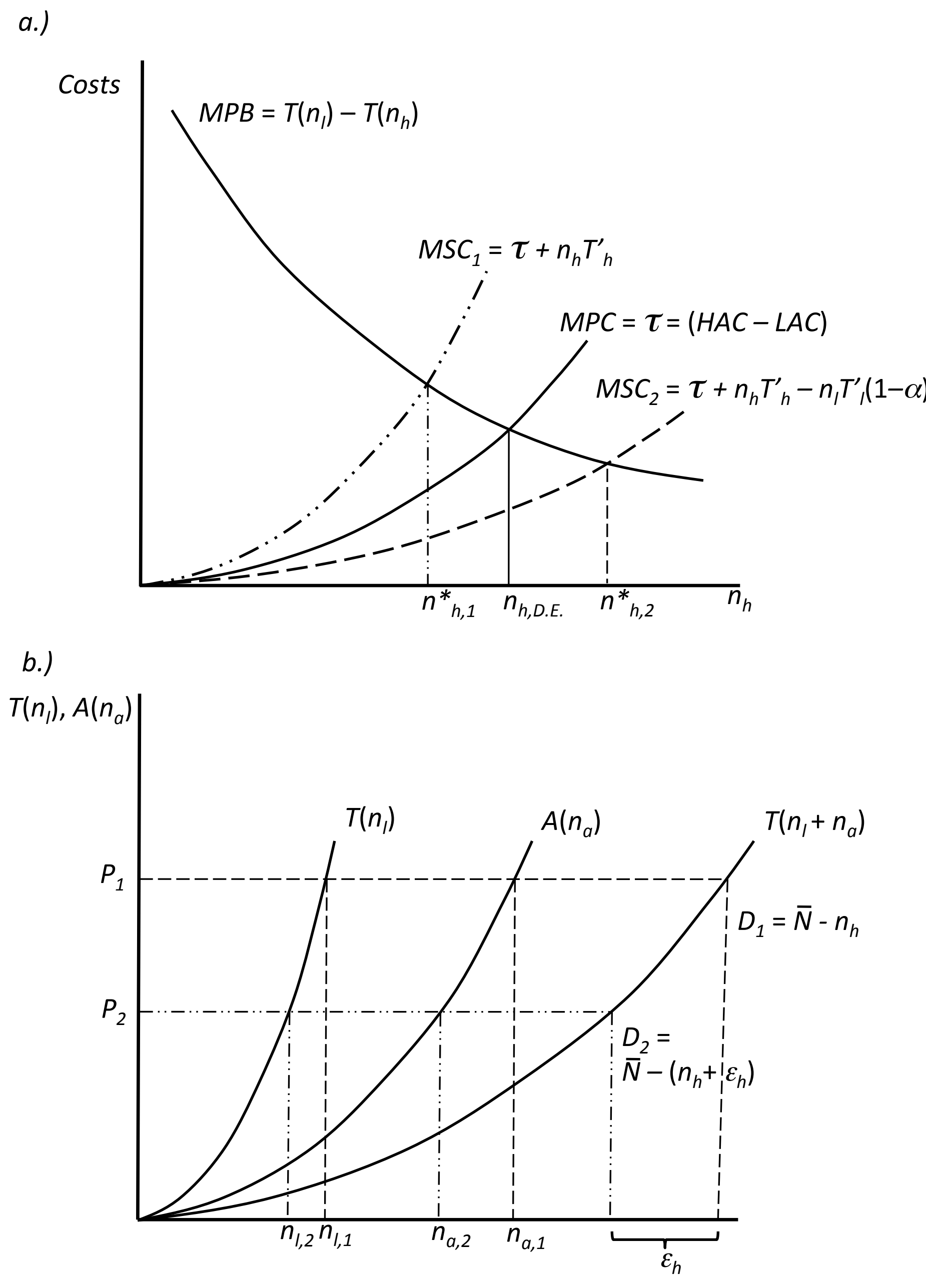
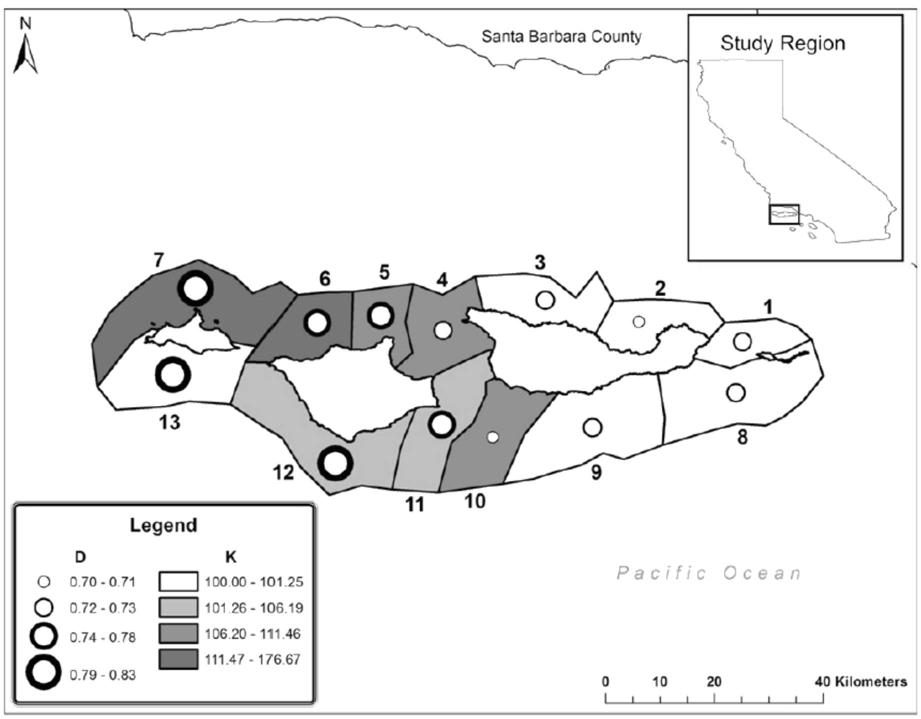
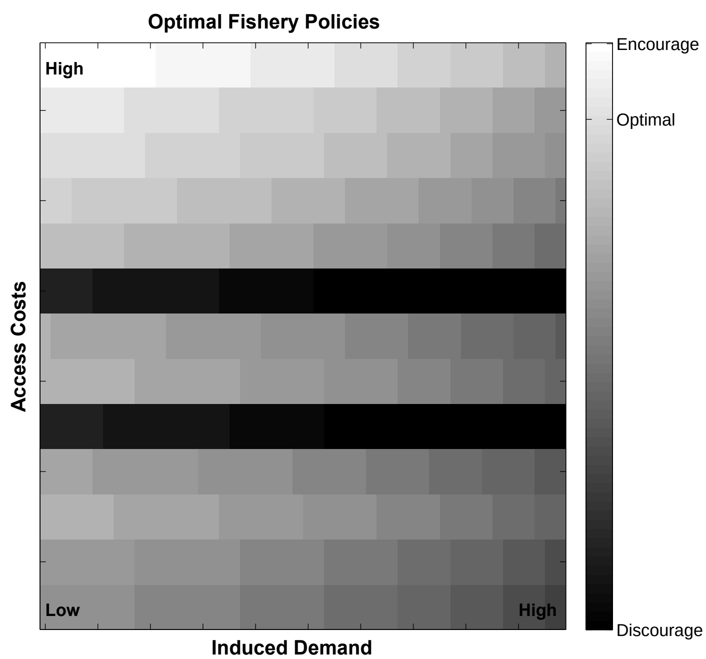


Figure 2: Fishery study area adapted from Costello, Quérou, and Tomini (2015).



Reprinted from: Journal of Public Economics, Vol. 121, Costello, Christopher, Nicolas Querou, and Agnes Tomini, "Partial Enclosure of the Commons," pp. 69-78, 2015, with permission from Elsevier.

Figure 3: Optimal policies (θ_j) for encouraging or discouraging effort in patch j across different levels of induced demand in a Southern-California fishery.



Appendix

A General model with $K+1$ resources

Suppose now that instead of only two fishery patches as in Section 4.1 there are $K+1$ patches. Let i represent a particular resource of interest and $\mathcal{K}$ the set of other common-property resources, with k indexing the $k = 1, ..., K$ other common-property resources. All effort $\bar{E}$ is allocated such that $\bar{E} = E_i + \sum_{k=1}^{K} E_k + E_w$. The return on fishing in each common-pool resource is given by $pX_j(E_j) - \tau_j$ for $j = i, 1, ..., K$.[35]

We begin by analyzing a decentralized equilibrium, where users allocated effort across i, $k \in \mathcal{K}$ and the outside (wage) option. Nash Equilibrium requires that no user be able to increase their earnings by reallocating their effort, such that:

$$\begin{aligned} pX_i(E_i) - pX_k(E_k) &= \tau_i - \tau_k \quad \forall k \\ pX_j(E_j) - \tau_j &= W(E_w) \quad j = i, 1, ..., K \\ \bar{E} &= E_i + \sum_{k=1}^{K} E_k + E_w. \end{aligned} \tag{26}$$

The first condition says that for all $K+1$ common-property resources, the difference in fishing earnings is equal to the access cost differential, such that net returns are equilibrated across all resources. The second condition requires that for any common-property resource, the marginal user is indifferent between the outside option and the common-property resource.

Next, we consider the allocation of users' effort by a constrained social planner. The constrained social planner is considering the allocation of effort to the resource of interest i to maximize total returns, while accounting for the fact that effort may enter (or exit) from

[35] Note that in contrast to the model in Section 2, here we simply assume τ_j is constant but different across resources.

the outside option into the remaining K common-property resources:

$$\max_{E_i, E_k, E_w} \quad \sum_{j=i,1}^{K} [pX_j(E_j)E_j - \tau_j E_j] + \int_0^{E_w} W(E)dE \tag{27}$$

$$s.t. \quad \bar{E} - E_i - \sum_{k=1}^{K} E_k - E_w = 0$$

$$pX_k(E_k) - \tau_k = W(E_w) \quad \forall k$$

with the corresponding Lagrangian:

$$\sum_{j=i,1}^{K} [pX_j(E_j)E_j - \tau_j E_j] + \int_0^{E_w} W(E)dE + \lambda(\bar{E} - E_i - \sum_{k=1}^{K} E_k - E_w) + \sum_{k=1}^{K} \mu_k (pX_k(E_k) - \tau_k - W(E_w)) \tag{28}$$

and first-order conditions:

$$pX_i + pX_i' E_i - \tau_i - \lambda = 0 \tag{29}$$

$$pX_k + pX_k' E_k - \tau_k - \lambda + \mu_k (pX_k') = 0 \quad \forall k \tag{30}$$

$$W - \lambda - \sum_{k=1}^{K} \mu_k W' = 0. \tag{31}$$

which define the earnings-maximizing, constrained socially optimal allocation of effort E_i, E_k, and E_w across all options.[36] The arguments in (29)-(31) are suppressed for simplicity.

With some iterative substitution, the first FOC can be written as:

$$pX_i + pX_i' E_i - \tau_i - pX_k + \tau_k - \frac{W' \sum_{k=1}^{K} E_k \prod_{k=1}^{K} pX_k'}{\prod_{k=1}^{K} pX_k' + W' \sum_{k=1}^{K} (\prod_{m \in \mathcal{K} \diagup k}^{K} pX_m')} = 0, \tag{32}$$

or

$$pX_i - pX_k = \tau_i - \tau_k - pX_i' E_i + \frac{W' \sum_{k=1}^{K} E_k \prod_{k=1}^{K} pX_k'}{\prod_{k=1}^{K} pX_k' + W' \sum_{k=1}^{K} (\prod_{m \in \mathcal{K} \diagup k}^{K} pX_m')}, \tag{33}$$

which states that the marginal private benefit of an additional unit of effort in resource i

[36] This allocation satisfies the second-order sufficient conditions for a local constrained maximization.

is equal to the marginal private cost of another unit of effort in resource i, plus the net marginal external costs. The final term reflects the complex substitution pattern across resources. Specifically, an increase in effort in i leads all other effort to be re-sorted across the K other common-property resources and the outside option. The intuition from Figure 1 is readily extended to the case with K common-property resources. Note also that setting $K = 1$, $i = h$, $k = l$, and $\tau_i - \tau_k = \tau$ recovers the expression in Equation 22 of the main text.[37] Finally, while further analytical results are challenging to interpret, these effects are critical in settings such as the numerical example analyzed in Section 4.2. There we numerically determine optimal policies for fishing effort taking into account the complex substitution patterns across many fishing locations.

[37]This is more clear when recognizing that the outside option can be thought of as 'equivalent' to another common-property resource such that $W' = pX'_{K+1}$, $K+1 \in \mathcal{K}$ and $|\mathcal{K}| = K+1$. In which case, the denominator of the final term in 33 can be expressed as $\sum_{k=1}^{K+1}(\prod_{m\in\mathcal{K}/k}^{K+1} pX'_m)$, such that this term is equal to $W' + pX'_k$ when there is only the single common-property resource and the outside option.