Harvesting efficiency and welfare in restricted open-access fisheries

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Abstract:

Small-scale and recreational fisheries often operate under conditions of restricted open access with a limited number of licensed fishers. Harvesting efficiency is limited both by the state of technology and by regulations of fishing gear and fishing practices, but under these constraints individual fishers can choose the amount of catch. We study how an increase in harvesting efficiency changes the different components of welfare – consumer surplus and producer surplus – in a restricted open access fishery in steady state, taking the feedback of harvesting on stock dynamics into account. We find that both components of welfare change in the same direction. If and only if initial efficiency is low enough that there is no maximum sustainable yield (MSY) overfishing in steady state, an improvement of harvesting efficiency increases welfare.

Keywords:

Fishing efficiency, myopic exploitation, bioeconomics, maximum sustainable yield

JEL: Q22

1 Introduction

Many fisheries worldwide are operating under restricted or regulated open access, including small-scale marine fisheries especially in developing countries (FAO, 2007), and recreational fisheries around the globe. About 90% of the world's fishermen and half of the fish consumed each year are captured by small scale, often inshore fisheries, which are of the restricted open access type, or local common pool resources (Ostrom, 1990, p. 27; FAO, 2007). Harvesting efficiency in those fisheries depends on the current state of technology, but often it is also limited by regulations of fishing gear and practices. Whereas improving efficiency would unambiguously enhance welfare in a first-best setting (see, e.g., Clark, 1990, Ch. 2), this is far from obvious in the actual second-best world of most fisheries, with the imperfect regulation of resource use. The reason is that improving efficiency tends to increase harvesting and reduce the stock, which may undermine long-run productivity of the resource and thus ultimately reduce welfare.

This paper aims to characterize conditions under which a costless improvement of harvesting efficiency increases or decreases welfare in a suboptimally regulated fishery. To this end, we set up a bioeconomic model of a restricted open access fishery. As common in the resource economic literature, we consider a fish population biomass, where surplus production – and thus potential steady-state yield – is maximized at some intermediate stock size that would give rise to the maximum sustainable yield (MSY). We consider restricted access to the fishery such that the number of fishermen (or vessels) is fixed. Changing profitability in the fishery thus has no effect on the extensive margin, but it will have an effect on the intensive margin, as the active fishermen will adjust fishing effort in response to profitability. Assuming that the number of fishermen is large – as it is the case for small-scale or recreational fisheries – individual fishermen will rationally ignore an effect of their harvest on fish stock dynamics. Welfare is derived from the fishery in terms of producer surplus and consumer surplus (Quaas et al., 2018), which is certainly relevant for small-scale fisheries in developing countries that serve as an important local source of food supply.

We find that the long run components of welfare – consumer and producer surplus – in the considered restricted open-access fishery change with harvesting efficiency in a non-monotonic fashion. This shows how more efficient fishing methods, or more lenient gear restrictions, may be a mixed blessing not only for the catch and fish abundance, but also for the profitability and the welfare of the local fishing community. Importantly, we characterize under which conditions increasing efficiency improves, or reduces welfare. We find that at low levels of efficiency an improvement of harvesting efficiency increases both consumer and producer surplus, while it decreases both components of welfare when the initial level of efficiency is high. We further find that the turning point is the same for both components of welfare. It is the level of efficiency for which the resulting steady-state population size would give rise to the maximum sustainable yield (MSY). This result holds true for a large range of specifications for benefits and costs derived from harvesting, allowing for stock-dependency of both benefits (as it would be the case in a recreational fishery, or when consumers of fish care for sustainability) and costs (a standard assumption in fishery economics).

A mixed blessing of more efficient fishing technology is discussed, among others, by Whitmarsh (1990), Murray (2007), and Squires and Vestergaard (2013a,b). The latter contributions are concerned with different types of technical progress, finding that the rapid technological progress in the past contributed to the decline of most, if not all, global fisheries. Gordon and Hannesson (2015) gives an in depth analysis of technological progress and the stock collapse in the Norwegian winter herring fishery, and provide evidence that the introduction of the power block technology was the principal factor in the demise of the stock. Hannesson et al. (2010) and Eide et al. (2003) find similar results for other fisheries.

The next section presents our bioeconomic model for a seach fishery and for a schooling fishery. Section 3 presents the results for both types of fishery. In Section 4 we proceed and show that our main results generalize to a much wider class of fishing technologies and utility derived from harvesting the resource, i.e. we consider a general function that describes (net) utility derived from fishing as a function of catch quantity, stock size, and harvesting efficiency. The final section summarizes our findings and concludes.

2 Model of a small-scale fishery under restricted open-access

We consider a single fish stock exploited instantaneously and simultaneously in a myopic manner in a local fishing community in continuous time. The population growth is described by:

$$\frac{dX_t}{dt} = F(X_t) - H_t \tag{1}$$

where $X_t > 0$ is the stock size (measured in biomass) at time t, $H_t \geq 0$ is the harvest, and $F(X_t)$ is the natural growth function, assumed to be density dependent. We adopt the standard assumptions $F(0) = F(K) = 0$, where $K > 0$ is the carrying capacity of the fish stock, $F(X_t) > 0$ for $X_T \in (0, K)$, $F''(X_t) < 0$, and assume that $F(\cdot)$ is single-peaked, i.e. there is a unique stock size X^{msy} that maximizes $F(\cdot)$, i.e. where $F'(X^{msy}) = 0$.

We first specify and analyze two models of harvesting technology and welfare standard in the literature – one closely follows the Gordon (1954) and Schaefer (1957) model of a search fishery, the other one the schooling fishery model where fishing costs are independent of the stock size (Bjorndal, 1988; Tahvonen et al., 2013). In both cases, and as we are considering a small-scale fishery, the fish is sold on a local market. The fish price consumers are willing to pay depends on the amount of fish available. We model this by considering an inverse demand function given as $p_t = P(H_t)$, with $P' < 0$. No market power is assumed, and the fishermen take the price p_t as given.

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2.1 Gordon-Schaefer model of search fishery

In this model we consider a harvest function given as $H_t = qE_t X_t$, such that the harvest, or catch, is proportional to fishing effort E_t and stock size X_t (Gordon, 1954; Schaefer, 1957). The efficiency parameter, or 'catchability' coefficient, q is assumed to be exogeneous, where a higher value indicates more efficient fishing gear. We can think of an increase in q as the result of technical progress (Squires and Vestergaard, 2013 a,b) or a more lenient regulation of fishing gear, equipement or methods (Stoeven, 2014).

Fishing effort E_t is costly, and we use $C(E_t)$ to denote the effort cost function. Marginal effort costs are positive, $C'(E_t) > 0$, and nondecreasing $C''(E_t) \geq 0$ [1]. We think of this cost function as describing the (opportunity) costs of fishing for the whole fishing community, reflecting different productivities (fishing skills) among the various fishermen (Pereau et al., 2012; Grainger and

[1] In the following the univariate function $C(\cdot)$ will always indicate the effort cost function. In contrast, costs expressed as function of catch, stock size and efficiency differ for the search fishery and the schooling fishery, which is indicated by superscripts.

Costello, 2016) and different productivities of outside options (Baland and Francois, 2005). Therefore, in this fishing community the fishermen with high fishing productivity, or low opportunity costs of fishing, earn intramarginal, or Ricardan, rent. Based on the Gordon-Schaefer harvest function, and the effort cost function, we can formulate the harvesting cost function for the search fishery as:

$$C_t = C^{GS}(H_t, X_t, q) = C\left(\frac{H_t}{qX_t}\right). \tag{2}$$

From the above assumptions, it follows that fishing cost are increasing and (weakly) convex in total catch, $C^{GS}_{H_t} > 0$, $C^{GS}_{H_tH_t} \geq 0$, decreasing and convex in stock size and catchability, $C^{GS}_{X_t} < 0$, $C^{GS}_{X_tX_t} > 0$, $C^{GS}_{q} < 0$, $C^{GS}_{qq} < 0$. Furhermore, the cross derivatives with respect to H_t and both stock size and catchability are negative, $C^{GS}_{H_tX_t} < 0$, $C^{GS}_{H_tq} < 0$. The current profit, or surplus, reads then:

$$\pi^{GS}_t = p_t H_t - C^{GS}(H_t, X_t, q). \tag{3}$$

Given the decreasing inverse demand function $p_t = P(H_t)$, the instantaneous welfare derived from the fishery is the sum of consumer and producer surplus,

$$U^{GS}_t = \int_0^{H_t} P(h)dh - p_t H_t + p_t H_t - C\left(\frac{H_t}{qX_t}\right) = \int_0^{H_t} P(h)dh - C\left(\frac{H_t}{qX_t}\right). \tag{4}$$

2.2 Schooling fishery model

Our model of the schooling fishery is similar to the previous model, except that we consider harvest as independent of the current stock size, $H_t = qE_t$. With a similar effort cost function as above, the cost function for the schooling fishery is

$$C_t = C^{S}(H_t, q) = C\left(\frac{H_t}{q}\right). \tag{5}$$

Again, from the above assumptions on the effort cost function, it follows that fishing cost are increasing and (weakly) convex in total catch, $C^S_{H_t} > 0$, $C^S_{H_t H_t} \geq 0$, decreasing and convex in catchability, $C^S_q < 0$, $C^S_{qq} > 0$, and the cross derivatives with respect to H_t and catchability is negative, $C^S_{H_t q} < 0$. With the current profit as:

$$\pi^S_t = p_t H_t - C^S(H_t, q)\,, \tag{6}$$

the instantaneous welfare derived from this fishery is,

$$U^S(H_t, X_t, q) = \int_0^{H_t} P(h)dh - C\left(\frac{H_t}{q}\right). \tag{7}$$

3 Analysis and results for the small-scale fishery under restricted open access

As the first step of the analysis, we characterize the harvest under restricted open access for the two models, $j \in \{GS, S\}$. Myopic profit maximization for the given stock $X_t > 0$, and where hence the fishing impact on the stock is neglected (the shadow price of the fish stock is zero), yields $\frac{\partial \pi_t}{\partial H_t} = p_t - \frac{\partial C^j(\cdot)}{\partial H_t} \leq 0$. This defines the (inverse) supply of fish to the local market. If marginal harvesting costs are increasing, inverse supply is a smoothly increasing function of H_t. If marginal harvesting costs are constant, inverse supply is a 'bang-bang' curve, i.e. zero whenever marginal costs are above p_t and maximum possible if they are below p_t [Pindyck(1984)]. In market equilibrium, it must hold that the inverse supply equals inverse demand, and for $H^*_t > 0$ thus

$$P(H^*_t) = C^j_{H^*_t}(\cdot)\,. \tag{8}$$

Note that the downward-sloping inverse demand function $P'(H_t) < 0$ guarantees a unique market equilibrium even for constant marginal harvesting costs.

3.1 Gordon-Schaefer model of search fishery

It follows that market equilibrium harvest in the restricted open access fishery is postive or zero according to:

$$H_t^* = \begin{cases} H(X_t, q) = 0 & \text{if } P(0) - C_{H_t}^{GS}(0, X_t, q) \leq 0 \\ H(X_t, q) > 0, & \text{else.} \end{cases} \quad (9)$$

For the case of a search fishery, H_t^* is an increasing function of fish abundance X_t, if $H_t* > 0$. This follows from differentiating (8) with respect to X_t, using the implict function theorem, yields

$$\frac{dH_t^*}{dX_t} = \frac{C_{H_t X_t}^{GS}}{P'(H_t) - C_{H_t H_t}^{GS}(H_t, X_t, q)} > 0, \text{ for } H_t^* > 0. \quad (10)$$

The harvest locus may be concave or convex, depending on third order derivates of inverse demand and cost functions.

Furthermore, more efficient fishing through a higher value of q shifts down the cost function as well as the marginal costs, and hence increases the catch for a given size of the fish stock. This follows from differentiating (9) with respect to q, which yields, using the implict function theorem,

$$\frac{dH_t^*}{dq} = \frac{C_{H_t q}^{GS}}{P'(H_t) - C_{H_t H_t}^{GS}(H_t, X_t, q)} > 0, \text{ for } H_t^* > 0. \quad (11)$$

Moreover, we have that, at any given stock size, the restricted open-access harvest varies from zero to a maximum $H^{\max} \leq \infty$ given by $p = P(H^{\max}) = 0$, as stated in the following lemma.

Lemma 1 *For any given level* $H^0 \in (0, H^{\max})$ *of harvest and any given stock size* X_t,

1. there exists a $\underline{q}$ such that $H_t^* < H^0$ for all $q < \underline{q}$,
2. there exists a $\overline{q}$ such that $H_t^* > H^0$ for all $q > \overline{q}$.

Proof. The function $g(z) = zC'(z)$ is defined and montonically increasing on the set of nonnegative real numbers $z \in (0,\infty)$. Furthermore, $g(0) = 0C'(0) = 0$ and $\lim_{z\to\infty} g(z) = \infty$. Thus for any given $H^0 \in (0, H^{\max})$ there exists a z^0 that solves $H^0 P(H^0) = z^0 C'(z^0)$. Define $\underline{q} \equiv \overline{q} \equiv H^0 / \left(z^0 X_t\right)$. The rest follows from the monotonicity of H_t^* as a function of q, result (11). □

Producer surplus and consumer surplus in the restricted open access market equilibrium are

$$\pi_t^* = C_{H_t}^{GS}(H_t^*, X_t, q)H_t^* - C^{GS}(H_t^*, X_t, q) \tag{12}$$

and

$$\mathrm{CS}_t^* = \int_0^{H_t^*} P(h)dh - P(H_t^*)H_t^*. \tag{13}$$

We have the following result.

Result 1 *In the short-term, i.e. for given fish abundance* X_t*, more efficient fishing technology*

1. increases producer surplus if the elasticity of the inverse demand function is smaller than one, $-HP'(H)/P(H) < 1$,
2. increases consumer surplus.

Proof. Differentiating (12) with respect to q, using the envelope theorem and doing a small rearrangements, we find (omitting arguments)

$$\frac{d\pi_t^*}{dq} = C_{H_tH_t}^{GS} H_t^* \frac{dH_t^*}{dq} + C_{H_tq}^{GS} H_t^* - C_q^{GS} \tag{14}$$

$$\stackrel{(11)}{=} \frac{C_{H_tH_t}^{GS} H_t^* C_{H_tq}^{GS}}{P'(H_t) - C_{H_tH_t}^{GS}} + C_{H_tq}^{GS} H_t^* - C_q^{GS} = \frac{P'(H_t) H_t^* C_{H_tq}^{GS}}{P'(H_t) - C_{H_tH_t}^{GS}} - C_q^{GS} \tag{15}$$

$$\stackrel{(2)}{=} \frac{P'(H_t)\left(-\frac{H_t^{*2}}{q^3 X_t^2} C''\left(\frac{H_t^*}{qX_t}\right)\right) - \frac{H_t^*}{q^4 X_t^3} C'\left(\frac{H_t^*}{qX_t}\right) C''\left(\frac{H_t^*}{qX_t}\right)}{P'(H_t) - \frac{1}{q^2 X_t^2} C''\left(\frac{H_t^*}{qX_t}\right)} \tag{16}$$

$$= \frac{\frac{H_t^*}{q^3 X_t^2} C''\left(\frac{H_t^*}{qX_t}\right)}{P'(H_t) - \frac{1}{q^2 X_t^2} C''\left(\frac{H_t^*}{qX_t}\right)} \left(-H_t^* P'(H_t^*) - \frac{1}{qX_t} C'\left(\frac{H_t^*}{qX_t}\right)\right) \tag{17}$$

$$\overset{(8)}{=} - \frac{\frac{H_t^*}{q^3 X_t^2} C''\left(\frac{H_t^*}{qX_t}\right)}{P'(H_t) - \frac{1}{q^2 X_t^2} C''\left(\frac{H_t^*}{qX_t}\right)} P(H_t^*) \left(1 - \left(-\frac{H_t^* P'(H_t^*)}{P'(H_t^*)}\right)\right) > 0. \tag{18}$$

□

The result that consumer surplus increases with q directly follows from the assumption of a downward sloping inverse demand function according to which consumer surplus increases with H_t^* and the result that catch increases with q, equation (11).

Therefore, not surprisingly, we find that in the short run and for a given fish abundance X_t, a more efficient harvesting technology improves welfare. For producer surplus, more efficient fishing equipment through reduced costs $C_q^{GS} < 0$ works in the direction of higher profit and this effect dominates the negative price effect due to a higher harvest and reduced price if the elasticity of the inverse demand function is small enough. Consumer surplus will for sure increase through the reduced market price following more efficient harvesting. More efficient technology is therefore not only beneficially for the local fishermen in the short-term as also shown in a somewhat other setting by, e.g., Anderson (1986), but is also improves the consumer surplus and welfare of the local community in the short term.

The more interesting question is, however, what is the welfare effect of an increase in harvesting efficiency in the long run; that is, when the effect of a higher valued q on the stock is taken into account as well. With the optimized harvest function $H_t^* = H(X_t, q) \geq 0$ from (9) inserted into the stock growth (1), the dynamics of the harvested fish population is described by:

$$\frac{dX_t}{dt} = F(X_t) - H(X_t, q). \tag{19}$$

A steady state is defined as X^* when $dX_t / dt = 0$ through:

$$F(X^*) = H(X^*, q). \tag{20}$$

Moreover, the steady state described by (20) is locally stable if the harvest function interesects with the natural growth function from below,

$$F'(X^*) - H_X(X^*, q) < 0. \tag{21}$$

Under Condition (21), a small deviation from the equilibrium stock size generates a dynamic that pushes the stock back to the equilibrium: It the stock is slightly smaller (larger) than the equilibrium value, biological growth exceeds (falls short of) harvest. The stock accordingly increases (decreases) again up (down) to the equilibrium level.

The given assumptions on the natural growth function, and the result that the harvest locus is strictly increasing in fish biomass, Equation (10), are not sufficient to characterize the number of steady states, i.e. the number of solutions to (20). If the inverse demand function is bounded from above, $P(0) < \infty$, there will always be an interval of sufficiently small stock sizes where marginal harvesting costs exceed the price of fish (see also Naevdal and Skonhoft2018). Combined with the result that harvest is (weakly) increasing with stock size, Equation (10), this implies that $P(0) < \infty$ is a sufficient condition for the existence of at least one steady state.

Figure 1 illustrates the phase diagram and steady states for a standard logistic specification of the natural growth function $F(X_t) = r X_t \left(1 - X_t / K\right)$, a linearly downward-sloping inverse demand function $P(H_t) = a - bH_t$, and constant marginal effort costs $C(E_t) = cE_t$, for three different levels of harvesting efficiency. In this case when the optimized harvest reads $H_t^* = (1/b)(a - c/qX_t)$, harvest is zero for stock sizes so small that the choke price a is below the marginal fishing costs at zero harvest, and concave for stock sizes above that critical level. As harvest is strictly increasing with q, it follows that there is exactly one globally stable steady state for low efficiency. There are three steady states for intermediate efficiency, two stable steady states at low and high stock sizes, and an unstable steady state at an intermediate stock size. If harvesting efficiency is very high, there is only one (stable) steady state at a low stock size.

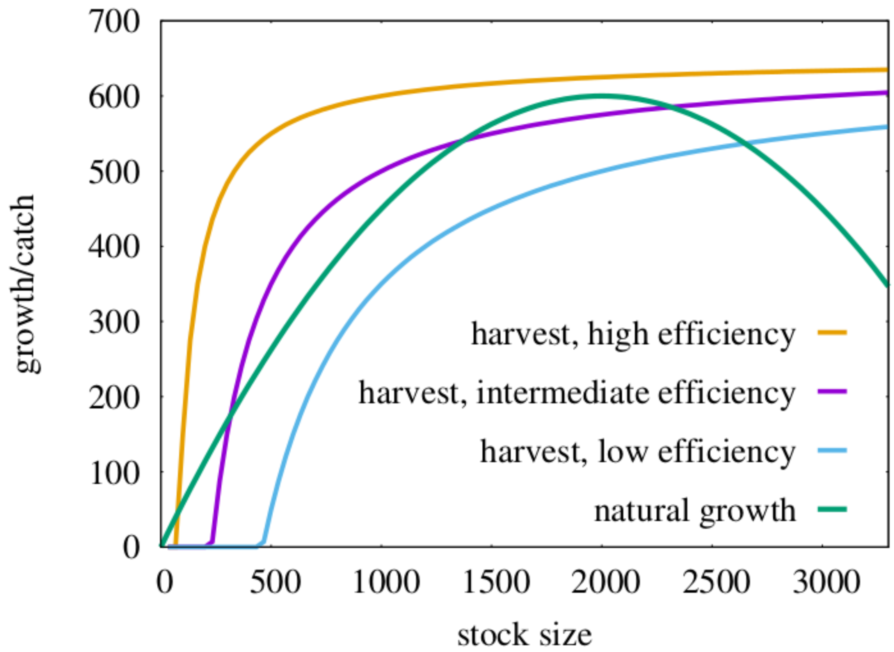

Figure 1: Phase diagram for the search fishery, assuming a logistic natural growth function $F(X_t) = rX_t(1 - X_t / K)$ *with intrinsic growth rate* $r = 0.6$, *carrying capacity* $K = 4000$, *linear inverse demand function* $P(H_t) = a - bH_t = 1{,}300 - 2H_t$, *and constant marginal effort cost* $c = 30000$. *For low, intermediate, and high efficiency, we set respectively,* $q = 0.05$, $q = 0.1$, *and* $q = 0.3$.

Independently of the particular specification of inverse demand and harvesting cost function, we find that for a low enough harvesting efficiency a unique steady state exists at a stock size above the level X^{msy} that generates the maximum sustainable yield.

Result 2 *There exists a level of harvesting efficiency* q^{msy} *such that for all* $q < q^{\text{msy}}$

1. the steady state is unique,
2. the steady state stock size exceeds the MSY fish population, $X^* > X^{\text{msy}}$.

Proof. Consider all potential (steady-state) stock sizes below or at X^{msy}, i.e. consider all $X^0 \in (0, X^{\text{msy}}]$, and the corresponding biological equilibrium harvest $H^0 = F(X^0)$. By Lemma 1, we can define a value $\underline{q}(X^0)$, and find a corresponding $\underline{q}(X^0)$, for every X^0 such that $H^* < H^0 = F(X^0)$ for all $q < \underline{q}(X^0)$. Now defining $q^{\text{msy}} = \min_{X^0 \in (0, X^{\text{msy}}]} \underline{q}(X^0)$, we have

$H(X^0,q) < F(X^0)$ for all $X^0 \in (0, X^{\text{msy}}]$ whenever $q < q^{\text{msy}}$: No steady state exists at a stock size below X^{msy}, and $H(X^{\text{msy}},q) < F(X^{\text{msy}})$, for all $q < q^{\text{msy}}$. As $H(X^{\text{msy}},q) < F(X^{\text{msy}})$, $H(X,q)$ is increasing in X, $F'(X) < 0$ for $X \in (X^{\text{msy}}, K)$, and $F(K) = 0$, a unique steady state $X^* > X^{\text{msy}}$ must exist for all $q < q^{\text{msy}}$. □

Of course, the lower bound on the level of harvesting efficiency defined in Result 2 depends on the natural growth rate and carrying capacity of the fish stock, and consumer demand and the unit effort cost. Everything else equal, the threshold is higher for a fast growing fish stock, high carrying capacity, and low demand.

We now turn, for this model, to the main question studied in this paper: How does increased harvesting efficiency affect consumer surplus and producer surplus in the long run? To this end, differentiate (20) with respect to q and apply the implicit function theorem. This leads to

$$\left(F'(X^*) - H_X^*(X^*,q)\right)\frac{dX^*}{dq} = H_q^*(X^*,q). \tag{22}$$

Through Equation (11), we have seen that a higher q always increases the harvesting pressure, i.e. the right-hand-side of (22) is positive. As we are considering a locally stable steady state, the factor in brackets on the left-hand side of (22) is negative. Hence, a small increase in harvesting efficiency will consistently lower the stable equilibrium stock, $dX^*/dq < 0$. On the other hand, more efficient technology may either reduce or increase $F(X^*)$, and hence by Equation (20) also either reduce or increase steady-state harvest. The critical steady-state stock size is here X^{msy}, and where steady-state harvest increases with efficiency if $X^* < X^{msy}$. As consumer surplus unambiguosuly increases with harvest, we have

$$\frac{d\text{CS}^*}{dq} \gtreqless 0 \quad \Leftrightarrow \quad X^* \gtreqless X^{\text{msy}}. \tag{23}$$

Thus, if the initial harvesting efficiency is low enough that the stock is not MSY-overfished in restricted open access steady state, an improvement in fishing efficieny – be it due to technical progress or be it due to a change in regulation – improves consumer surplus both in the short run and in the long run. According to Result 2 a sufficient condition for this is $q < q^{\text{msy}}$.

However, the effect of an increase in q on producer surplus is not quite as straightforward, as producer surplus is also directly affected by the decrease in stock size triggered by an increase in q. To answer this question, consider producer surplus, (12), at steady state i.e. for $X_t = X^*$, and differentiate this expression with respect to q, taking the effect of q on X^* and on $H_t^* = F(X^*)$ into account. Using (8) for $H_t^* > 0$, this yields (omitting arguments of functions)

$$\frac{d\pi^*}{dq} = C_{H_tH_t}^{GS} H^* H_q^* + \left(C_{H_tX_t}^{GS} H^* + C_{H_tH_t}^{GS} H H_X^* - C_{X_t}^{GS} \right) X_q^* + C_{H_tq}^{GS} H^* - C_q^{GS}. \tag{24}$$

Obviously, this expression contains positive and negative expressions. Therefore, while Result 1 indicates that the short-run effect of more efficient fishing increases producer surplus suggested that the elasticity of the inverse demand function is less than one, the long-term effect in the search fishery is generally ambiguous. The reason is that the long-run effect comprises two opposite forces, and where the direct positive effect of a higher q working through the cost function is counterbalanced by a negative indirect effect also working through the cost function by a reduction of the stock abundance.

Under the given assumptions, we can characterize the sign of the net effect of more efficient harvesting on steady-state welfare as follows.

Result 3 *The following three statements are equivalent*

1. The steady state stock size is above/below the stock that generates the maximum sustainable yield.
2. Consumer surplus increases/decreases with harvesting efficiency.
3. Producer surplus increases/decreases with harvesting efficiency.

Formally,

$$X^* \gtreqless X^{\text{msy}} \quad \Leftrightarrow \quad \frac{d\text{CS}^*}{dq} \gtreqless 0 \quad \Leftrightarrow \quad \frac{d\pi^*}{dq} \gtreqless 0. \tag{25}$$

Proof. We have already proven the result for consumer surplus. Here we show that we obtain the same for producer surplus. Using (22) in (24), we have

$$\frac{d\pi^*}{dq} = \frac{1}{F'(X^*) - H_X}(\left(C^{GS}_{H_t X_t} H^* + C^{GS}_{H_t H_t} H H^*_X - C^{GS}_{X_t}\right) H^*_q$$

$$+\left(C^{GS}_{H_t H_t} H^* H^*_q + C^{GS}_{H_t q} H^* - C^{GS}_q\right)\left(F'(X^*) - H_X\right)) \tag{26}$$

Differentiating Condition (8) that determines harvest under restricted open-access with respect to X_t and q, we obtain

$$\left(P'(H^*_t) - C^{GS}_{H_t H_t}\right) H^*_X = C^{GS}_{H_t X_t},$$

$$\left(P'(H^*_t) - C^{GS}_{H_t H_t}\right) H^*_q = C^{GS}_{H_t q}.$$

Combining the two, we have $C^{GS}_{H_t X_t} H^*_q = C^{GS}_{H_t q} H^*_X$. Note that the cost function (2) implies $X_t C^{GS}_{X_t} = q C^{GS}_q$ and $X_t C^{GS}_{H_t X_t} = q C^{GS}_{H_t q}$. We thus also have $C^{GS}_{X_t} H^*_q = C^{GS}_q H^*_X$. Using these results, (26) simplifies to

$$\frac{d\pi^*}{dq} = \frac{F'(X^*)}{F'(X^*) - H_X}\left(C^{GS}_{H_t H_t} H^* H^*_q + C^{GS}_{H_t q} H^* - C^{GS}_q\right) \tag{27}$$

The term in brackets is the short-term effect of more efficient fishing technology on profit, as given in (14). Under the assumptions given in Result 1, it is positive. Thus, the sign of $d\pi^* / dq$ depens on the sign of the first factor. For a stable steady state, the denominator is negative. Thus, $d\pi^* / dq > 0$ if and only if $F'(X^*) < 0$, which is the case if and only if $X^* > X^{\text{msy}}$. □

This result shows that in a situation with a high exploitation pressure, channeled through a high harvesting efficiency and $X^* < X^{msy}$, more efficient technology will reduce steady-state producer surplus while the opposite happens when initially $X^* > X^{msy}$. Result 3 contrasts the outcome of the standard sole owner biomass model where improved harvesting technology, and hence lower catch costs, unambiguously increases the equilibrium rent (again, see Clark, 1990, Ch. 2).

Both steady-state consumer surplus and steady state producer surplus will be at its maximum when the steady stock size is equal to the stock size that generates the maximum sustainable yield,

$X^* = X^{\text{msy}}$. As consumer surplus increases with harvest, the maximum of consumer surplus in the search fishery will be higher the larger the MSY is. Therefore, the maximum consumer surplus will be higher for larger biological productivity. Maximum producer surplus in the search fishery can be written as $\pi^{\max} = P(H^{\text{msy}})H^{\text{msy}} - C^{GS}\left(H^{\text{msy}}, X^{\text{msy}}, q\right)$. For the case of a cost function with a constant elasticity $\beta \geq 1$ of cost with respect to harvest, i.e. where $C^{GS} = \beta H_t C^{GS}_{H_t}$, we have, using (9), $\pi^{\max} = P(H^{\text{msy}})H^{\text{msy}} - C^{GS}\left(H^{\text{msy}}, X^{\text{msy}}, q\right) = \dfrac{1-\alpha}{\alpha} P(H^{\text{msy}})H^{\text{msy}}$, which does not depend on harvesting efficiency q. We thus have the following result.

Result 4 *For constant marginal harvesting cost, or more generally an iso-elastic harvesting cost function, the maximum steady state welfare is unrelated to fishing efficiency.*

However, while the maximum rent in our model is not contingent upon the technological level, it is also clear that there will be a certain value of q that yield the highest rent. This possibly efficiency level $q = q^{\max}$ solves the stock equilibrium equation $F(X^{msy}) = H^*(X^{msy}, q^{\max})$ and is hence contingent upon all the parameters of the model.

3.2 The schooling fishery

For the case of a schooling fishery, harvesting costs do not depend on the current stock size. Thus, also the level of harvest that fulfills equation (8) is independent of X_t. Therefore, in the stock - harvest space, the restricted open-access harvest schedule $H_t^* = H^S(q)$ will be a straight horizontal line. As above, the harvest shifts up with higher harvesting efficiency q, $H_q^S(q) > 0$. With the specification (5), there exists a $\bar{q}$ for all $\bar{H}$ such that $H^S(q) > \bar{H}$ for all $q > \bar{q}$. In particular, there exists a $q^{\max}$ such that $H^S(q) > H^{\text{msy}}$ for all $q > q^{\max}$.

A steady state is given by

$$F(X^*) = H^S(q) \tag{28}$$

Equation (28) yields two equilibria when $F(X^{\text{msy}}) > H^S(q)$, $\underline{X}^*$ and $\overline{X}^*$, with $\underline{X}^* < X^{\text{msy}} < \overline{X}^*$, where $\underline{X}^*$ is unstable, while $\overline{X}^*$ is locally stable. Thus, the fish stock will be depleted in a schooling fishery under restricted open access with an initial stock size located below that of $\underline{X}^*$. In that case, more efficient technology shifts up the harvest locus and drive the stock even faster to extinction. The situation will be of the opposite with an equilibrium defined through $F(\overline{X}^*) = H(q)$. In this case more efficient harvest technology and lower harvesting costs for sure will reduce the stock (this follows from $H_q^* > 0$ and the stability condition for the steady state), but increase the steady state catch, $H^S(q) = F(\overline{X}^*)$.

In the locally stable steady state consumer and producer surpluses can be expressed as

$$\text{CS}^* = \int_0^{H^*} P(h)dh - P(H^*)H^*, \tag{29}$$

$$\pi^* = P(H^*)H^* - C^S(H^*, q). \tag{30}$$

Both are strictly increasing with H^*. Thus, we have the following result.

Result 5 *In a stable steady state in the schooling fishery, and if* $q < q^{\max}$*, more efficient fishing increases both consumer surplus and producer surplus.*

4 Generalization

To obtain some indications of how robust the above results are, we will look at a very general model of harvesting and welfare derived from the fishery. In general, aggregate instantaneous welfare derived from the fishery is described by a utility function

$$U_t = U(H_t, X_t, q), \tag{31}$$

which is increasing in harvest, $U_{H_t} > 0$, nondecreasing in stock size, $U_{X_t} \geq 0$, and increasing in efficiency $U_q > 0$. We further assume that marginal utility of catch weakly increases with stock size, $U_{H_t X_t} \geq 0$, and increases with efficiency, $U_{H_t q} > 0$. As above, the assumption $U_q > 0$ implies that the immediate effect of increasing efficiency – when keeping stock size constant – is positive.

The instantaneous welfare function (31) can capture net economic surplus – the sum of consumer and producer surplus – in a commercial fishery. The general formulation (31), applied to a commercial fishery, also allows to consider that consumers' willingness to pay for fish includes concerns for sustainability, for example in a way that the demand for fish positively depends on stock size. The instantaneous welfare function (31) can also model a recreational fishery, where (31) describes the utility of a representative individual in recreational fishing or hunting. It is sensible to assume that the recreational fishing experience positively depends on the catch quantity and stock size.

We assume that the net utility is separable as follows

$$U(H, X, q) = \hat{U}(H, y(X, q)) \qquad \text{(Assumption 1)}$$

Harvesting profit with a Gordon-Schaefer cost function is a special case, where $y(X, q)$ can be interpreted as the catch per unit of effort.

The condition determining harvest in restricted open access simply is

$$U_H(H_t^*, X_t, q) = 0 \qquad (32)$$

Differentiating (32) with respect to X and q gives, adopting (Assumption 1),

$$U_{HH} H_X^* = -U_{HX} = -\hat{U}_{Hy} y_X \qquad (33)$$

$$U_{HH} H_q^* = -U_{Hq} = -\hat{U}_{Hy} y_q \qquad (34)$$

Under Assumption 1, it follows that $U_X H_q^* = U_q H_X^*$, where $U_x = \hat{U}_y y_X$ and $U_q = \hat{U}_y y_q$. From the assumptions on U it also follows that $H_q^* > 0$.

Differentiating the steady-state condition $F(X^*) = H^*$ with respect to q gives

$$\left(F' - H_X^*\right) X_q = H_q^* \qquad (35)$$

Stability requires $F' - H_X^* < 0$. Thus, $X_q < 0$.

Now consider a steady state in which changes in q lead to changes in h, which has repercussions on the steady state stock size X. Taking these feedbacks into account, we obtain the following long-term relationship between U and q:

$$\frac{dU}{dq} = U_q + U_X X_q = U_q + U_X H_q^* \frac{1}{F' - H_X^*} = U_q \frac{F'}{F' - H_X^*} \tag{36}$$

The first equality holds by virtue of the Envelope theorem. The second equality uses equation (35) that states how steady state stock size reacts to changes in q via changes in h. In the last step we have used Assumption 1, which implies $U_X H_q^* = U_q H_X^*$, as shown above. Thus, we conclude that our main results hold for this very general harvesting model. This is summarized as follows.

Theorem 1 *The following statements are equivalent*

1. The steady state stock size is above/below the stock that generates the maximum sustainable yield.

2. Steady-state welfare increases/decreases with harvesting efficiency.

Formally,

$$X^* \gtreqless X^{\text{msy}} \quad \Leftrightarrow \quad \frac{dU^*}{dq} \gtreqless 0. \tag{37}$$

5 Concluding remarks

This paper has theoretically analyzed how increasing harvesting efficiency affects steady-state welfare in a restricted open-access fishery, where a fixed number of fishermen exploit a fish stock in a myopic profit-maximizing manner. This model describes a situation typical for many small-scale or recreational fisheries world wide.

Our most important finding is that the effect of more efficient harvesting goes in the same direction for the different components of welfare, and that an increase of harvesting efficiency has an ambiguous long-term effect on consumer surplus, producer surplus, or more generally, welfare, in the fishery. All components of welfare increase with harvesting efficiency in steady state if the steady state stock exceeds the size that would generate the maximum sustainable yield (MSY). In contrast, if the steady fish population is smaller than the MSY stock size, i.e., if there is MSY overfishing, increasing harvesting efficiency reduces steady-state welfare. As the steady state stock size decreases with harvesting efficiency in restricted open access, it depends on the initial harvesting efficiency whether an increase is welfare-enhancing or detrimental. The critical level of harvesting efficiency depends on the market price of harvest and on the biological productivity of the stock.

Our results have clear policy relevance, especially in the case where resource use is subject to regulations that affect harvesting efficiency, such as gear regulations, regulations of harvesting locations or seasons, in fisheries. In these cases, a less restrictive regulation is welfare-enhancing if and only if there is no MSY overfishing in steady state. Our results further imply that in the second-best setting of restricted open access the maximum sustainable yield is the appropriate policy target, even in a situation where harvesting costs are stock-dependent.

We have shown that these main results are very general. Although we had a small-scale or recreational fishery in mind, the result holds equally for other resources that are harvested under restricted open access. This includes many cases of wildlife hunting, timber and non-timber use forests, or rangelands. In all cases, an increase in harvesting efficiency has the described ambiguous effect.

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