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ORIGINAL PAPER

Triple benefits from spatial resource management

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Abstract Standard fishery management models suggest that regulations designed to produce maximum rent should reduce effort – and thus employment – from its open-access level. Using a simple diffusion model, we show that the opposite can be true when the spatial distribution of effort, as well as the total amount of effort, can be controlled. Under certain ecological and economic circumstances that we describe, optimal spatial management can produce "triple benefits" compared to open access: an increase in rent, an increase in standing stock, and an increase in employment.

Keywords Bioeconomics · Maximum sustainable rent · Fisheries management · Renewable resources · Employment · Spatial models

Introduction

When harvesters competitively exploit a renewable resource, they tend to disregard the costs they impose on each other. In particular, they tend to discount the forgone future productivity of the biomass they harvest. They may also raise each other's costs of harvesting by reducing the stock density or by getting in each other's way. These costs erode the rents (i.e., profits) that the resource is capable of producing. In the extreme "tragedy of the commons" (Hardin 1968), society derives no pecuniary benefit from the existence of the resource.

To increase rents, a regulator imposes constraints (e. g. quotas or taxes) on the exploitation of the resource. It is widely perceived that a consequence of regulation, regardless of the mechanism used, is a reduction in effort employed. This perception stems in part from the classic work of Gordon (1954) on fishery economics, which is illustrated in virtually every resource economics textbook, in many ecology texts, and in popular treatments, with a figure similar to Fig. 1 (Clark 1990; Kula 1992; Beeby 1993; Seijo et al. 1998; Iudicello et al. 1999; Field et al. 2002; Ostrom et al. 2002; Grafton et al. 2004; Van Cooten and Folmer 2004). In this figure, total revenue (TR) and total cost (TC) are plotted versus effort (E). In an unregulated, or so-called *open access*, fishery, effort equilibrates at the point E_{oa}, where the rent is completely dissipated, i.e., where TR = TC. In contrast, a regulator (or equivalently, a sole-owner) attempts to maximize rent by reducing effort to E_{so}.

Policies designed to reduce effort are also perceived to drive people out of the industry. In many resource industries, such as coastal fisheries, participation spans generations. Displacing people from the industry is viewed as erosion of a "way of life," and the traditional structure of the industry often constitutes an important part of local culture (see Hall-Arber et al.

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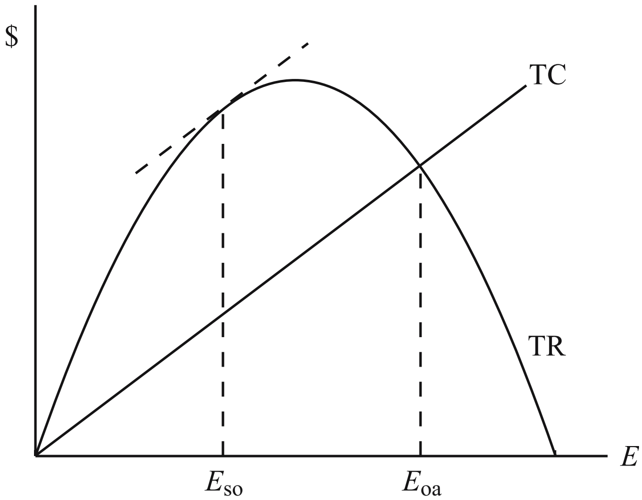

Fig. 1 Total revenue (TR) and total cost (TC) as a function of total effort (E). In open access, effort increases to the level E_{oa} where the rent (TR − TC) is completely dissipated. A regulator would try to reduce the effort level to E_{so} where rents are maximized

2001, and references therein). Participants themselves experience high psychic costs when compelled to leave. Effort reduction policies, therefore, are often politically unpalatable.

So according to the iconic Fig. 1, regulators would seem to be caught between the Scylla of rent dissipation and the Charybdis of reduced employment. However, it is not necessarily so. Using a simple diffusion model, we show that a regulator who can control the spatial distribution of effort may end up *increasing* aggregate effort above the open-access level. In addition to rent and employment, the equilibrium stock size also increases. Below, we characterize the set of ecological and economic conditions that give rise to such *triple-benefit* scenarios. While our model is formulated with fisheries in mind, our findings are generally applicable to other common-pool resources.

Model

Following Clark (1990), Neubert (2003) and Kellner et al. (2007), we use a spatially extended Gordon–Schaefer model (Table 1) in which biomass density $N(x,t)$ obeys the partial differential equation

$$\frac{\partial N(x,t)}{\partial t} = rN(x,t)\left(1 - \frac{N(x,t)}{K}\right) + D\frac{\partial^2 N(x,t)}{\partial x^2} - qE(x,t)N(x,t). \quad (1)$$

See Tuck and Possingham (1994, 2000), Sanchirico and Wilen (1999, 2001, 2005), and Sanchirico et al. (2006) for alternative formulations that treat space as a collection of discrete patches.

The first term on the right-hand-side of Eq. 1 represents logistic population growth, where r is the intrinsic growth rate and K is the environmental carrying capacity. The second term describes the movement of the population as by diffusion; the parameter D is the diffusion coefficient. The final term describes the spatial density of harvest. The harvest rate at any location is proportional to both the stock density N and the effort density E. We emphasize that effort density may vary spatially by writing "$E(x,t)$." The "catchability coefficient" q represents availability of the resource to the harvest technology.

Table 1 Variables, parameters, and their typical units

Symbol	Description	Units
Variables		
x	Space	km
t	Time	Year
N	Stock density	Tonnes km^{-1}
E	Effort density	Vessel days km^{-1} year^{-1}
$\langle E\rangle$	Total effort	Vessel days year^{-1}
ρ	Rent density	Dollars year^{-1} km^{-1}
Π	Equilibrium rent	Dollars year^{-1}
Parameters		
r	Intrinsic growth rate	Year^{-1}
K	Carrying capacity	Tonnes km^{-1}
D	Diffusion coefficient	km^2 Year^{-1}
L	Habitat length	km
q	Catchability coefficient	km (vessel day)$^{-1}$
p	Price	Dollars tonne^{-1}
w_0	Effort cost	Dollars (vessel day)$^{-1}$
w_1	Congestion cost	Dollars (vessel day)$^{-2}$ km year

Biological populations live in spatially heterogenous environments. Basic models of spatial heterogeneity distinguish habitat (places where the species can live) from nonhabitat (where it cannot). In the simplest case, we can assume that the population occupies a single habitable patch of length L surrounded by uninhabitable areas. We approximate this situation by imposing the boundary conditions

$$N(-L/2,\ t) = N(L/2,\ t) = 0. \tag{2}$$

At equilibrium $\partial N/\partial t = 0$, and we can write $N(x,t) = N(x)$ and $E(x,t) = E(x)$.

Neubert (2003) used this model to investigate the spatial effort distributions that maximize equilibrium yield. In the present analysis, we assume that harvesters and regulators are motivated by profit considerations. We assume that revenues are generated by selling the harvested stock at a fixed price per unit biomass p; i.e.,

$$\mathrm{TR} = \int_{-L/2}^{L/2} p\,q\,E(x)N(x)\,dx. \tag{3}$$

To represent the costly effects of interference between harvesters, we also assume that the cost per unit effort of fishing in any location increases linearly with the effort exerted at that location; i.e.,

$$\mathrm{TC} = \int_{-L/2}^{L/2} (w_0 + w_1 E(x))\,E(x)dx. \tag{4}$$

Congestion effects will vary from fishery to fishery and, in some cases, will be unimportant. Later, we explore the behavior of the solutions to our model as the congestion cost (w_1) becomes small.

The equilibrium rent in model Eqs. 1–4 is

$$\Pi[E(x), N(x)] = \mathrm{TR} - \mathrm{TC} = \int_{-L/2}^{L/2} \rho(x)\,dx, \tag{5}$$

where $\rho(x)$ is the “rent density”

$$\rho(x) = [pqN(x) - (w_0 + w_1 E(x))]\,E(x). \tag{6}$$

In open access, rent is dissipated at every point in space, i.e., $\rho(x) = 0$ for all x. We call the resulting effort and stock distributions $E_{oa}(x)$ and $N_{oa}(x)$, respectively. A regulator, or sole owner, on the other hand, tries to prescribe an effort distribution $E_{so}(x)$ that, in conjunction with the resulting stock distribution $N_{so}(x)$, maximizes the equilibrium rent. We determined these four distributions for a variety of parameter values (see the Appendix).

Our choice of a compensatory growth function (the logistic model) and our economic model guarantee that if the stock persists in the absence of harvesting it will also persist under open access conditions. When stock dynamics include critical depensation (a. k. a. strong Allee effects), open access exploitation can drive the stock to extinction (Clark 1990). In this case triple-benefits are trivial. We therefore limit the interpretation of the results that we present next to the case where the stock persists at the open-access equilibrium.

Results

Our numerical exploration of this model has revealed four striking patterns (Fig. 2). First, the rent-maximizing equilibrium stock density is larger everywhere than it would be under open-access conditions. Second, the spatial distributions of effort are relatively consistent. In open access, effort concentrates at the center of the domain and drops to zero near the boundaries where the stock density is low and, consequently, marginal harvest costs are high. While the regulator also prohibits fishing near the boundaries (for the same reason that open-access harvesters avoid these regions; in fact, these would be nonbinding “prohibitions”), he/she also restricts effort in the center of the habitat where the stock density is relatively high. Between the center and the boundary, the regulator allows effort to increase, often dramatically above open-access levels. Third, the optimal solution often contains a *no-take reserve* – a region which in which extraction is completely prohibited – when costs are low. (See Sanchirico et al. 2006, for a discussion of the conditions under which reserves will optimize profit.)

The fourth pattern surprised us because it is contrary to the prescriptions of the standard Gordon model (Fig. 1). It is clear (Fig. 2a–c, e) that the total amount of effort used by the regulator to maximize rent, $\langle E_{so}\rangle = \int_{-L/2}^{L/2} E_{so}(x)\,dx$, can be larger than the total amount of effort used in open access, $\langle E_{oa}\rangle = \int_{-L/2}^{L/2} E_{oa}(x)\,dx$. In our model, total effort is measured in units of (standardized) vessel days per year. If one equates a vessel day to a fixed number of person hours, then the inequality $\langle E_{so}\rangle/\langle E_{oa}\rangle > 1$ translates to an increase in employment defined as the total number of labor hours per year.

To see how often and under what parameter conditions this result holds, we calculated the ratio $\langle E_{so}\rangle/\langle E_{oa}\rangle$ over a range of the parameters. We have plotted the results as contours in Fig. 3.

A change of variables (see the Appendix) shows that the ratio $\langle E_{so}\rangle/\langle E_{oa}\rangle$ is determined by only three dimensionless parameter groupings: $\ell = L\sqrt{r/D}$, $c_0 = w_0/(pqK)$, and $c_1 = rw_1/(pq^2K)$. ℓ is proportional to

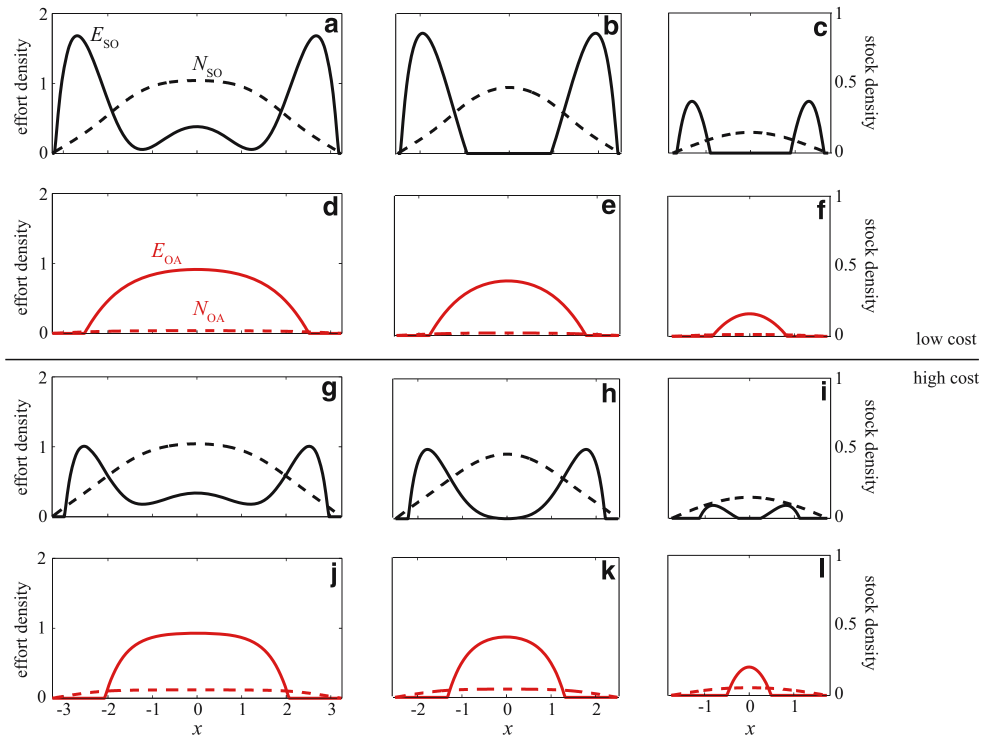

Fig. 2 Equilibrium distributions of effort (*solid curves*) and standing stock (*dashed curves*) as prescribed by a rent-maximizing regulator (*black curves*; **a**–**c**, **g**–**i**)and under open access (*red curves*; **d**–**f**, **j**–**l**) as functions of space (x). In each *panel*, $r = q = K = D = 1$, and $w_1 = 0.01$. In **a**–**f**, $w_0 = 0.01$; in **g**–**l** $w_0 = 0.05$. The parameter L is given by the length of the x axis (6.5 in **a**, **d**, **g**, and **j**; 5.0 in **b**, **e**, **h**, and **k**; 3.5 in **c**, **f**, **i** and **l**)

the size of the smallest habitat that can support an unharvested population. If $\ell < \pi$, the population will eventually become extinct (Skellam 1951; Kot 2001). c_0 is the cost per unit effort when effort is small, relative to the revenue per unit effort when the stock is at its carrying capacity. All else equal, large values of c_0 represent a less profitable resource. c_1 measures the negative effects of interference between harvesters.

There are four mutually exclusive regions in Fig. 3. In the region labeled "biological extinction," the habitat is too small to support a population even in the absence of harvesting. In the region labeled "economically infeasible," harvesting costs exceed potential revenues at each point in space, so the resource is never exploited. The two remaining regions are separated by the bold contour satisfying $\langle E_{so}\rangle/\langle E_{oa}\rangle = 1$. Outside of this contour (e. g. for large c_0), regulation decreases aggregate effort relative to open-access conditions. Inside this contour, efficient regulation increases aggregate effort, in some cases by a factor greater than two. Proportional increases are largest when both the habitat and the cost of harvesting are small.

It might seem that such increases in effort would have the adverse effect of reducing the standing stock and consequently diminishing nonharvest benefits (e. g. recreational uses or ecological functions). In fact, the rent-maximizing equilibria we obtain have a larger standing stock density than the open-access equilibria

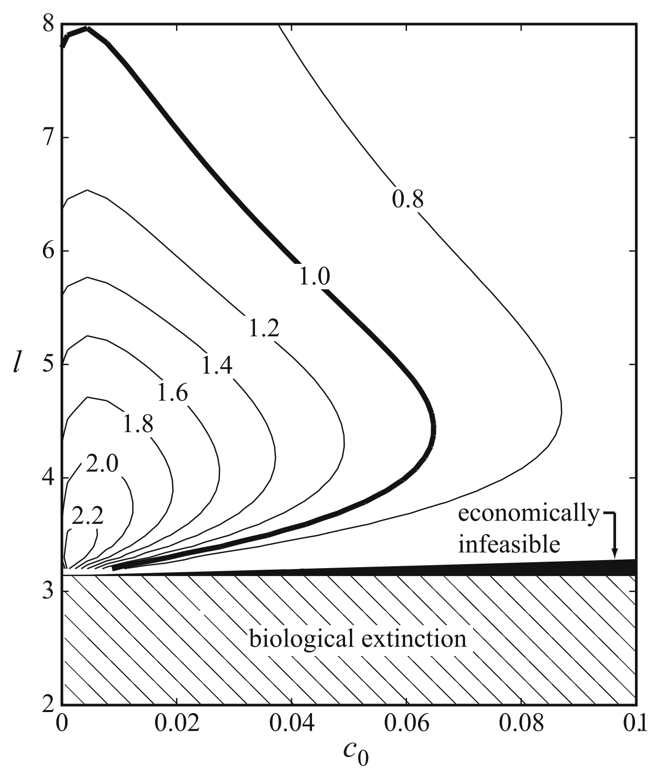

Fig. 3 Contours of the ratio $\langle E_{so}\rangle/\langle E_{oa}\rangle$, the total equilibrium effort that maximizes rent over the total equilibrium effort in open access as a function of the dimensionless cost per unit effort c_0 and the dimensionless habitat size ℓ. In this figure, $c_1 = 0.01$. The *black* and *hatched regions* are described in the text

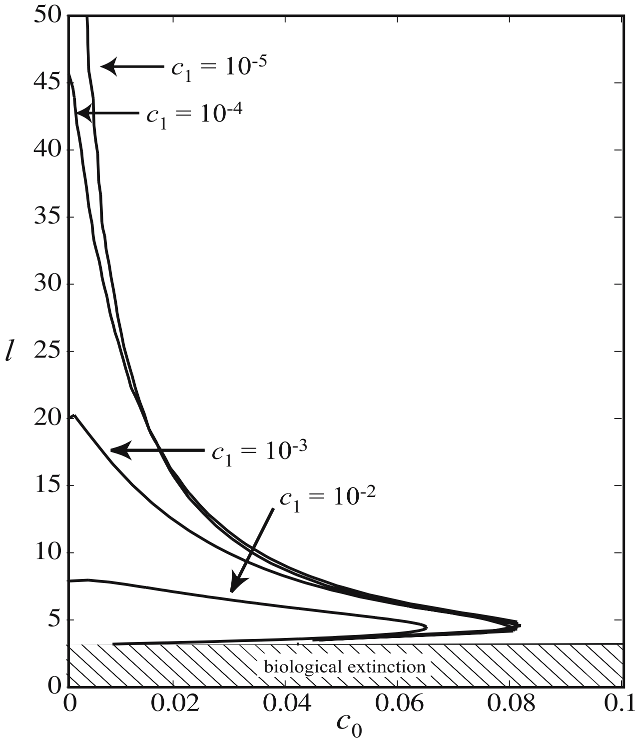

Fig. 4 The contour $\langle E_{so}\rangle/\langle E_{oa}\rangle = 1$ for various values of the dimensionless interference cost parameter c_1. The ratio is larger than one to the left of each *curve*

($N_{so}(x) > N_{oa}(x)$ for all x). Rather than necessitating tradeoffs between management objectives, optimal spatial management can thus have "triple benefits," simultaneously increasing rent, employment, and standing stock.

The effect of interference between harvesters, as captured by the quadratic term in the cost function, is not essential to our results. In fact, interference costs tend to make triple benefits less likely. (Interference costs do, however, prevent unrealistic infinite effort densities.) We repeated our calculations for a variety of values of the interference parameter c_1. We found that, as this parameter decreases, the triple-benefit region expands (Fig. 4) and that, within this region, the ratio $\langle E_{so}\rangle/\langle E_{oa}\rangle$ grows larger.

Discussion

Our results suggest two conditions that must be satisfied to give rise to triple-benefit scenarios in equilibrium:

1. *Heterogeneity* First, the system must be heterogeneous along some "secondary regulatory dimension" other than effort exerted per unit time, and the regulator must be able to control the distribution of effort along this dimension.
   In the example presented above, the secondary regulatory dimension is space. Spatial heterogeneity arises from the fact that the habitat is surrounded by uninhabitable regions (as captured by the boundary conditions Eq. 2). In lieu of spatial heterogeneity, we could have introduced stage, age, or sex structure in the stock, coupled with heterogeneity across these groups in natural mortality or reproductive rates (and therefore in in situ values). In Appendix S1 of the Electronic Supplementary Material, we show that triple benefits are possible in a two-patch model with heterogeneity either in the population growth rate or the carrying capacity. We also show that they are possible in a two-stage model that distinguishes juveniles from adults.
   Any change that homogenizes a system along the secondary regulatory dimension reduces the ability of the regulator to achieve efficiency gains by constraining behavior along that dimension, thereby reducing opportunities to increase employment. Figure 3 shows that opportunities for the employment benefit disappear for extreme values of ℓ. Very large or small domains effectively homogenize the stock with regard to losses due to flux of the boundaries: when ℓ is large, only a small portion of the resource near the edges is subjected to flux out of the habitat; in a small domain, virtually all biomass is subject to this flux.
2. *Incentive misalignment* The second condition for the existence of triple-benefits is an inclination on the part of harvesters to act in such a way as to dissipate rents along the secondary dimension. That is, the distribution of open-access effort along the secondary regulatory dimension has to be significantly uncorrelated, or negatively correlated, with that associated with rent maximization.
   In our example, harvesters tend to exert effort in the center of the habitat, which yields higher instantaneous profits because the stock density is high; in contrast, the regulator strives to reduce effort in this region because biomass there is more productive and therefore has higher in situ value. Such misalignments of incentives do not always exist. If, for example, the costs of harvesting in the center of the habitat were higher than that near the edges (e.g. because the center of the habitat was further from port), *both* harvesters and the regulator would tend to avoid the center area, thus better aligning the spatial effort distributions and reducing the dissipation of rents along the spatial dimension. If the secondary regulatory dimension

were age, size, or sex structure, the existence of triple benefits would depend upon whether harvesters tend to focus their efforts on more or less biologically productive individuals.

Changes in the system that increase the correlation between the open-access and rent-maximizing effort distributions reduce the possibility of triple benefits. Figure 3 shows that, for any given habitat size ℓ, high costs eliminate the triple benefit. When costs are large, there are larger regions near the edge of the habitat that are not cost-effective to harvest. The sole owner's effort distribution therefore moves inward toward the center of the habitat; though it remains bimodal, it necessarily overlaps more with the open-access effort distribution.

Two caveats are worth noting. First, we have designated increased employment – defined as the total number of hours worked per year – as one of three benefits of spatial management. Employment defined in this way is the product of the number of workers and the number of hours labored per worker. If employment increases are small, or if many participants are involuntarily working part-time, then the result of increased employment may not be an increase in the number of people working in the industry but, rather, an increase in the number of hours worked by each participant.

A second caveat is that our analysis deals only with open-access behavior and the maximization of rents arising at equilibrium. In this sense, our analysis parallels that of the static Gordon–Schaefer model and is subject to the same criticisms. In particular, we have ignored transitional dynamics, as well as the effect of intertemporal discounting. The former is more pertinent to our discussion of triple benefits; it may not be profitable or feasible for harvesters to move immediately from their open-access locations to the new, socially efficient equilibrium. As a result, short-term displacements from the industry may be inevitable as the distribution of the resource converges to its new equilibrium. While these transitional dynamics may also be politically undesirable, temporary displacements from the industry are less objectionable than permanent ones, and it may be feasible to support participants until the new equilibrium can be obtained and they return to employment in the industry.

From a policy standpoint, the important conclusion is that heterogeneity matters. Efficient management of a resource with regard to different types of heterogeneity can allow for greater participation, thus reducing the legal and political barriers associated with curtailing access to fisheries and other "public trusts." These barriers are substantial. For example, National Standard 8 (16 U.S.C. §1851), one of the guiding principles underlying the USA's Magnuson–Stevens Fisheries Conservation and Management Act (16 U.S.C. §1801), requires that the impact of management actions on fishing communities be explicitly considered. In particular, regulations are expected "to provide for the sustained participation of such communities and, to the extent practicable, minimize adverse economic impacts on such communities." Explicit inclusion of "participation" in the Act highlights the importance of access, or employment, in the policy arena.

Our findings suggest important tasks for natural and social scientists, as well as policy makers. The role of the natural scientist in this context is to identify and characterize the heterogeneities (spatial and otherwise) that exist in natural resource systems. The role of the social scientist is to characterize the incentive structure as it pertains to these heterogeneities, i.e., to characterize how well aligned the predilections in aggregate of the industry participants are with those of society. The joint understanding of heterogeneities in system attributes and harvester incentives will suggest avenues for achieving more politically palatable changes in behavior. Finally, it falls to the policy maker to structure regulations that (a) serve to better align harvester and social incentives along the dimension in question and (b) are enforceable or otherwise feasible and cost-effective to implement.

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Appendix

The model of Eqs. 1–5 has eight parameters. However, after introducing the change of variables

$$u = N/K, \quad \tau = rt, \quad \xi = x\sqrt{r/D}, \quad f = (q/r)E, \quad \text{and} \quad \pi = \Pi/(pK\sqrt{rD}), \tag{7}$$

the model (at equilibrium) becomes

$$\frac{d^2u}{d\xi^2} = -[u(1-u) - f(\xi)u], \tag{8}$$

$$\pi[f(\xi), u(\xi)] = \int_{-\ell/2}^{\ell/2} [u(\xi) - (c_0 + c_1 f(\xi))] f(\xi) d\xi, \tag{9}$$

with the boundary conditions

$$u(-\ell/2) = u(\ell/2) = 0, \tag{10}$$

and with only three parameters:

$$\ell = L\sqrt{r/D}, \quad c_0 = w_0/(pqK), \quad \text{and} \quad c_1 = rw_1/(pq^2K). \tag{11}$$

Open access

In open access, we assume that the (dimensionless) rent density $[u(\xi) - (c_0 + c_1 f(\xi))] f(\xi)$ vanishes everywhere. Thus, if $f_{oa}(\xi)$ is the dimensionless effort distribution in open access, and $u_{oa}(\xi)$ is the resulting dimensionless stock distribution, then

$$f_{oa}(\xi) = \begin{cases} 0, & \text{if } u_{oa}(\xi) < c_0, \\ (u(\xi) - c_0)/c_1, & \text{if } u_{oa}(\xi) \geq c_0. \end{cases} \tag{12}$$

Substituting Eq. 12 into the state Eq. 8 gives us a two-point boundary value problem that we solve numerically for $u_{oa}(\xi)$. $E_{oa}(x)$ and $N_{oa}(x)$ can then be calculated via Eq. 7.

Rent maximization

To determine effort distribution ($f_{so}(\xi)$) and stock distribution ($u_{so}(\xi)$) a regulator would try to achieve to maximize equilibrium rent, we first introduce the new state variable $v = du/d\xi$, which allows us to convert the state Eq. 8 into a system of two first-order ordinary differential equations. We then use optimal control theory to find the optimal solution.

The Hamiltonian for the optimization problem is

$$H[u, f, \lambda_1, \lambda_2] = f[u - (c_0 + c_1 f)] + \lambda_1 v + \lambda_2 u(f + u - 1). \tag{13}$$

Pontryagin's maximum principle then tells us that $f_{so}(\xi)$, $u_{so}(\xi)$, and the adjoint variables $\lambda_1(\xi)$ and $\lambda_2(\xi)$ simultaneously satisfy the system of ordinary differential equations

$$du/d\xi = \partial H/\partial \lambda_1, \tag{14}$$

$$dv/d\xi = \partial H/\partial \lambda_2, \tag{15}$$

$$d\lambda_1/d\xi = -\partial H/\partial u, \tag{16}$$

$$d\lambda_2/d\xi = -\partial H/\partial v, \tag{17}$$

along with the boundary conditions Eq. 10 and transversality conditions $\lambda_1(-\ell/2) = \lambda_1(\ell/2) = 0$. At the same time, f_{so} and u_{so} maximize H at each point on the trajectory; i.e.,

$$H[u_{so}, f_{so}, \lambda_1, \lambda_2] = \max_{f \geq 0} H[u, f, \lambda_1, \lambda_2]. \tag{18}$$

We solve this last equation for f_{so} in terms of the other variables and substitute into the system of ordinary differential equations to obtain a two-point boundary-value problem that we solve numerically. $E_{oa}(x)$ and $N_{oa}(x)$ can then be calculated via Eq. 7.

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