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DECOMPOSING FISHING EFFORT: MODELLING THE SOURCES OF INEFFICIENCY IN A LIMITED-ENTRY FISHERY

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DISCUSSION PAPER 16.23

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Abstract:

We introduce a modified version of the Gordon-Schaefer (GS) fishery model that neatly describes different sources of inefficiency in limited entry fisheries. In our modified model, each vessel chooses the number of fishing days as well as the rest of the inputs, where the choice of the latter determines its catchability coefficient. Consequently, our model explicitly isolates two sources of fishery inefficiency: (i) excess vessel days (vessels operate for more than the optimal number of days); and (ii) capital stuffing (vessels spend more than optimal on increasing their catchability coefficient). Our model predicts that when vessels cannot choose the number of fishing days as they like, both of the two sources of inefficiency become relevant in assessing the policy effects. We find that, in fisheries with fish stocks below maximum-sustainable-yield levels, introducing restrictions on fishing days or day-based access fees can increase harvest, fish stocks and total rents.

Keywords: Fishery management, overfishing, capital-stuffing, limited entry, catchability coefficient, Gordon-Schaefer model

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1. Introduction

Effort restrictions are a major element of traditional fisheries management and fisheries economics literature. It is often argued that limiting entry is a flawed approach to restricting effort, which does not solve the problems of overfishing and stock depletion. For example, Grafton *et al.* (2004) note that, although it is easy to attempt to control effort by limiting the number of boats that enter the fishery, regulating the effort of each boat once they have gained access is more problematic. The argument goes: once fishers have gained entry, the equilibrium outcome for harvest and stock levels is still likely to end up being the same as in the unregulated fishery because each fisher would have incentive to increase their investments in technology to increase their harvests.

Some time ago, Townsend (1990) offered a long list of fisheries that experienced an increase in overall effort, despite controls such as limited entry, gear restrictions and seasonal restrictions. This excessive effort is sometimes the result of too many vessels operating in the fishery, but a key problem appears to be excessive use of inputs by each vessel. For example, the number of vessels in the British Columbian Salmon Fishery was reduced from 1969, but this did not stop fishing power from continuing to grow. Fresh water fisheries in Ontario were subject to entry restrictions prior to 1984, but this simply led to the use of more powerful gear, and the amount of effort in the fishery still increased. Likewise, in Norway, entry restrictions reduced the number of purse seiners, but each vessel increased its use of inputs and the capacity of the fleet still increased. In the Alaskan Salmon fishery dramatic increases of capital and labour per licence occurred, despite gear restrictions. Here, the level of capital per licence doubled between 1973 and 1982, and that of labour increased by one third. Based on this pattern, Townsend concludes that limited entry is "at best, one element in a broader program of fisheries management" (Townsend 1990, p.374).

These examples focus on fisheries where an inefficiently large amount of effort is brought about by excessive input utilisation by each of the vessels. In the literature examining limited entry fisheries, this excessive input utilisation by a vessel appears to be a synonym to *capital-stuffing*. For example, Townsend (1985, p.195) describes capital-stuffing as "the increased use of capital by each firm." Dupont (1990, p.26) notes that capital-stuffing "occurs when fishermen attempt to increase their catches by using more unrestricted inputs in place of the restricted input, usually vessel size." Aside from the examples mentioned above, over many decades, similar stories regarding capital-stuffing behaviour have been reported in the literature (e.g., Wilen, 1988; Dupont, 1990, 1996; Clark and Munro, 2002; Kirkley, Morrison Paul and Squires, 2002; Kompas, Che and Grafton, 2004; Smith, Zhang and Coleman, 2008), indicating the importance of the phenomenon.

Thus, there is abundant recognition in the fisheries literature that effort in a fishery can be increased via three key margins: a larger number of vessels; a greater number of days fished per vessel; and increasing the catchability coefficient (Grévobal 2003) by increasing the use of other inputs such as labour and gear. It is vessels' ability to make decisions about all three of these types of effort that can render regulator's attempts to reduce fishing power ineffective.

In the theoretical literature, the excessive effort in a fishery has been described predominantly at the industry level under different policy environments. Whilst the seminal work by Gordon (1954) focussed on the excessive industry effort in an unregulated open access fishery, Homans and Wilen (1997) present a model of a regulated open access fishery where a total allowable catch (TAC) is enforced with a seasonal closure. They predict that regulated fisheries are likely to end up with a greater redundant capital than in Gordon's unregulated open access model. Deacon, Finnoff and Tschirhart (2011) extend their work by allowing substitution between restricted and unrestricted inputs to take into account the industry effort expansion on the uncontrolled margin.

Meanwhile, little theoretical work has focused on individual vessels and their excessive use of effort. Anderson (1976) examines the link between a fishery and firms (vessels) in operation. Karpoff (1987) studies how firms, hence a fishery in aggregate, might respond to a regulation that restricts the use of effort, which Campbell and Lindner (1990) extend by allowing for substitution between restricted and unrestricted inputs. More recently, Boyce (2004) has offered a general model that compares inefficiencies under various policy environments both at vessel and industry levels, whilst Costello and Deacon (2007) have developed a model to uncover potential inefficiency in fisheries under the individual transferable quota (ITQ) regulation.

Our paper adds to the above literature by presenting a modified version of the Gordon-Schaefer (GS) model which disaggregates 'effort' into its three components; number of vessels, days fished and fishing technology. We model vessel choices about the number of days fished and expenditure on fishing technology under a limited-entry regulation. Accordingly our model separately identifies the two main sources of inefficiency and rent dissipation in limited-entry fisheries. The first source of inefficiency is called '*excess vessel days*', which is caused by the entire fleet of vessels fishing greater than the optimal number of days. Excess vessel days are influenced by the regulator that exogenously sets the total number of vessels and, potentially, the total number of fishing days (for example, through seasonal entry restrictions). Importantly, excess vessel days can lead to rent dissipation even when each vessel is efficiently equipped.[5] The second source of inefficiency is '*capital stuffing*', which is caused by excessive or inefficient input utilisation by each vessel. Such capital-stuffing behaviour is influenced by vessels that endogenously choose their level and type of gearing.

Our paper is in the same spirit of Anderson (1976; 1985), Karpoff (1987) and Campbell and Lindner (1990) in terms of explicitly focussing on the vessel level inefficiency, but ours is distinct in examining fisheries under a limited-entry regulation. Boyce (2004) describes vessel's capital stuffing in an entry-restricted fishery, but in a more generic framework. Instead, we describe vessel's capital stiffing behaviour in an explicit bioeconomic framework which enables us to illustrate various outcomes using diagrams that conform to those used in the standard GS model.

Our focus on limited-entry fisheries is important, due to the prevalence of this management approach around the world. Many fisheries still rely on limited entry and effort regulations, despite the large literature on their drawbacks discussed earlier. This is especially the case in

[5] The existing literature has pursued the now familiar notion of '*fleet redundancy*', which is a similar but different idea to excess vessel days. Fleet redundancy is relevant to fisheries where the seasonal harvest, rather than the number of vessels, is restricted – usually by setting a TAC. If more than the minimum number of vessels required to harvest the TAC actually operate in these fisheries, and if some vessel costs are non-malleable, total fishery costs are higher and rents lower than otherwise. This excess of vessels in a fishery with harvest restrictions is called fleet redundancy. Rent dissipation caused by fleet redundancy is theoretically presented in Munro and Scott (1985) by employing Clark's (1990) seasonal fishery model, and is found to be significant in the British Columbia commercial salmon fishery in the empirical work by Dupont (1990). In our modified version of the GS model, though, as in the standard one, all vessel costs are assumed to be malleable, so fleet redundancy in the sense of Munro and Scott (1985) is precluded.

developing countries as effort restrictions are generally easier to implement (Grévobal, 2003). In addition, there is growing research interest in managing fishing capacity, which includes vessel entries (see for example Pascoe, 2007; Nostbakken, Thébaud and Sørensen, 2011; and Pomeroy, 2012). By separately identifying inefficiencies caused by capital stuffing and excess vessel days, our model can explicitly examine how various policies affect vessel behaviour in a limited-entry fishery. This, in turn, allows the model to describe the effect on fishery rents and fish stocks. Our model is therefore a powerful tool to assess the benefits and costs of alternative management programs in limited-entry fisheries; for example, our model can assess a policy change that has taken place in the Western and Central Pacific tuna fishery.

This paper is organised as follows. In Section 2 we describe the model, particularly emphasising the departure from the standard GS model. Various equilibria in the model will be explained in Section 3, where important equilibria in the standard GS model are represented as those under extreme cases in our model. Section 4 introduces additional regulations and access fees and we examine their effect on the equilibrium. Section 5 discusses the implications of our model and concludes.

2. The model

The modelling approach adopted will broadly follow that of Clark (1990), who first derives the decisions of single vessels according to their profit maximisation problems and then aggregates these decisions to arrive at the equilibrium conditions for the entire fishery. The disaggregation of the decision making process to the individual vessel level is different to the GS model, and allows us to describe possible capital-stuffing behaviour by each vessel. The aggregation of the vessels in the steady-state equilibrium, however, allows us to examine a diagram which is conformable to that used in the GS model.

2.1 Departures from the GS model

The classification of 'effort' will be central to the analysis. As noted in the Introduction, the term 'effort' is used in a variety of ways in the literature. Usually 'effort' refers to the most general notion of fishing effort, and is used as an index encompassing all measures of effort such as days fished, number of vessels, labour, fuel, technology and so on.

We use the total number of days vessels operate as the basic measure of effort, and delegate the other traditional measures (labour, fuel, gear *etc.*) each vessel chooses to employ to items that determine *technology*, which will be explained shortly. B is used to represent the number of vessels (or boats) allowed to operate in the limited-entry fishery, and is assumed to be fixed by the regulator. 'Days,' $D_i \geq 0$, is the number of days Vessel *i* chooses to operate. Hence, the total number of days in the limited-entry fishery is given by $\sum_{i=1}^{B} D_i$.

Each vessel chooses harvest levels in order to maximise their profit. The harvest function for a single vessel is written as:

$$h_i = h(D_i, w_i, X) = q_i(w_i) D_i X, \tag{1}$$

for $i = 1, 2, \ldots, B$, and where:

h_i:	harvest for Vessel i,
$h(D_i, w_i, X)$:	harvest function,
X:	total stock of fish,
$q_i(w_i)$:	'catchability coefficient,' which is a function of w_i,
w_i:	cost (per day) of using Vessel i.

The function is similar to the harvest function in the traditional GS model, but there are three important differences. First, the Schaefer harvest function specifies the harvest level for the whole fishery, but our harvest function specifies the harvest for each vessel. Second, the harvest level is a function of *days* instead of *effort* since we delegate the other traditional measures of effort to technology. For that reason, third but not the least, unlike in the GS model, the catchability coefficient for each vessel is assumed to be a function of w_i. This specification of the harvest function is the most important departure from the GS model whose harvest function has only one choice variable, effort, which encompasses both days and technology.

As in the GS model, the catchability coefficient, $q_i(w_i)$, describes the biological and technological characteristics of the fishery that control how easy it is to catch the fish. More specifically, in our vessel's harvest function, $q_i(w_i)$ determines the proportion of stock that any vessel will capture for *a day's* fishing.

Assuming that the catchability coefficient is a function of expenditure per day allows the model to capture the observed inefficient gearing behaviour at the vessel level, or capital-stuffing. By increasing the level of per day expenditure on technology, w_i, the vessel operator can increase their catchability coefficient. In order to reflect inefficient gearing behaviour, the $q_i(w_i)$ schedule must be non-linear, as shown in the expenditure-catchability schedule depicted in Figure 1.

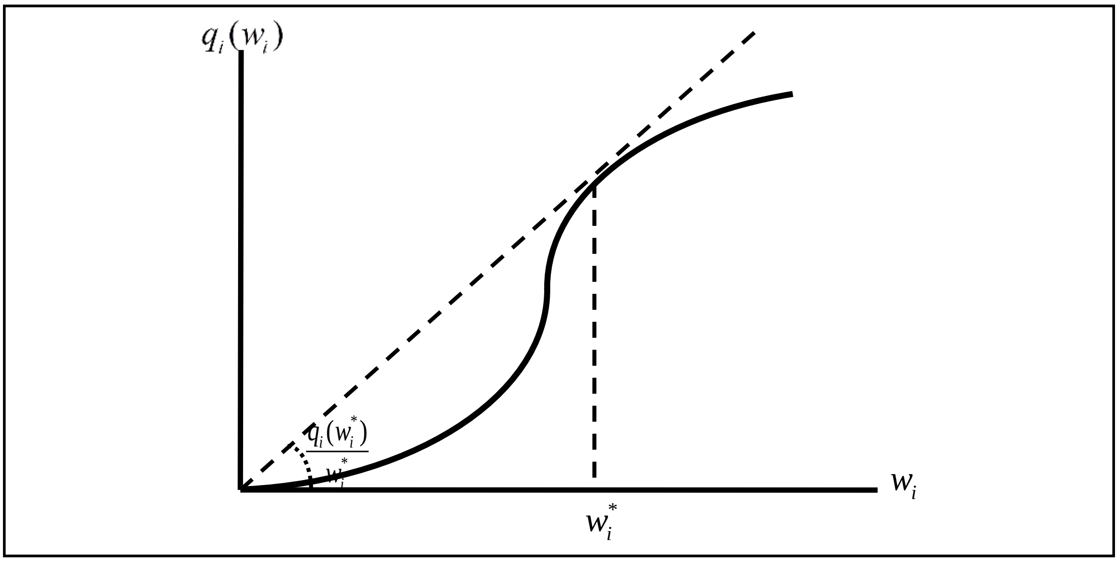

Figure 1: Catchability and expenditure

As expenditure per day increases from a very small level, catchability will increase at an increasing rate, as shown in Figure 1. For example, if a vessel uses larger nets or travels further to reach more productive fishing areas, it can be expected to have a significant positive impact on harvest. Thus, at low levels of daily expenditure, the $q_i(w_i)$ curve will be increasing and convex. However, at some point, the cost of increasing catchability by one unit will begin to increase. This gives rise to the S-shape of the curve shown in Figure 1.

The slope of any ray from the origin might be loosely termed as 'catchability per expenditure,' the inverse of which is the average cost of catchability. The S-shape of the catchability curve implies that the average cost curve for an individual vessel is the familiar U-shape. Thus, there will exist a unique efficient scale, where average costs will be minimised. This level is shown in Figure 1 as w_i^*. Capital-stuffing occurs whenever a vessel spends more than w_i^*.

2.2 Vessel's optimisation problem and equilibrium in the fishery

Provided our harvest function, profit for Vessel *i* is written as:

$$\pi_i = p_h q_i(w_i) D_i X - w_i D_i \tag{2}$$

where:

π_i:	profit for Vessel *i*,
p_h	exogenously given price per unit of harvest.

The following conditions must hold in any steady state Nash equilibrium:

1. every vessel maximises profits given the other vessels' behaviour, i.e. no vessel has an incentive to deviate from the equilibrium outcome, and;

2. the biological steady state condition holds, that is, total harvest is equal to biological growth in the fish stock.

The first condition implies that vessels $i = 1, 2, \ldots, B$ maximise π_i by choosing $w_i \geq 0$ and $D_i \geq 0$. However, in equilibrium, the second condition must also hold, and to discuss it we need to introduce the growth function $F(X)$ for the fish stock X. As in the GS model, it is assumed to be the logistic growth function, where r is the natural growth rate of the stock and K is the carrying capacity so that:

$$F(X) = rX\left(1 - \frac{X}{K}\right). \tag{3}$$

Condition 2 implies that $F(X) = H$ in the steady state, where H is the total harvest in the fishery. Together with the fact that $H = \sum_{i=1}^{B} h_i = \sum_{i=1}^{B} q_i(w_i) D_i X$, the following must hold in equilibrium:

$$rX\left(1 - \frac{X}{K}\right) = \sum_{i=1}^{B} q_i(w_i) D_i X. \tag{4}$$

which simplifies to:

$$X = K\left[1 - \frac{1}{r}\sum\nolimits_{i=1}^{B} q_i(w_i)D_i\right]. \tag{5}$$

It is apparent that the steady state level of fish stock depends on total harvest. The equation therefore also implies that each vessel's level of profits is affected by the decisions of the other vessels, since the stock level depends not only on its harvest, but also on the harvest of the other operating vessels. This is the well-established stock externality. Substituting Equation (5) into the vessels' profit identity gives:

$$\pi_i = p_h q_i(w_i)D_i K\left[1 - \frac{1}{r}\sum_{i=1}^{B} q_i(w_i)D_i\right] - w_i D_i. \tag{6}$$

Hence, vessels i's optimisation problem can be written as:

$$\max_{w_i, D_i}\left[p_h q_i(w_i)D_i K\left[1 - \frac{1}{r}q_i(w_i)D_i - \frac{1}{r}\sum_{j\neq i}^{B} q_j(w_j)D_j\right] - w_i D_i\right], \tag{7}$$

subject to $w_i \geq 0$ and $D_i \geq 0$, $\forall i = 1, 2, ..., B$.

First-order conditions for interior solutions are as follows:

$$p_h q_i(w_i)K\left[1 - \frac{2}{r}q_i(w_i)D_i - \frac{1}{r}\sum_{j\neq i}^{B} q_j(w_j)D_j\right] = w_i \tag{8}$$

$$p_h q_i'(w_i)K\left[1 - \frac{2}{r}q_i(w_i)D_i - \frac{1}{r}\sum_{j\neq i}^{B} q_j(w_j)D_j\right] = 1 \tag{9}$$

Putting the two conditions together yields the following:

$$\frac{q_i(w_i)}{w_i} = q_i'(w_i) \qquad \text{or} \qquad q_i'(w_i)\frac{w_i}{q_i(w_i)} = 1 \tag{10}$$

Equation (10) will hold for any vessel operating in the limited-entry fishery and imply that the vessel's choice of w_i does not depend on the decisions of their competitors. The first expression says that the average 'catchability' per unit of expenditure is equal to the marginal benefit of increasing expenditure. Based on the cost structure developed in the previous subsection, this implies that each vessel operates at minimum average cost. The second, equivalent, expression says that the elasticity of catchability with respect to expenditure per day is set equal to unity, which makes intuitive sense. For example, consider the case where the elasticity of $q_i(w_i)$ with respect to w_i is greater than unity, then if the vessel increased expenditure by one per cent, catchability would increase by more than one per cent. In this situation, the vessel would be able to increase revenue from harvest by a greater proportion than it increased costs, and so it would be profitable to increase w_i. By the same reasoning, it would be profitable to decrease w_i whenever the elasticity is less than unity. Hence, the equilibrium outcome involves the elasticity at unity. In Figure 1, the catchability coefficient $q_i(w_i^*)$ for a profit maximising vessel i is illustrated.

3. Equilibrium analysis

The previous section examined the profit maximising choices of each vessel in a limited-entry fishery. In this section we will compare static steady-state equilibrium outcomes for the case of a single-vessel fishery and a multiple-vessel fishery. These outcomes can be illustrated using diagrams that conform to those used in the GS model. The equilibrium analysis here will serve as a reference point for the following section where we examine the effects of additional regulations.

3.1 Single-vessel equilibrium

Consider the case where there is only one vessel operating in the fishery. Finding the decisions of this firm will be equivalent to maximising the rents in the entire fishery. This is because the stock externality mentioned in the previous section is completely internalised since the single vessel is the only one to bear any cost of a decreased fish stock. The profits of the single vessel are known as the maximum economic yield (MEY) and they acts as a benchmark against which to compare other outcomes for the limited-entry fishery. The vessel, however, is still considered to be a price taker in the product and factor markets as in the GS model.

For the single vessel, the maximisation problem is the same as the profit maximisation problem specified above except that the terms involving the harvest of other vessels drop out. Removing the *i* subscripts the maximisation problem becomes:

$$\max_{w,D} \left[p_h q(w) D K \left[1 - \frac{1}{r} q(w) D \right] - wD \right] \tag{11}$$

subject to $w \geq 0$ and $D \geq 0$. Assuming an interior solution, then, the first order conditions are:

$$p_h q(w) K \left[1 - \frac{2}{r} q(w) D \right] = w \tag{12}$$

and

$$p_h q'(w) K \left[1 - \frac{2}{r} q(w) D \right] = 1. \tag{13}$$

Using (12) and (13), the optimal level of *w* is implicitly determined by the following, as before:

$$q'(w) \frac{w}{q(w)} = 1. \tag{14}$$

This equation means that the single vessel will operate at minimum average cost w^*, i.e. $w_{mey} = w^*$. This equation and the first order conditions imply that the optimal vessel days, D_{mey}, are:

$$D_{mey} = \frac{r}{2q(w^*)} \left[1 - \frac{w^*}{p_h q(w^*) K} \right]. \tag{15}$$

For D_{mey} to be positive, the only requirement is that $p_h q(w^*)K > w^*$. That is, the parameters have values such that it is possible to make positive profits by fishing the first day, starting with the fish stock at its carrying capacity.

The stock of fish (X_{mey}), the harvest (H_{mey}), and the rent (π_{mey}) for the single-vessel equilibrium are given, respectively, as follows:

$$X_{mey} = \frac{1}{2}\left[K + \frac{w^*}{p_h q(w^*)}\right], \tag{16}$$

$$H_{mey} = \frac{1}{4}Kr\left[1 - \left(\frac{w^*}{p_h q(w^*)K}\right)^2\right], \tag{17}$$

$$\pi_{mey} = \frac{1}{4}p_h Kr\left(\frac{w^*}{p_h q(w^*)K} - 1\right)^2. \tag{18}$$

In the single-vessel equilibrium, rents are maximised in the fishery: the vessel is geared efficiently and there are no excess vessel days. The fish stock is also at its rent-maximising level, which is even larger than the level associated with maximum sustainable yield, so there is no overfishing problem.

3.2 Multiple-vessel equilibrium

Now consider the case of a limited-entry fishery with multiple vessels, $B > 1$. The profit maximisation problem for each vessel in this situation has been discussed in Section 2.2, and was represented in Equation (7). As shown in Equation (10), vessels will choose to operate at minimum average cost, w_i^*.

In this limited-entry fishery the vessel numbers are exogenously set, so the zero profit condition cannot be invoked in order to close the model. Instead, using the first order condition in Equation (8) to solve for the profit maximising number of days for Vessel *i* gives:

$$D_i = \frac{r}{2q_i(w_i^*)}\left[1 - \frac{w_i^*}{p_h q_i(w_i^*)K}\right] - \frac{\sum_{j\neq i}^{B} q_j\left(w_j^*\right)D_j}{2q_i(w_i^*)}. \tag{19}$$

The first term in this expression is the same as the vessel's choice of days for the single vessel case. The second term accounts for the effect that other vessels operating in the fishery have on each vessels' choice of days. The number of days chosen by any vessel is a negative function of the total harvest of other operators.

Since the profit maximising choice of days must now take into account the choices of other vessels, the identity above can be viewed as a reaction function. In a Nash Equilibrium, each vessel's choice of days must be a best response to the harvest decisions of the remaining vessels. Hence, at the equilibrium the following will hold, where all decisions are taken to maximise profits of individual vessels:

$$\sum_{i=1}^{B} D_i = \frac{r}{2}\left[\sum_{i=1}^{B}\frac{1}{q_i(w_i^*)} - \frac{1}{p_h K}\sum_{i=1}^{B}\frac{w_i^*}{q_i(w_i^*)^2}\right] - \sum_{i=1}^{B}\left[\frac{\sum_{j\neq i}^{B} q_j(w_j^*)D_j}{2q_i(w_i^*)}\right]. \tag{20}$$

Assuming identical vessels and a symmetric solution simplifies this equilibrium condition to:

$$BD_B = \left(\frac{B}{B+1}\right)\frac{r}{q(w^*)}\left[1 - \frac{w^*}{p_h q(w^*) K}\right], \tag{21}$$

and hence we have:

$$D_B = \left(\frac{1}{B+1}\right)\frac{r}{q(w^*)}\left[1 - \frac{w^*}{p_h q(w^*) K}\right]. \tag{22}$$

For the multiple-vessel limited-entry fishery, the stock of fish (X_B), the total harvest (H_B), and the rent for *each vessel* (π_B) can be derived as follows.

$$X_B = \frac{1}{B+1}\left[K + B\frac{w^*}{p_h q(w^*)}\right], \tag{23}$$

$$H_B = \frac{B}{(B+1)^2} rK\left[1 + (B-1)\left(\frac{w^*}{p_h q(w^*) K}\right) - B\left(\frac{w^*}{p_h q(w^*) K}\right)^2\right], \tag{24}$$

$$\pi_B = \frac{1}{(B+1)^2} p_h K r\left(\frac{w^*}{p_h q(w^*) K} - 1\right)^2. \tag{25}$$

Comparing these multiple-vessel outcomes with the single-vessel optimum in Equations (15) to (18), it is apparent that the single-vessel equilibrium is just a special case of the more general limited-entry equilibrium, where $B = 1$.

As the number of vessels in a limited-entry fishery increases, the number of days fished per vessel falls, but the total number of fishing days for the whole fishery increases. Total rent in the multiple-vessel fishery, $B\pi_B$, also falls as the number of vessels increase, as might be expected since the single-vessel case maximises profits for the fishery as a whole. Since overall rents are not maximised, this is an inefficient outcome.

Interestingly, each of the vessels that are allowed to enter this fishery choose to operate at minimum average cost, w^*, so the inefficiency is not a result of capital stuffing. Instead, the inefficiency occurs because the fleet operates for too many days compared to the single-owner optimum. That is, in a limited-entry fishery, where there are no other restrictions, rent dissipation is caused by excess vessel days, rather than capital stuffing – there is no excessive expenditure on fishing technology that causes a 'race to fish'.[6]

[6] This result may sound counter-intuitive to some readers, but it is driven by the parsimonious nature of our model. Namely, our model is static and so the vessels are assumed to be non-myopic. For non-myopic vessels, if number of fishing days can be adjusted freely, investing further in fishing technology is not rent-maximising. Whilst myopic vessels are not the focus of our paper, in the following section we shall examine the situation where the other choice variable, number of days, is restricted and show that even non-myopic vessels with perfectly malleable capital engage in capital-stuffing behaviour.

Along with rents, the fish stock is also smaller than in the single-vessel equilibrium, which could cause overfishing if the fish stock falls below the regulator's desired level. For fisheries targeting a fish stock at the rent-maximising level, X_{mey}, overfishing occurs whenever more than one vessel is allowed to enter the fishery. However, many fisheries instead target a fish stock that delivers maximum sustainable yield, X_{msy}. For these fisheries, overfishing is present if the stock is lower than this level.

In passing, it can also be shown that equilibrium in an open access fishery is another special case of the multiple-vessel limited-entry equilibrium presented above. Under open access, the number of vessels is endogenous, but perfect competition means that each vessel operates at zero economic profits. The equilibrium presented in this section tends towards the open access outcome as the number of vessels increases.

3.3 Diagrammatic representation

The equilibrium outcomes for the fishery can be represented graphically, as in Figure 2. The diagram is a representation of the entire fishery, and is similar in appearance to diagrams used to represent the GS model. However, a key difference is that total days, *BD*, is on the horizontal axis rather than the single index of effort used in the GS model. Here, total days can increase through either an increase in days per vessel, *D*, or through an increase in the number of vessels, *B*.

The curves depicted show the total revenue, *TR*, and total cost, *TC*, which are the aggregated revenue and costs for the entire fishery as functions of total days. The functions are:

$$TR = pKq(w^*)BD\left(1 - \frac{1}{r}q(w^*)BD\right), \quad (26)$$

$$TC = w^* BD \quad (27)$$

The fishery rents, Π, are total revenue minus total cost. Sketching the two curves, we get a GS-style diagram as in Figure 2, which depicts the three key equilibrium outcomes discussed above.

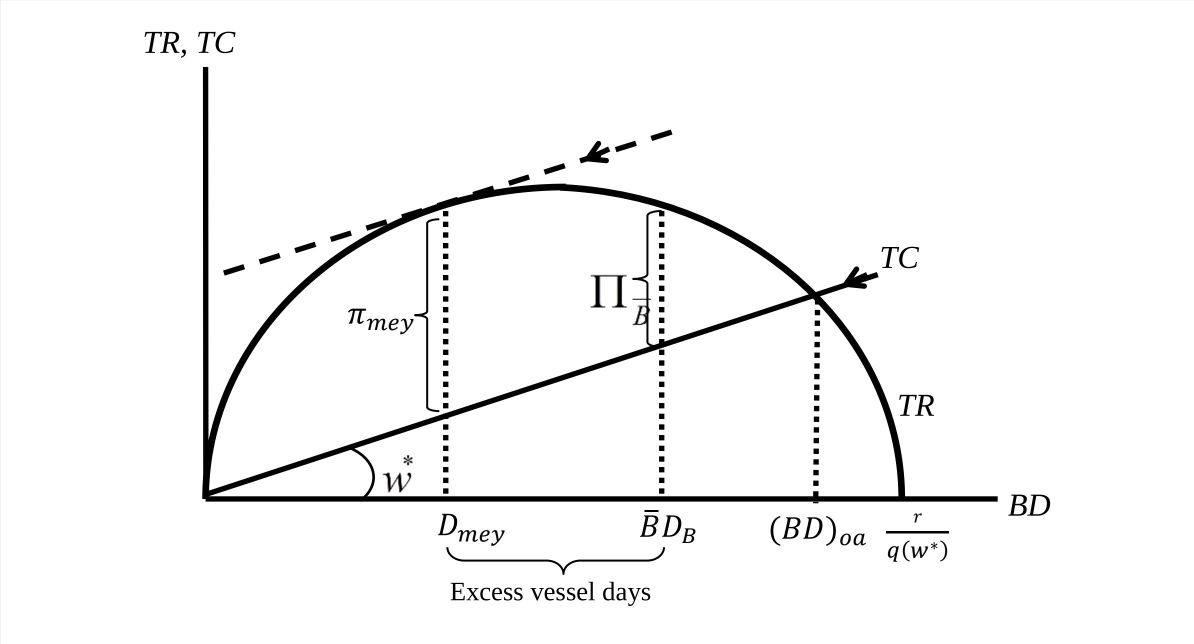

Figure 2: Fishery equilibria

As in the standard GS analysis, the MEY occurs at the level of total fishery days where the slope of total revenue curve is equal to the slope of total costs curve. That is, marginal revenue from an extra day fished in the fishery is equal to the marginal cost of a day, the optimally chosen w^*. Total fishery rent will be maximised at D_{mey}, since here the difference between *TR* and *TC* is maximised.

On the other hand, rents will be zero in an open access equilibrium. As shown in Figure 2, the open access level of vessel days, $(BD)_{oa}$, is at the intersection of the total revenue and total cost curves.

The limited-entry equilibrium where $\bar{B}$ vessels are allowed to enter is shown as $\bar{B}D_B$, which is a case where the restriction on vessel numbers implies positive rents (Π_B) in the fishery. Π_B is smaller than the maximum economic yield, implying that some fishery rents are dissipated. In this case, this inefficiency is caused by vessels operating for too many days, i.e. 'excess vessel days' which can be illustrated by the horizontal distance between D_{mey} and $\bar{B}D_B$ in Figure 2.

At the limited-entry equilibrium outcome shown in the diagram, overfishing is present. The rent-maximising level of fish stock, X_{mey}, is associated with D_{mey}, and the harvest-maximising level of fish stock, X_{msy}, is associated with a $\bar{B}D_B$ at the peak of the *TR* curve. Depending on the regulator's targets for fish stock, any *BD* above these respective levels would imply overfishing.

4. Effect of regulations in limited-entry fisheries

The previous section examined the equilibrium outcome for a limited-entry fishery which faced no other restrictions. However, in practice, limited entry is often only one aspect of the regulatory environment. For example, seasonal restrictions are enforced which cap the number of days that each vessel can fish. Regulators also seek to raise revenue and (in some cases) restrict effort by charging fees for access to the fishery. For example, these could be paid as a lump sum licence fee, or as a per-day payment. The model developed in the previous sections is used to investigate the effect on fishery outcomes from these additional regulations.

4.1 Restrictions on days fished

So far, it has been assumed that vessels operating under the limited-entry program are able to increase their fishing days indefinitely. If, however, vessels were to face an upper limit to the days that they can fish per regulatory period, the outcome would be altered. In a typical limited-entry fishery, a seasonal entry restrictions are usually enforced, and hence it is perhaps more reasonable to assume that each boat is faced with a constraint on days.

Under these conditions, the maximisation problem becomes:

$$\max_{w_i, D_i}[p_h q(w_i) D_i X - w_i D_i] \qquad \text{such that } \left(\bar{D} - D_i\right) \geq 0 \text{ and } D_i, w_i \geq 0, \tag{28}$$

where $\bar{D}$ is the limit for the number of days that can be fished per regulatory period by each vessel.

Considering the case where the constraint on days is binding, the first order conditions imply that:

$$p_h q_i(w_i) K \left[1 - \frac{2}{r} q_i(w_i) D_i - \frac{1}{r} \sum_{j \neq i}^{B} q_j(w_j) D_j\right] > w_i, \tag{29}$$

$$p_h q_i'(w_i) K \left[1 - \frac{2}{r} q_i(w_i) D_i - \frac{1}{r} \sum_{j \neq i}^{B} q_j(w_j) D_j\right] = 1. \tag{30}$$

Together, these conditions imply that:

$$q_i'(\bar{w}_i) \frac{\bar{w}_i}{q_i(\bar{w}_i)} < 1, \tag{31}$$

where $\bar{w}_i$ is the level of expenditure chosen by a vessel when the constraint on days is binding. Equation (31) says that the elasticity of catchability with respect to expenditure is less than unity. In other words, if expenditure increases by one percent, catchability is raised by less than one per cent. Here, the vessel is no longer operating their technology at the minimum efficient scale, as shown in Figure 3. This excessive gearing is the vessels' attempt to compensate for the fact that they cannot choose to fish as many days as they would like to.

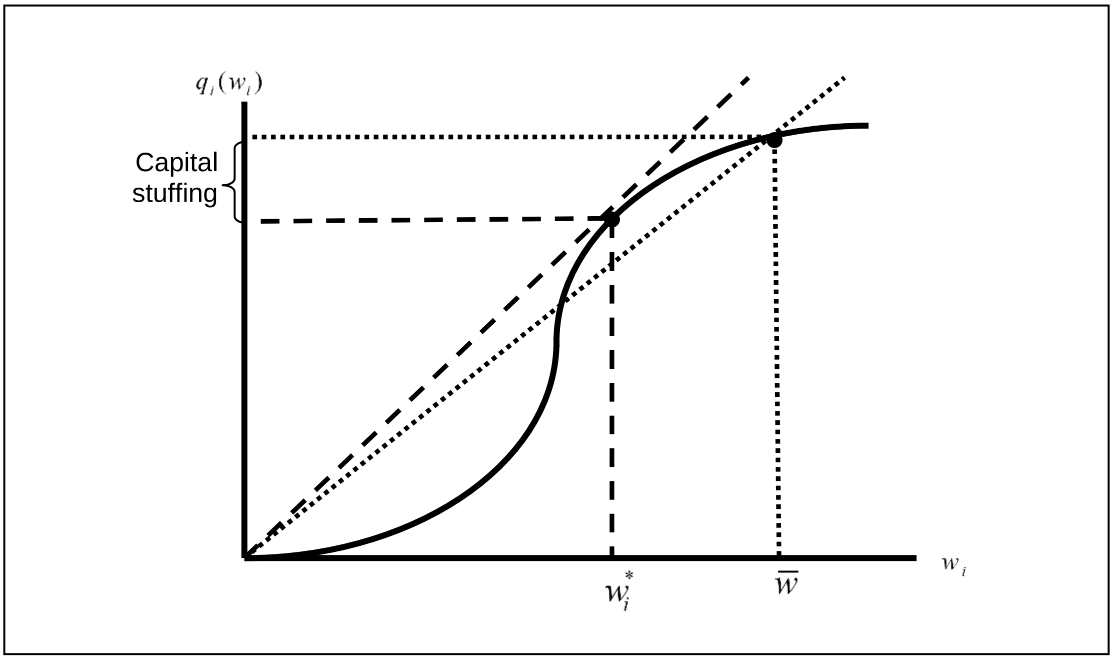

Figure 3: Capital stuffing

This behaviour is the capital stuffing that our model has been designed to incorporate. As discussed in the introduction, this type of vessel-level inefficiency has been observed in many fisheries (see for example, Townsend, 1990; Dupont, 1990). To see how this inefficiency affects the outcomes for the limited-entry program, note that the total revenue and total cost curves for the fishery, assuming identical vessels, are now:

$$TR_{\overline{D}} = pKq(\overline{w})B\overline{D}\left(1 - \frac{1}{r}q(\overline{w})(B\overline{D})\right), \tag{32}$$

$$TC_{\overline{D}} = \overline{w}B\overline{D}. \tag{33}$$

Compared to the unconstrained equilibrium, the total revenue and total cost curves shift, as shown in Figure 4. They are labelled as TC_D and $TC_{\overline{D}}$, respectively. The higher catchability coefficient, $q(\overline{w})$, moves the non-zero intercept of the total revenue curve towards the origin as shown, although the maximum value of the curve is unchanged. The rise in *w* also increases the slope of the *TC* curve.

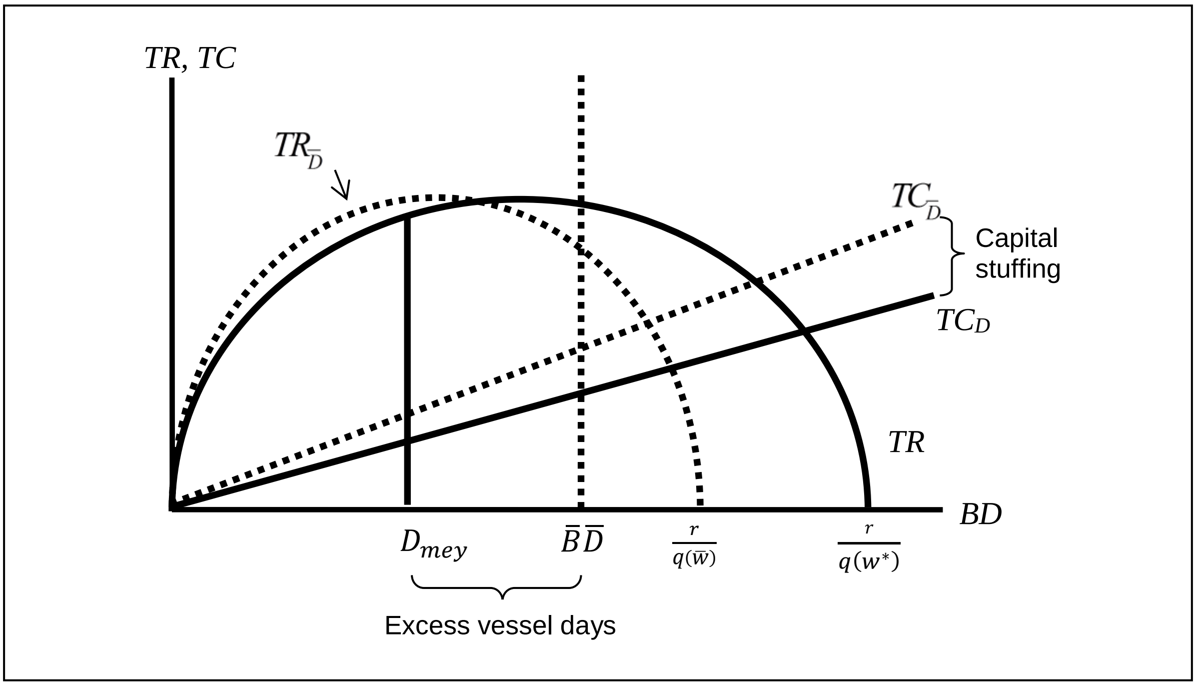

Figure 4: Limited-entry fishery with a constraint on fishing days

While vessel-level inefficiency may rise due to capital stuffing, the constraint on fishing days acts to reduce the other type of inefficiency that we mentioned earlier: 'excess vessel days.' Excess vessel days is the number of fishing days over and above the rent-maximising level (evaluated when all vessels are efficiently equipped). In Figure 4, it is represented by the horizontal distance between the rent-maximising number of days, D_{mey}, and the level at the constrained equilibrium, $\bar{B}\bar{D}$.

The overall impact of restricting fishing days on harvest, fish stock and rents will depend on the relative size of two opposing effects on total 'fishing power' (the multiple of catchability, $q(\bar{w})$, and days fished, $\bar{D}$). On one hand, fewer excess vessel days works to decrease overall fishing power. On the other hand, reduced fishing days gives vessels an incentive to substitute towards using more powerful gear, engaging in capital stuffing to raise the catchability coefficient, which increases overall fishing power.

However, it turns out that the elasticity of catchability with respect to the number of fishing days is less than unity (in absolute value), i.e.:[7]

$$\left|\frac{\partial q(\bar{w})/q(\bar{w})}{\partial \bar{D}/\bar{D}}\right| < 1. \tag{34}$$

Thus, the increase in catchability per vessel day does not fully offset the reduction in fishing days, and overall fishing power will fall. Reduced fishing power implies a recovery in the equilibrium fish stock and hence the steady state fish stock under the day constraint $\bar{X}$ rises:

$$\left|\frac{\partial q(\bar{w})/q(\bar{w})}{\partial \bar{D}/\bar{D}}\right| < 1 \;\Rightarrow\; \frac{\partial \bar{X}}{\partial \bar{D}} < 0. \tag{35}$$

Given the biological characteristics as in Equation (3), it follows that:

[7] See Appendix A for some calculation details for the following equations.

$$\begin{cases} \dfrac{\partial \bar{h}}{\partial \overline{\overline{D}}} < 0 \quad \text{if} \quad \bar{X} < X_{msy}, \\ \dfrac{\partial \bar{h}}{\partial \overline{\overline{D}}} > 0 \quad \text{if} \quad \bar{X} > X_{msy}. \end{cases} \tag{36}$$

where $\bar{h}$ is each vessel's harvest under the day constraint and X_{msy} is the level of fish stock that maximises harvest and therefore revenue. Equation (36) shows that in a biologically-inefficient fishery, where the stock has been depleted below X_{msy}, introducing the constraint on fishing days will lead to a higher level of equilibrium harvest than previously. This is illustrated in Figure 4.

How restrictions on fishing days might affect fishery rents ($\bar{\pi}$) depends on how it affects both revenues and costs in the fishery. For a biologically-inefficient fishery, as discussed above, a tighter restriction on days will lead to an increase in harvest, so revenues will increase when the number of fishing days is reduced. There are two offsetting effects on costs; costs could be lower because fewer days are fished, but on the other hand the cost per day increases due to the induced capital stuffing. Thus, the effect of tightening restrictions on fishing days is ambiguous, a priori. However, we show in Appendix A that, for a biologically-inefficient fishery, overall fishery rents will be higher whenever the restriction on fishing days is tightened. That is, when $\bar{X} < X_{msy}$:

$$\frac{\partial \bar{\pi}}{\partial \overline{\overline{D}}} < 0\,. \tag{37}$$

Hence our model shows that both harvests and rents unambiguously increase when a restriction on fishing days is tightened.[8]

4.2 Access fees

Regulators of limited-entry fisheries may impose access fees with the aim of either sharing in the fishery rents or providing an incentive for vessels to reduce fishing power. This section examines the effect of two such policy options: the first is a lump-sum licence fee, and the second is a daily access fee.

Lump-sum licence fees

Returning to the case of a fishery with unconstrained fishing days, a lump-sum licencing fee could be levied on each vessel with access to the limited-entry fishery. A licencing fee, L, set by the regulator would adjust each vessel's profit maximisation problem as follows:

$$\max_{w_i, D_i} \left[p_h q_i(w_i) D_i K \left[1 - \frac{1}{r} \sum_{i=1}^{B} q_i(w_i) D_i \right] - w_i D_i - L \right] \tag{38}$$

subject to $w_i, D_i \geq 0$. Assuming an interior solution, then, the first order conditions are:

[8] For a biologically efficient fishery, where $\bar{X} > X_{msy}$, the effect tightening restrictions on fishing days on fishery rents is ambiguous. (see Appendix A).

$$p_h q_i(w_i)K\left[1-\frac{2}{r}q_i(w_i)D_i-\frac{1}{r}\sum_{j\neq i}^{B}q_j(w_j)D_j\right]=w_i \tag{39}$$

and

$$p_h q_i'(w_i)K\left[1-\frac{2}{r}q_i(w_i)D_i-\frac{1}{r}\sum_{j\neq i}^{B}q_j(w_j)D_j\right]=1. \tag{40}$$

These are the same conditions as the unconstrained equilibrium, presented in Section 2.2. Therefore, by itself, a lump-sum licencing fee does not give rise to any capital stuffing, it is a sunk cost each period that does not affect vessel behaviour. Instead, it simply shares any fishery rents between vessels and the regulator.

For a fishery with a binding constraint on the number of days fished each period, capital stuffing would be observed, as described in the previous section. However, this inefficiency is caused by the constraint on days, and is unrelated to the licencing fee.

Day-based access fees

Alternatively, a regulator may choose to impose an access fee paid based on the number of days that each vessel fishes. If vessels must pay a daily access fee, of p_D, but face no other restrictions, then each vessel's profit maximisation problem becomes:

$$\max_{w_i,D_i}\left[p_h q_i(w_i)D_i K\left[1-\frac{1}{r}\sum_{i=1}^{B}q_i(w_i)D_i\right]-(w_i+p_D)D_i\right] \tag{41}$$

subject to $w_i, D_i \geq 0$. Assuming an interior solution, then, the first order conditions are:

$$p_h q_i(w_i)K\left[1-\frac{2}{r}q_i(w_i)D_i-\frac{1}{r}\sum_{j\neq i}^{B}q_j(w_j)D_j\right]=w_i+p_D \tag{42}$$

and

$$p_h q_i'(w_i)K\left[1-\frac{2}{r}q_i(w_i)D_i-\frac{1}{r}\sum_{j\neq i}^{B}q_j(w_j)D_j\right]=1. \tag{43}$$

Thus, dropping subscripts again, the profit maximising level of *w* is determined by:

$$q'(w_D)\frac{w_D+p_D}{q(w_D)}=1, \tag{44}$$

where the subscript *D* on *w* indicates the expenditure chosen by vessels in the equilibrium under a certain p_D.

This implies that vessels engage in capital stuffing by increasing expenditure on fishing technology, even in the absence of a constraint on the number of days fished. This behaviour is induced as vessels aim to boost per-day harvest to compensate for the daily access fee.

The number of days that each vessel chooses to fish under a day-based access fee, D_D, is as follows:

$$D_D = \left(\frac{1}{B+1}\right)\frac{r}{q(w_D)}\left[1 - \frac{w_D + p_D}{p_h q(w_D) K}\right]. \tag{45}$$

It can be shown that this is fewer than the number of days that each vessel will fish in the absence of a day-based access fee (see Appendix B). Thus, when a day-based access fee increases the cost of fishing per day, vessels substitute away from using days as a fishing input and towards technology.

The effect of an increase in the day-based access fee is similar to that of tightening the restriction on fishing days. It can be shown that, following an increase in the daily fee, the per cent reduction in fishing days is always larger (in absolute value) than the percent increase in the catchability coefficient, i.e.:[9]

$$\frac{\left|\frac{\partial D_D}{\partial p_D}\right|}{D_D} > \frac{\frac{\partial q(w_D)}{\partial p_D}}{q(w_D)} \tag{46}$$

Thus, the decrease in excess vessel days outweighs the increase in capital stuffing and overall fishing power in the fishery will fall. The fall in fishing power increases the equilibrium fish stock in the fishery, and so if the fish stock is initially smaller (larger) than the level associated with maximum sustainable yield, then this improved fish stock leads to an increase (decrease, respectively) in equilibrium harvests.

$$\begin{cases} \frac{\partial h_D}{\partial p_D} > 0 \quad \text{if} \quad X_D < X_{msy}, \\ \frac{\partial h_D}{\partial p_D} < 0 \quad \text{if} \quad X_D > X_{msy}. \end{cases} \tag{47}$$

where the subscript *D* on *h* and *X* indicates their equilibrium values under a certain p_D.

As for the effect on *total* rents accruing to the fishery, which now comprises vessels' profits as well as the access-fee revenue, we have an ambiguous result. Since any change in access-fee revenue is simply a transfer between the vessels and management, to determine the change in total fishery rents, it suffices to examine the impact on vessel profits before day-based access fees are paid:

$$\pi_D = p_h h_D - w_D D_D. \tag{48}$$

How a rise in p_D might affect π_D depends on how the two terms on the right hand side (RHS) of Equation (48) change. In the following, we shall focus on a biologically-inefficient fishery where $X_D < X_{msy}$. Following Equation (47), we know that the first term of the RHS of Equation (48) increases, but the second term is unclear. On one hand, w_D rises (increased capital stuffing), but on the other hand, D_D decreases (reduced excess vessel days), and so the overall effect is uncertain. When the former effect dominates the latter, the second term of the RHS of Equation (48) rises, and if that rise is greater than that of the first term, then π_D might fall as p_D rises. However, as shown in Appendix B, it turns out that when p_D is sufficiently small relative to w_D, π_D will increase following a rise in the day-based access fee, i.e.:

[9] See Appendix B for some calculation details for the following equations.

$$\frac{\partial \pi_D}{\partial p_D} > 0 \quad \text{if} \quad X_D < X_{MSY} \text{ and } p_D \text{ suffciently small relative to } w_D. \tag{49}$$

Therefore, in a biologically-inefficient fishery, increasing the day-based access fee will work to recover its fish stock and also reduce rent dissipation, so long as p_D is sufficiently small relative to w_D.[10]

5. Discussion and concluding remarks

This paper has presented a model of the limited-entry fishery which separately identifies two distinct sources of rent dissipation, motivated by ample evidence of capital-stuffing behaviour from the fisheries literature. Our model is a modified version of the well-known Gordon-Schafer (GS) static model. However, instead of classifying all forms of fishery 'effort' into a single index, it disaggregates effort into three components in order to separately identify the main sources of inefficiency and rent dissipation observed in empirical studies. By isolating inefficiency caused by *excess vessel days* from that caused by *capital stuffing*, our model enables us to understand rent dissipation in fisheries within the familiar GS framework, and hence is useful in providing a theoretical assessment of the effect of regulations in limited-entry fisheries.

Our model has illustrated that limited entry, by itself, does not cause capital stuffing. As long as all other inputs, such as days fished, are unrestricted, there is no incentive to over-invest in fishing technology. Rent-dissipation and overfishing in this kind of fishery can be wholly attributed to excess vessel days.

However, regulators in limited-entry fisheries often enforce seasonal restrictions, limiting the number of days that each vessel can operate. While such a restriction can reduce excess vessel days, our model predicts that this also causes capital stuffing, as each vessel attempts to boost their per-day harvest to compensate for the lower number of fishing days. This outcome is consistent with the observations reported in much of the literature, where a restriction on some inputs (such as fishing days) leads to substitution towards other inputs (such as technology).

Despite the capital stuffing that is induced, our model also predicts that a restriction on fishing days has the intended impact so long as the fishery in question is biologically-inefficient. For biologically-inefficient fisheries, the net effect of the restriction will be to increase fish stocks, harvest and rents, that is. the benefit from reduced excess vessel days outweighs the cost of additional capital stuffing. Thus, in biologically-inefficient limited-entry fisheries, regulators can both reduce overfishing and improve the profitability of the fishing fleet by tightening a restriction on fishing days.[11] This policy implication is in line with a finding in Dupont (1990) where capital stuffing's contribution to dissipated rent in the British Columbia commercial fishery is found to be less significant than other types of inefficiency.

Instead of directly restricting the number of fishing days, the fishery management might want to give vessels incentive to operate for fewer days by increasing the per-day fishing cost. Limited-entry fisheries often impose access fees, and in this regard we have investigated the

[10] In Appendix B, it is shown that Equation (49) also holds in a biologically efficient fishery where $X_D > X_{msy}$.
[11] An important caveat is that the rent-maximising equilibrium will not be achieved.

effects of lump-sum licence fees and day-based access fees. Our model has shown that, whilst a lump-sum licence fee does not affect vessel behaviour, a rise in a day-based access fee turns out to affect a fishery in a similar way as tightening a restriction on fishing days. Again, we have shown that a day-based access fee works to increase the level of both fish stocks and economic profits in a biologically-inefficient limited-entry fishery, as the effect of reduced excess vessel days dominates the effect of increased capital stuffing.

In 2007 a limit on vessel numbers has been replaced with a limit on total fishing days in the Western and Central Pacific tuna fishery, and this switch has recently been affirmed as a permanent policy.[12] Accordingly, the total fishing days are limited and each vessel day is priced through day-based licences. In light of our model, this policy change can be seen as mixture of the two regulations discussed above. Hence, in principle, this Vessel Day Scheme (VDS) is likely to be capable of achieving one of its major objectives: to promote the conservation of tuna resources.

Our model, however, is rather silent on the other major objective of the VDS, which is to increase economic returns to the governments in the region, through licensing revenues. To evaluate rent sharing between fleets and the fishery management, a different model that can adequately describe negotiation process between the two parties may be required.

Our model and analysis, needless to say, have other limitations. As Dupont (1990) reports, fleet composition is an important source of inefficiencies in fisheries when regulations perpetuate a fleet composition in which some types of vessels are less efficient than others. Our analysis lacks this aspect as we have only focussed on static equilibria with identical vessels. Another important item in our analysis that requires further attention may be the shape of the *q* function. We have used an *S*-shaped function because it is consistent with well-known capital-stuffing behaviour by vessels, but to our best knowledge there is no empirical work that measures the relationship between vessel's expenditure and catchability. Finally, the static model developed here could be extended to a dynamic framework. These tasks are left for future research.

[12] See Havice (2013) regarding the Vessel Day Scheme (VDS) introduced in the PNA (Parties to Nauru Agreement) countries in this fishery. Also see PNA (2016).

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Appendix A: Impacts of a restriction on days

This appendix presents a detailed analysis on the effect of further restricting the number of days fished in a limited-entry fishery, where there is already a binding constraint on the number of days that each vessel can fish. We examine the effect on harvest decisions and rent levels for an individual vessel. However, total fishery harvests and rents will move in the same direction as each vessel's harvest and rents since we are examining limited-entry fisheries with identical vessels and no access fees. The results presented in this appendix are discussed in Section 4.1.

Effect of restricting fishing days on harvest

Starting from the harvest function for an individual vessel, as in Equation (1), together with the equation for total fish stock, as in Equation (5), the effect on harvest from a further restriction in days can be found, as follows:

$$\frac{\partial \bar{h}}{\partial \bar{D}} = \frac{K}{r}\left(q'(\bar{w})\frac{\partial \bar{w}}{\partial \bar{D}}\bar{D} + q(\bar{w})\right)\left(r - 2B\bar{D}q(\bar{w})\right). \tag{A1}$$

In this equation, the term in the second set of brackets is related to the steady state level of fish stock. Specifically,

$$\text{sign}\left(r - 2B\bar{D}q(\bar{w})\right) = \text{sign}\left(\bar{X} - X_{msy}\right). \tag{A2}$$

In words, if the second bracketed term in equation (A1) is negative (positive), then the fishery is biologically-inefficient (efficient, respectively) since the fish stock level is lower (greater, respectively) than the case for maximum sustainable yield.

Now consider the first bracketed term in equation (A1). This term turns out to be positive as shown below. Note that showing this is equivalent to proving that the elasticity of catchability with respect to the constraint on fishing days is less than unity (in absolute value).

$$q'(\bar{w})\frac{\partial \bar{w}}{\partial \bar{D}}\bar{D} + q(\bar{w}) > 0 \tag{A3}$$

$$\Leftrightarrow \frac{\partial q(\bar{w})}{q(\bar{w})}\frac{\bar{D}}{\partial \bar{D}} > -1 \tag{A4}$$

$$\Leftrightarrow \left|\frac{\partial q(\bar{w})/q(\bar{w})}{\partial \bar{D}/\bar{D}}\right| < 1. \tag{A5}$$

To prove (A5) is the case, first of all, differentiate Equation (30) with respect to $D_i = \bar{D}$:

$$q_i''(\bar{w}_i)\frac{\partial \bar{w}_i}{\partial \bar{D}} = \frac{2}{r}q_i'(\bar{w}_i)D_i\frac{\partial \bar{w}_i}{\partial \bar{D}} + \frac{2}{r}q_i(\bar{w}_i). \tag{A6}$$

Hence, removing subscripts, we obtain

$$\frac{\partial \overline{w}}{\partial \overline{D}} = \frac{2q(\overline{w})}{rq''(\overline{w}) - 2q'(\overline{w})\overline{D}.} \tag{A7}$$

Therefore,

$$\frac{\partial q(\overline{w})}{\partial \overline{D}} = \frac{2q(\overline{w})q'(\overline{w})}{rq''(\overline{w}) - 2q'(\overline{w})\overline{D}}. \tag{A8}$$

Using the above we can obtain the elasticity we are after:

$$\frac{\partial q(\overline{w})}{\partial \overline{D}} \frac{\overline{D}}{q(\overline{w})} = \frac{2q'(\overline{w})\overline{D}}{rq''(\overline{w}) - 2q'(\overline{w})\overline{D}} = \frac{1}{rq''(\overline{w})/2q'(\overline{w})\overline{D} - 1}. \tag{A9}$$

Since the term $rq''(\overline{w})/2q'(\overline{w})\overline{D}$ is negative, the elasticity of catchability with respect to days is less than unity. The catchability coefficient increases by less than one percent when fishing days are reduced by one per cent.■

Therefore, together with Equation (A2), we can conclude that:

$$\text{sign}\frac{\partial \overline{h}}{\partial \overline{D}} = \text{sign}(\overline{X} - X_{msy}). \tag{A10}$$

In words, tightening (already binding) restrictions on fishing days will result in greater (less) harvests in a biologically-inefficient (efficient) fishery.

Effect of restricting fishing days on rents

This section uses the result found above to investigate the effect on rent from tightening restrictions on fishing days.

First, since the equilibrium rent of an individual vessel is $\overline{\pi} = p_h\overline{h} - \overline{w}\overline{D}$:

$$\frac{\partial \pi}{\partial \overline{D}} = p_h \frac{\partial \overline{h}}{\partial \overline{D}} - \overline{w}\left[1 + \frac{\partial \overline{w}/\overline{w}}{\partial \overline{D}/\overline{D}}\right]. \tag{A11}$$

This condition decomposes the change in rent from tightening the restriction on fishing days into two effects. The first is the effect on revenue through the effect on harvest. As shown above, a tighter restriction on days will lead to an increase in harvest, so this first term will be negative and revenues will increase when the number of fishing days is reduced. The second term is the effect on costs. On the one hand, costs could be lower because fewer days are fished, and on the other hand costs could be higher because the cost per day increases due to the capital stuffing. Thus, the impact of tightening restrictions on fishing days is ambiguous, a priori. However, it can be shown that, overall, fishery rents will be higher whenever the restriction on fishing days is tightened in a biologically-inefficient fishery.

Substituting (A1) into (A11) yields:

$$\frac{\partial \bar{\pi}}{\partial \bar{D}} = \frac{p_h K}{r}\left(\frac{\partial q(\bar{w})}{\partial \bar{D}}\bar{D} + q(\bar{w})\right)\left(r - 2B\bar{D}q(\bar{w})\right) - \frac{\partial \bar{w}}{\partial \bar{D}}\bar{D} - \bar{w}$$

$$= \frac{p_h K q(\bar{w})}{r}\left(\frac{\partial q(\bar{w})}{\partial \bar{D}}\frac{\bar{D}}{q(\bar{w})} + 1\right)\left(r - 2B\bar{D}q(\bar{w})\right) - \frac{\partial q(\bar{w})}{\partial \bar{D}}\frac{\bar{D}}{q(\bar{w})}\frac{q(\bar{w})}{q'(\bar{w})q'(\bar{w})} - \bar{w}. \tag{A12}$$

The sign of (A12) is ambiguous in general, however, the sign can be determined for a biologically-inefficient fishery. In the presence of a binding constraint on fishing days, profit maximising vessels choose w so that $q(w)/q'(w) > w$. Therefore, we have:

$$\frac{\partial \bar{\pi}}{\partial \bar{D}} < \frac{p_h K q(\bar{w})}{r}\left(\frac{\partial q(\bar{w})}{\partial \bar{D}}\frac{\bar{D}}{q(\bar{w})} + 1\right)\left(r - 2B\bar{D}q(\bar{w})\right) - \bar{w}\left(\frac{\partial q(\bar{w})}{\partial \bar{D}}\frac{\bar{D}}{q(\bar{w})} + 1\right)$$

$$= \left(\frac{\partial q(\bar{w})}{\partial \bar{D}}\frac{\bar{D}}{q(\bar{w})} + 1\right)\left(p_h K q(\bar{w}) - \bar{w} - \frac{2B\bar{D}q(\bar{w}) \cdot p_h K q(\bar{w})}{r}\right) \tag{A13}$$

$$< \left(\frac{\partial q(\bar{w})}{\partial \bar{D}}\frac{\bar{D}}{q(\bar{w})} + 1\right)(-\bar{w}).$$

The final inequality above follows from the assumption that the first bracketed term is positive from Equation (A9), and that the fishery is biologically-inefficient, so that $r < 2B\bar{D}q(\bar{w})$, from equation (A2).

Thus, we have shown that, in a limited-entry fishery with fish stocks at inefficiently low levels, tightening an already binding restriction on fishing days will unambiguously increase rents in the fishery.

$$\frac{\partial \bar{\pi}}{\partial \bar{D}} < -\bar{w}\left(\frac{\partial q(\bar{w})}{\partial \bar{D}}\frac{\bar{D}}{q(\bar{w})} + 1\right) < 0. \tag{A14}$$

Appendix B: Effects of a day-based access fee

This appendix presents further details on the effect of imposing a day-based fee on a limited-entry fishery. First, we show that a day-based access fee reduces the number of days that vessels choose to operate. Second, we assess the effect of a day-based access fee on harvest and overall fishery rents. The results presented in this appendix were discussed in Section 4.2.

Effect of day-based access fee on days fished

As discussed in Section 4.2, the number of days that each vessel in a limited-entry fishery with a day-based access fee chooses to fish is as follows:

$$D_D = \left(\frac{1}{B+1}\right)\frac{r}{q(w_D)}\left[1 - \frac{w_D + p_D}{p_h q(w_D) K}\right]. \tag{A15}$$

An increase in the price of days, p_D, will induce vessels to increase their expenditure per day, w_D, in order to raise their catchability coefficient, q. To show that the number of days chosen by each vessel in the presence of a day-based access fee, D_D, is less than the days chosen in the unconstrained equilibrium, D_B, we must show that as p_D rises, D_D falls. To achieve this, it suffices to show that:

$$\frac{\partial(w_D + p_D)}{\partial p_D} > \frac{\partial(p_h q(w_D) K)}{\partial p_D}, \tag{A16}$$

or equivalently:

$$p_h K \frac{\partial q}{\partial w_D}\frac{\partial w_D}{\partial p_D} - \frac{\partial w_D}{\partial p_D} - 1 < 0. \tag{A17}$$

In the meantime, note that for an interior solution, where $D_D > 0$, it must be that $pq(w_D)K > w_D + p_D$. It therefore follows that the above inequality in Equation (A17) is met whenever:

$$\frac{w_D + p_D}{q(w_D)}\frac{\partial q(w_D)}{\partial w_D}\frac{\partial w_D}{\partial p_D} - \frac{\partial w_D}{\partial p_D} - 1 < 0. \tag{A18}$$

Given Equation (44), the above inequality is met. Therefore, we have proven that vessels will choose to fish fewer days when a day-based access fee is imposed, compared to the case of unrestricted fishing days and no access fee.

Effect of day-based access fee on harvest

Again, starting from the harvest function for an individual vessel, as in Equation (1), together with the equation for total fish stock, as in Equation (5), the effect on harvest from an increase on the day-based access fee can be found, as follows.

$$\frac{\partial h_D}{\partial p_D} = \frac{K}{r}\left(\frac{\partial q(w_D)}{\partial p_D} D_D + q(w_D)\frac{\partial D_D}{\partial p_D}\right)(r - 2BD_D q(w_D)). \tag{A19}$$

As discussed in Appendix A, the term $(r - 2BD_D q(w_D))$ is related to biological efficiency of the fishery.

$$\text{sign}(r - 2BD_D q(w_D)) = \text{sign}(X_D - X_{msy}) \tag{A20}$$

Now we investigate the first bracketed term in (A19). By partially differentiating the vessels' choice of days, from Equation (45) with respect to to p_D, we get:

$$\frac{\partial D_D}{\partial p_D} = \frac{r}{p_h K[q(w_D)]^3(B+1)}\left[\left[(w_D + p_D) - p_h K\left(1 + \frac{1}{q'(w_D)}\right)\right]\frac{\partial q(w_D)}{\partial p_D} - q(w_D)\right]. \tag{A21}$$

It follows that the elasticity of catchability with respect to days (following a change in the price of days) is given by the following:

$$\frac{\frac{\partial q(w_D)}{\partial p_D} \cdot D_D}{\frac{\partial D_D}{\partial p_D} \cdot q(w_D)} = \frac{1}{-1 - A}, \tag{A22}$$

where:

$$A = \frac{q(w_D)\left(\frac{\partial w_D}{\partial p_D} + 1\right)}{q'(w_D)[p_h q(w_D)K - (w_D + p_D)]\frac{\partial w_D}{\partial p_D}}.$$

Since $A > 0$, the (absolute value of) the elasticity will always be less than unity, that is:

$$\frac{\left|\frac{\partial D_D}{\partial p_D}\right|}{D_D} > \frac{\frac{dq(w_D)}{dp_D}}{q(w_D)}. \tag{A23}$$

Equation (A23) implies that the first bracketed term in Equation (A20) is negative. In words, it implies that the percent change in D_D is larger than the percent change in $q(w_D)$ following a change in p_D, when the day-based access fee is increased. This, in turn implies reduced overall fishing power and greater fish stocks. Accordingly, together with Equation (A21), it then follows that:

$$\text{sign}\left(\frac{\partial h_D}{dp_D}\right) = -\text{sign}(X_D - X_{msy}) \tag{A24}$$

If a biologically-inefficient fishery, an increase in the day-based access fee causes harvest to increase as fish stocks recover.

Effect of day-based access fee on fishery rents

The total fishery rent is of interest, which comprises vessel profits and the fees collected. As discussed in the main text, to see how it is affected by an increase in the day-based access fee, it suffices to see how the profit of an individual vessel before the day-based access fee is paid ($\pi_D = p_h h_D - w_D D_D$) is affected.

$$\frac{\partial \pi_D}{\partial p_D} = p_h \frac{\partial h_D}{\partial p_D} - D_D \frac{\partial w_D}{\partial p_D} - w_D \frac{\partial D_D}{\partial p_D}. \tag{A25}$$

Given $\partial h_D / \partial p_D$ from equation (A19), and that profit-maximising vessels will operate where $q'(w_D) = q(w_D)/(w_D + p_D)$, we have:

$$\begin{aligned}\frac{1}{D_D}\frac{\partial \pi_D}{\partial p_D} &= \left[\frac{p_h K q(w_D)}{r(w_D + p_D)}\big(r - 2BD_D q(w_D)\big) - 1\right] D_D \frac{\partial w_D}{\partial p_D} \\ &\quad + \left[\frac{p_h K q(w_D)}{r}\big(r - 2BD_D q(w_D)\big) - w_D\right] \frac{\partial D_D}{\partial p_D}\frac{1}{D_D}.\end{aligned} \tag{A26}$$

In the meantime, it turns out that:

$$\frac{\partial D_D}{\partial p_D}\frac{1}{D_D} = -\left[\frac{1}{(w_D + p_D)}\frac{\partial w_D}{\partial p_D} + \frac{1}{p_h K q(w_D) - (w_D + p_D)}\right]. \tag{A27}$$

Which, in turn, implies that:

$$\begin{aligned}\frac{r(w_D + p_D)}{D_D}\frac{\partial \pi_D}{\partial p_D} &= \\ &- \frac{\big[p_h K q(w_D)\big(r - 2BD_D q(w_D)\big) - w_D r\big](w_D + p_D)}{p_h K q(w_D) - (w_D + p_D)} - r p_D \frac{\partial w_D}{\partial p_D}\end{aligned} \tag{A28}$$

$$\frac{1}{D_D}\frac{\partial \pi_D}{\partial p_D} = -\frac{\left[\frac{p_h K q(w_D)}{r}\big(r - 2BD_D q(w_D)\big) - w_D\right]}{p_h K q(w_D) - (w_D + p_D)} - \frac{p_D}{(w_D + p_D)}\frac{\partial w_D}{\partial p_D} \tag{A29}$$

By substituting in the expression for days fished, Equation (45) in Section 4.2, this simplifies further to:

$$\frac{1}{D_D}\frac{\partial \pi_D}{\partial p_D} = \frac{2B}{B+1} - \frac{[p_h K q(w_D) - w_D]}{p_h K q(w_D) - (w_D + p_D)} - \frac{p_D}{(w_D + p_D)}\frac{\partial w_D}{\partial p_D} \tag{A31}$$

This result implies that the effect of increasing daily access fees on total fishery rents depends on both the number of vessels operating in the fishery, and the size of p_D relative to w_D.

For any number of vessels greater than one, the first term is greater than one, and is close to 2 for large B. If the price of fishing days is small relative to $p_h K q(w_D) - w_D$, then the second term will be close to -1 . If the price of fishing days is small relative w_D, then the third term will be close to zero. Thus, for large B and small p_D, fishery rents are likely to increase when the price of fishing days is increased.

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