BIOECONOMICS OF SUSTAINABLE HARVEST OF COMPETING SPECIES: A COMMENT*

by

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Abstract

Flaaten's (1991) study on competing species conjectures that a higher price (harvesting costs) of one species yields a lower (greater) own stock-size and a greater (lower) stock-size of the competing species. I show both conjectures are wrong.

Keywords: fishery management, multiple species model, renewable resources

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There exists a growing sense among resource scientists that scientific effort should be directed at multiples species, community and ecosystem approaches. (van Kooten and Bulte 2000, p. 217; quoted also in Finnoff and Tschirhart 2003)

1. Introduction

Growth of a fishery population is determined to a large extent by its environment. Since one species only forms part of a complex ecological system including prey, competitors or predators, modeling its dynamics with a single differential or difference equation neglects such ecological interdependence, and can lead to wrong assessments. In the literature, it was pointed out that spillovers that occur from one population onto another might change crucially the optimal extraction plan in a fishery (Clark, 1976; Ragozin and Brown, 1985; Hannesson, 1986; Conrad and Adu-Asamoah, 1986; Wilen and Brown, 1986; Flaaten, 1991; Tu and Wilman, 1992; Conrad and Salas, 1993; Stroebele and Wacker, 1995; Flaaten and Stollery, 1996; van Ierland and De Man, 1996; Wacker, 1999; Arnason, 2000; Barbier, 2001; Imeson, van den Bergh and Hoekstra, 2002; Tschirhart, 2002; Finnoff and Tschirhart, 2003). In contrast to the single species model, the optimal solution can involve harvesting of some species at a loss as a lower stock increases the profits from the fishery of the interdependent species.

One frequently quoted paper of this literature which studies the bioeconomics of Gause's (1934) deterministic competing species model is by Flaaten (1991). Flaaten provides six theorems of which the last two involve general conjectures on the impact of market parameter changes on the long run stock levels. In his Theorem 5 (Theorem 6), Flaaten conjectures that a higher price (harvesting costs) of one species will yield a lower (greater) own stock level and a greater (lower) stock level of the competing species in the steady state. In this paper, I show that the theorems are no general results. In fact, Theorem 5 is reversed if costless harvesting is assumed.

In the remainder of the paper, I review the competing species model and derive the optimal harvesting decision of the sole owner. I follow closely the steps of Flaaten (1991). I show where the proof of the theorems is flawed and I provide counter examples for both theorems. Finally, I sum up.

2. The model

In the notation I follow Flaaten (1991). The growth function of species i is given by the logistic production function:

$$G_i(X_1, X_2) = r_i X_i\,(1 - X_i - \alpha_i X_j),\ (i,j = 1, 2, i \neq j), \tag{1}$$

where $X_i \in [0,1]$ denotes the stock of species i relative to its carrying capacity, α_i is the dimensionless competition parameter,[1] and r_i is the intrinsic growth rate. In contrast to the single species model the competition parameter is incorporated to describe by how much the living space of species i is affected through the presence of the competing species j. The greater the competition parameter is the "flatter" is the curve of the growth function of species i, and the lower is the species' stock level in the biological equilibrium without harvesting.

Harvesting from both resource stocks is assumed to be independent from each other. Each unit of effort E can be dedicated either to catching species 1 or species 2 but not to both at the same time. The catch rates are $y_i(X_i) = E_i X_i$ ($i = 1, 2$). Given Schaefer's harvest function and assuming constant costs per unit effort, the unit harvesting costs are $c_i(X_i) = c_i/X_i$ ($i = 1, 2$).[2] Under the assumption of constant prices p_1 and p_2 of species 1 and 2, respectively, the total profit from harvesting the two species is

[1] Throughout the paper we will assume that $\alpha_i \in (0,1)$, i=1,2. This is a necessary condition for having an interior, positive stable steady state without harvesting (see Flaaten [7, 166]).
[2] The unit cost of harvesting species i accounts for i's catchability quotient.

$$\pi(X_1, X_2) = b_1(p_1, X_1)\, y_1 + b_2(p_2, X_2)\, y_2, \tag{2}$$

where $b_i(p_i, X_i) = p_i - c_i(X_i)$ ($i = 1, 2$) denotes the net profit per unit harvest of species i.

The management problem of the competing species problem involves the maximization of the present value (PV) of the total profit from both fisheries subject to the two equations of motion. Thus, the externality of the production of species 1 is internalized in the production of species 2, and vice versa. The planner faces the following two-control problem:

$$max\ PV = \int_0^{\infty} e^{-\delta t} \pi(X_1, X_2)\, dt$$

$$s.t.\ \ \dot{x}_i(t) = G_i(X_1(t), X_2(t)) - y_i(t), i = 1, 2 \tag{3}$$

where δ denotes the discount rate and the dot in the constraints indicates time derivatives. The stocks change in time due to the difference between growth and catch. Assuming an interior solution the following equation pair determines the optimal solution to the planner's maximization problem,

$$b_1(X_1^*) = 1/\delta\ [b_1(X_1^*)\, G_{11} + b_2(X_2^*)\, G_{21} - c_1'(X_1^*)\, G_1(X_1^*, X_2^*)]$$
$$b_2(X_2^*) = 1/\delta\ [b_1(X_1^*)\, G_{12} + b_2(X_2^*)\, G_{22} - c_2'(X_2^*)\, G_2(X_1^*, X_2^*)] \tag{4}$$

where $G_{ji}(X_1^*, X_2^*) = \partial G_i / \partial X_j^*$ ($i, j = 1, 2$) is the derivative of species j's growth function with respect to i's steady state stock level. In the steady state, the total profit of the marginal unit extracted from the stock (on the left hand side) must equal the discounted marginal rent of this unit (on the right hand side), which reflects the present value of all future losses that result through harvesting from a lower stock. In the steady state, growth must equal catch, $y_i = G_i$. Hence, we can rewrite (4) using (2) to obtain

$$b_i(X_i^*) = \frac{1}{\delta}\frac{\partial \pi(X_1^*, X_2^*)}{\partial X_i^*}(i = 1,2)\,. \tag{5}$$

Flaaten (1991) starts from equation (5) to analyze how equilibrium stock levels change when prices or costs change. Following his steps we differentiate with respect to p_1 to yield the following

$$b_{1p} + b_{1x}\frac{\partial X_1^*}{\partial p_1} = \frac{1}{\delta}\left(\frac{\partial \pi^1}{\partial p_1} + \pi^{11}\frac{\partial X_1^*}{\partial p_1} + \pi^{12}\frac{\partial X_2^*}{\partial p_1}\right) \tag{6}$$

$$b_{2x}\frac{\partial X_2^*}{\partial p_1} = \frac{1}{\delta}\left(\frac{\partial \pi^2}{\partial p_1} + \pi^{21}\frac{\partial X_1^*}{\partial p_1} + \pi^{22}\frac{\partial X_2^*}{\partial p_1}\right) \tag{7}$$

where $$b_{ip} = \frac{\partial b_i(\cdot)}{\partial p_i},\; b_{ix} = \frac{\partial b_i(\cdot)}{\partial X_i^*},\; \pi^i = \frac{\partial \pi(\cdot)}{\partial X_i}, \text{ and } \pi^{ij} = \frac{\partial^2 \pi(\cdot)}{\partial X_i \partial Xj}. \tag{8}$$

Rearranging equations (6) and (7) with respect to stock-price derivatives we obtain

$$(\pi^{11} - \delta b_{1x})\frac{\partial X_1^*}{\partial p_1} + \pi^{12}\frac{\partial X_2^*}{\partial p_1} = \delta b_{1p}\frac{\partial \pi^1}{\partial p_1} \tag{9}$$

$$\pi^{21}\frac{\partial X_1^*}{\partial p_1} + (\pi^{22} - \delta b_{2x})\frac{\partial X_2^*}{\partial p_1} = -\frac{\partial \pi^2}{\partial p_1}. \tag{10}$$

Applying Cramer's rule, equations (9) and (10) can be solved with respect to the stock-price derivatives, yielding the following equations,

$$\frac{\partial X_1^*}{\partial p_1} = \frac{(\delta b_{1p} - \frac{\partial \pi^1}{\partial p_1})(\pi^{22} - \delta b_{2x}) + \pi^{12}\frac{\partial \pi^2}{\partial p_1}}{|D|} \tag{11}$$

$$\frac{\partial X_2^*}{\partial p_1} = \frac{(\delta b_{1x} - \pi^{11})\frac{\partial \pi^2}{\partial p_1} + \pi^{21}(\frac{\partial \pi^1}{\partial p_1} - \delta b_{1p})}{|D|} \tag{12}$$

where
$$|D| = \begin{vmatrix} \pi^{11} - \delta b_{1x} & \pi^{12} \\ \pi^{21} & \pi^{22} - \delta b_{2x} \end{vmatrix}. \tag{13}$$

Equations (11) and (12) coincide with equations (54) and (55) in Flaaten only if $\partial\pi^i/\partial p_1 = 0$ (i =1, 2). Since $\partial\pi^1/\partial p_1 = G_{11} = r_1 (1 - 2X_1^* - \alpha_1 X_2^*)$ and $\partial\pi^2/\partial p_1 = G_{12} = - \alpha_1 r_1 X_1^* < 0$ are different from zero, the proofs to Theorem 5 and Theorem 6 in Flaaten are wrong. In fact, we can find an illustrative example which reverses Theorem 5 as the following observation reveals.

Observation *If harvesting in the competing species model (with $\alpha_i>0$, $i=1,2$) is costless the following holds:* $\frac{\partial X_1^*}{\partial p_1} \geq 0$*, and* $\frac{\partial X_2^*}{\partial p_1} \leq 0$.

As shown in Flaaten, it follows from the second order condition for the existence of an interior solution that the denominator to both equation (11) and (12) is positive, i.e. $|D| > 0$, and the second derivative of the profit function with respect to the own stock, $\pi^{ii} = - 2\, r_i\, p_i < 0$ (i = 1, 2), is negative. Note $b_{ip} = 1$, and $c_i = 0$ (i = 1, 2) implies $b_{ix} = 0$. Taking into account $\pi^{ij} = - \alpha_1 r_1 p_1 - \alpha_2 r_2 p_2 < 0$, and $G_{12} < 0$, the proof reduces thus to showing that the marginal growth rate in the steady state exceeds the interest rate, i.e., $G_{11} \geq \delta$. This is trivially satisfied, because if the interest rate is greater than the marginal growth rate the optimal management decision is to extinguish the species. At the corner solution the stock-price derivatives are zero. If both stocks are positive the inequalities are strict. A higher price of species 1 implies its higher relative efficiency. In other words, if there are no extraction costs and 1's price increases the planner cares less about the spillovers from species 1 to species 2 and more about the externality that affects species 1.

Figure 1 illustrates for given parameter values ($\alpha_1 = \alpha_2 = c_1 = c_2 = \delta = ½$ and $r_1 = r_2 = 1$) that Flaaten's Theorem 5 is not verified either if positive costs are allowed. Figure 1 displays the signs of the derivatives for the price ranges $p_1, p_2 \in [1, 10]$. Note that prices in this range are at least double as high as costs. In the northwest area of Figure 1 where the competing species' price is sufficiently greater than the own species' price, i.e., approximately when $p_2 > - 2.75 + 3.75\ p_1 \geq 1$, derivatives are in line with Flaaten's theorem. However, for other price ratios the theorem must be rejected.

---- Insert Figure 1 about here ----

As pointed out above, the proof to Flaaten's Theorem 6 has the identical flaw as the proof to Theorem 5. Theorem 6 states that the steady state stock level of one species is (*i*) increasing in own harvesting costs and (*ii*) decreasing in the harvesting costs of the competing species. Using the same parameter values and price ranges as in Figure 1, Figure 2 depicts the signs of the derivatives with respect to harvesting costs. In the south east area of Figure 2, i.e., approximately where $1 \leq p_2 < - 1/6 + 2.4\ p_1$, the second part of the theorem must be rejected.

---- Insert Figure 2 about here ----

3. Summary

In the paper, it has been shown that two essential theorems of Flaaten's (1991) well-known paper on optimal management of competing species are wrong. These theorems make a claim about how the equilibrium stock in the sole owner fishery moves when prices or costs are changed. A higher price of one species does not imply necessarily a lower bioeconomic equilibrium stock as Flaaten conjectured. This result is important since it shows that the competing species model does not behave the same as the single species model.[3] Particularly in the case of costless harvesting the optimal resource management decision might induce more extraction of the competing species in order to enhance the stock of the more valuable species. Furthermore, the steady state stock level is not necessarily decreasing in the harvesting costs of the competing species as conjectured in Flaaten's Theorem 6. It turns out that for some values the opposite is true. Finally, I cannot reject both conjectures of Flaaten's Theorem 6 since the steady state stock level is increasing in own harvesting costs for all values I considered. However, I am not able to provide a proof in favor of the theorem either.

[3] Flaaten 1991 shows that even harvesting one species at a loss can be optimal in the long-run equilibrium.

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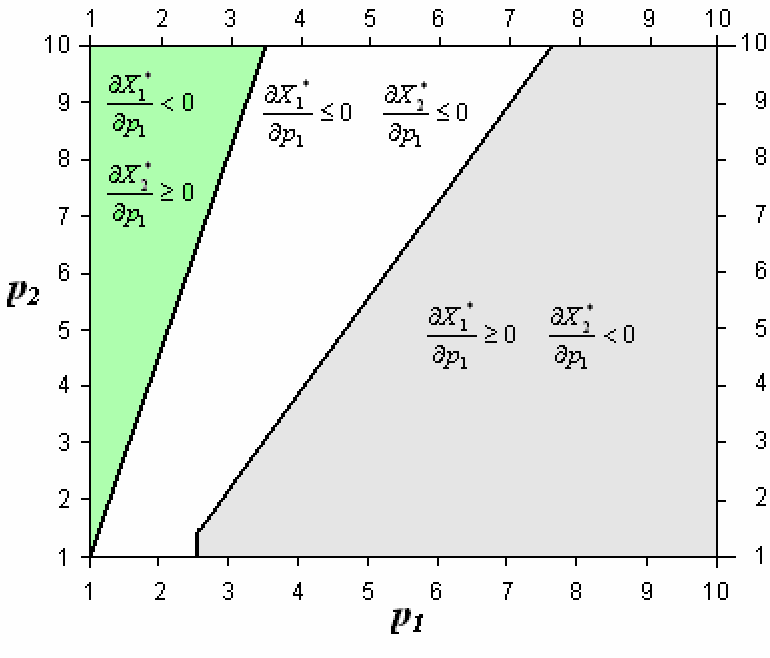
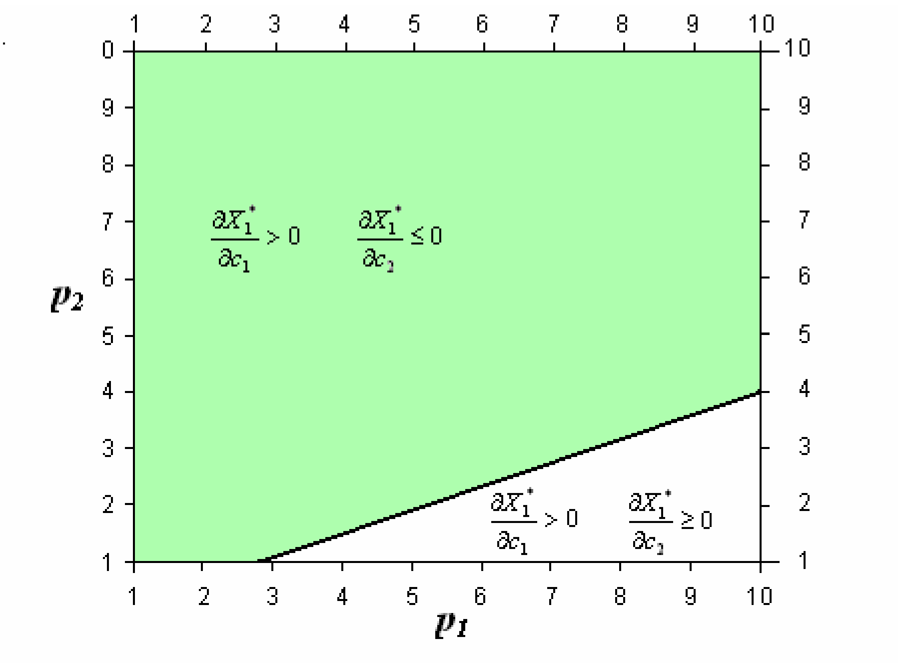
Figure 1. Sign of price derivatives



Parameter values: $\alpha_1 = \alpha_2 = c_1 = c_2 = \delta = 0.5$, $r=1.5$, $p_1, p_2 \in [1,10]$

Figure 2. Sign of costs derivatives



Parameter values: $\alpha_1 = \alpha_2 = c_1 = c_2 = \delta = 0.5$, $r=1.5$, $p_1, p_2 \in [1,10]$