The Impact of Upstream Catch and Global Warming on the Grey Mullet Fishery in Taiwan: A Non-cooperative Game Analysis

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Abstract This paper examines the problem of non-cooperative fishing between Mainland China (MC) and Taiwan (TW) as well as the effects of rising sea surface temperature (SST) on the grey mullet fishery. The results show that Taiwan can expand its fleets to a greater extent when facing an imperfectly elastic demand for fish than when facing a perfectly elastic demand. In addition, when consumer welfare is included in the determination of the size of fleets, fleet size can expand more than when profit is considered alone. It is also shown that the expansion of the fleets in MC and the rising SST cause the rent obtained from the TW fishery to decline, and that Taiwan may partially offset such an adverse effect by adjusting the fleet size.

Key words Grey mullet, non-cooperative game, sea surface temperature.

JEL Classification Codes Q22, Q28, Q54.

Introduction

This paper studies an interesting fishing situation that has arisen in recent years in the Taiwan Strait. The grey mullet (Mugil cephalus L.) fishery in Taiwan (TW) has a long tradition of over one hundred years, with the main fishing of spawning grey mullet taking place in the winter months along the west coast of Taiwan. Tung (1981) noted that the grey mullet lives in the coastal waters of Mainland China (MC), becomes mature at the age of three or four, and migrates to the coastal waters of southwestern TW for spawning in December and January. In TW, all parts of the grey mullet are fully utilized. The ovaries of the adult female grey mullet are the most valuable part, and can be processed with salt to make Botarga Caviar, which is a favorite delicacy in TW and Japan. In addition, the testes of the male grey mullet and the stomach are mouthwatering ingredients for seafood cuisine. Thus, the grey mullet is also referred to as “Grey Gold.”

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The fishing season and the catching of grey mullet are closely related to temperature and sea conditions. According to infrared images around the waters of the Taiwan Strait during the fishing season in the winter, catch data, and oceanographic data gathered by research vessels from the Taiwan Fisheries Research Institute (TFRI), schools of grey mullet migrate along the protruding cold filament of the China Coast Current between the warm branch of the Kuroshio Current and the coast of Western TW (figure 1). This cold filament, with its lower temperature and salinity, protrudes from the mid-western coast and extends gradually southward. The width of this cold filament is narrower in the south (from 10 to 5 miles) and forms an obvious front to the warm branch of the Kuroshio Current. It has been suggested that schools of grey mullet become concentrated within the tip of the cold filament.

Figure 1. Breeding and Spawning Grounds of Grey Mullet in Taiwan’s Regional Waters
and form a dense school that is available for fishing activity in which the sea surface temperature (SST) is 20–23°C, a range that is optimal for grey mullet to spawn (Shyu and Lee 1986).

Catches exhibited sharp fluctuations during the 1967–2005 period (figure 2). The size of the annual catch increased during 1967–78, when the average number of fish caught in a year was approximately one million. After almost doubling in size, the average annual catch was about two million during the 1979–86 period. The size of the catch reached a peak of 2.5 million in 1980, followed by a sharp decline to a low of 91,439 in 2005.

The sharp decline in the annual catch has astonished many people in TW. Two major factors are believed to have affected the grey mullet resource in recent years (Huang 2005). One is the participation of and expansion in the size of the fleets from MC (Huang, Lin, and Huang 2005) and the other is the rising SST in the Taiwan Strait (Huang, Lin, and Huang 2005; Lee 2004). First, the people in MC have not traditionally regarded the grey mullet as valuable food, but people in TW have favored the delicious mullet roe and other parts of the fish. Therefore, almost all of the grey mullet were harvested by TW fishing vessels before 1998. However, the high economic value of grey mullet has led some people in TW to help MC establish a grey mullet fishery by introducing new technology, and the fish captured in this way are smuggled into TW. Due to their geographical advantage, the fishermen in MC can first harvest the fish at the point from which the grey mullet migrate; i.e.,

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1 Fishing gear commonly used for catching grey mullet in TW include purse seine, drift gill nets, trap nets, and surrounding nets. Among them, the purse seine is the most effective, accounting for at least 90% of total landings.

2 Overfishing may be another reason explaining the decline in annual catch in the 1980s. Tung (1981) estimated the maximum sustained yield (MSY) as 0.82 million (in numbers of fish) from 1958 to 1964. However, Hwang (1982) estimated the MSY as 2.46 million (in numbers of fish) from 1963 to 1980. The former supports the overfishing argument but the latter does not. Now it is considered that the low catch in recent years has been due to the overfishing by MC. Admittedly, this needs more rigorous investigation.
the East China Sea, giving rise to consistently low catches in the Taiwan Strait and
touching off the collapse of the grey mullet fishery in TW. In 1997, the catch by TW
vessels was 927,333 fish, but it was only 577,388 in 1998 and declined thereafter
(figure 2). In 2003, the estimated number of grey mullet harvested by MC was 1.6
million, which was far greater than the total catch (250,000) of TW’s harvesters in
that year (Huang, Lin, and Huang 2005). Due to the long-term cross-Strait political
rivalry, negotiations on fishery management between the two authorities remain in-
conceivable. The lack of an effective cooperative fishery management institution
and the strong demand for grey mullet in TW have both served to accelerate the
depletion of the grey mullet stock and have had a negative effect on the welfare of
the people in TW.

Second, rising SST is another significant factor that has reduced the catch size
in TW. Figure 3 shows that the SST in the Taiwan Strait has increased by about 1°C
in the last forty years. Hung and Su (1986) and Lee (2004) have shown that a sig-
nificant negative relationship exists between catch and temperature along the coast
of TW. Since the optimum SST for grey mullet to spawn is in the range of 20–23°C,
the rising SST prevents schools of grey mullet from migrating southward. It is also
observed that the main fishing grounds in TW have gradually moved northward (fig-
ure 4). It is envisaged that the global warming effect will push the migratory stock
further north and result in the spawning of grey mullet beyond TW’s traditional fish-
ing grounds. Accordingly, this will bring an end to the TW grey mullet fishery even
without the participation of MC.

We seek to study this interesting and peculiar fishing case analytically. First, we
analyze the effects of the non-cooperative competition between the grey mullet fish-
eries in MC and TW on the behavior of the fishing industry using a game theoretic
approach. We then study the combined effects of non-cooperative competition and

Figure 3. Time Series of SST to the West of Taiwan, 1981–2004
Source: National Centers for Environmental Prediction of the US National Weather Service. The authors
are indebted to Professor Hong-Yang Tseng for providing this figure.
Notes: “Ano” stands for the deviation of week-average SST (November to February) from the baseline
(the average SST from 1982 to 1992) observed in the 119.5–120.5 (°E) and 24.0–24.5 (°N) area. The
“Trend” is the trend of SST during the 1981–2004 period.
global warming. Several policy implications are drawn from the analyses.

Non-cooperative competition within the fishing industry both internationally and locally leading to depleted fish stocks and dissipated rents is widespread, even though the United Nations Convention on the Law of the Sea, which entered into force in 1994 but has been accepted as customary international law since 1982, has created coastal property rights over most of world’s commercial fisheries. Rent-shifting motivation arising from non-cooperative competition has resulted in increased subsidies in rival nations and the expansion of fleets. Most world fisheries subsidies are immense, and many of these are seriously detrimental to resource conservation and management (Clark, Munro, and Sumaila 2005; Munro and Sumaila 2002; Rosenberg et al. 1993). Ruseski (1998), in developing a one-period, non-cooperative international fishing game to examine strategic management policies, showed that the strategic rent-shifting effect arising from fleet licensing and effort subsidies led each nation to be more aggressive, which resulted in the prisoner’s dilemma outcome. Naito and Polasky (1997) developed a two-period non-cooperative
game of highly migratory fish stocks between coastal state and distant water fishing harvesters. The strategic tactic of expanding fleet size resulted in a second-best outcome as well. The shortcomings of these papers mainly stem from the assumption of perfectly elastic demand. In other words, the price of fish is constant. First, the constant fish price prevents a country from playing a strategic role in affecting the rival’s harvest through a price adjustment mechanism, and consequently only a strategic stock depletion effect between rival nations can be implemented. Secondly, this particular demand function excludes consumer welfare in determining the best management policies. Only rent in this fishery matters. The resulting best management policy is actually not the best from the standpoint of the country’s overall population, especially when the fish is a valuable species for the people of that country.

The analysis of climate change has been a hot topic since the 1990s. Some researchers have found that temperature and other environmental conditions related to climate appear to influence the abundance of fish resources (Markowski et al. 1999). Sissener and Bjørndal (2005) discussed the connection between altering climate conditions and the size, year class-strength, and migratory pattern of Norwegian spring-spawning herring (Clupea harengus). Lee (2004) found that the migratory pattern of grey mullet had changed due to the higher seawater temperature. Miller and Munro (2004) presented evidence for the significance of climate regime shifts, and drew upon the recent history of conflict between Canada and the United States over Pacific salmon management to illustrate the dangers that unpredicted environmental regime shifts pose for efforts to maintain international cooperation. Pendleton and Mendelsohn (1998) linked models related to global climate circulation, ecology, and economic valuation methods (the hedonic travel cost and random utility models) to value the impact of global warming on freshwater sportfishing in the northeastern United States. Markowski et al. (1999) developed climate change scenarios to analyze the sensitivity of commercial fisheries and the corresponding welfare effect (i.e., consumer surplus) to climate change. However, using a non-cooperative game framework to engage in the economic analysis of global climate change on the fishery industry remains limited.

This paper builds mainly on the fleet licensing model described in Ruseski (1998) and on the analysis of migratory fish stocks in Naito and Polasky (1997). In addition, we incorporate four important facts regarding the grey mullet fishery into the non-cooperative fishing game. The first is the expansion in the size of fleets in Mainland China in recent years as well as harvests at the starting point of migration. This fact gives rise to stock depletion of TW harvesters downstream. The second relates to the particular characteristics of the grey mullet market. Almost all fish harvested in both the TW and MC fishing grounds are sold to TW, and the market price is significantly influenced by the number of fish landed. The third is the lack of official communication between the authorities in MC and TW due to political hostility. This makes the comanagement of the grey mullet stock impossible. The fourth and last is the altered migratory pattern caused by global warming.

The first of these facts is modeled since there are sizeable fleets harvesting both in the upstream region (MC) and in the downstream region (TW), respectively. The second and third facts are described by means of a linear and imperfectly elastic demand function, and catches compete in the TW grey mullet market. The last one, the global warming effect on the grey mullet fishery, is examined in an analytical way.

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3 Naito and Polasky (1997) also conducted a good review of non-cooperative fisheries.
4 Note that in the grey mullet fishery, one fleet is usually composed of two boats working on the fishing ground. It is assumed, for simplicity, that each harvester in MC and TW owns one fleet, and one fleet consists of two boats in the model.
In particular, our analysis focuses on the effects of both the expansion in fleet size upstream and global warming on TW, and the corresponding strategies that the TW authority can adopt in view of its relatively inferior position. These notions are examined through a three-stage game theoretic model in which the TW authority chooses the fleet size to maximize its social welfare in the first stage, the harvesters in MC choose their harvest level in the second stage, and then the TW harvesters choose the harvest level from the remaining stock in the third stage. All catches compete in the TW grey mullet fish market.

The assumption of imperfectly elastic demand provides at least two interesting implications in terms of policy choices that have not been fully explored in the literature. First, the authority can influence market price through fleet regulation. An increase in the size of the fleets in TW can increase the aggregate harvest for TW, lower the market price of the fish, and reduce the harvest in MC. In turn, it can increase the stock that migrates to the TW fishing ground. Second, the range of fleet size choices is greater when consumer welfare is also considered in the decision making regarding fleet size than in the case when only fishery rent is considered, because increasing the fleet size can reduce the market price and improve the consumer welfare.

In addition, there are two findings from this paper. First, the expansion of fleets in MC increases its harvest and decreases the stock left downstream, which erodes the rent in the TW fishery through a reduction in market price and an increase in the cost of harvesting. Secondly, a higher SST prevents fish from migrating further south and results in a smaller harvest in TW and a higher market price for grey mullet roe. This will motivate harvesters upstream to harvest more, and will further decrease the stock left for TW. In equilibrium, both rent and the consumer surplus in TW are dwindling. When faced with fleet expansion in MC, the TW authority can strategically adjust the fleet size through the market mechanism to partially alleviate the damage to the TW fishery.

The remainder of this article is organized as follows. The next section develops the fleet regulation model to analyze the fleet expansion effects in grey mullet fishery and discusses the optimal fleet size in TW. The following section examines the effects of rising SST on the fishery and welfare in TW, while the final section draws conclusions.

**Fleet Regulation Model**

Suppose there are \( n_m \) symmetric harvesters in MC and \( n_t \) symmetric harvesters in TW. The individual harvests reaped by the MC and TW harvesters are \( h_i^m \) and \( h_j^t \), respectively, where \( i = 1,2,...,n_m \) and \( j = 1,2,...,n_t \). It is assumed, for simplicity, that each harvester in the MC and TW owns one fleet, and one fleet consists of two boats. The total harvest for all harvesters is:

\[
H = \sum_{j=1}^{n_t} h_j^m + \sum_{j=1}^{n_t} h_j^t = H_m + H_t,
\]  

5 Dockner, Feichtinger, and Mehlmann (1989) studied the case of a duopoly in which price depends on the total biomass harvested by two harvesters being at the market. Though their paper and ours both consider the market demand, they focused their attention on the different results between the Nash and Stackelberg models. However, we are very concerned with policy implications when facing the imperfect demand function in the framework of the Stackelberg model.
where $H_m$ and $H_t$ denote the aggregate harvest levels by the MC and TW harvesters, respectively.

The initial size of the grey mullet stock is $S_m$. The remaining stock for TW to harvest is $S_t$, which depends on harvest size in MC because the grey mullet migrates from MC. It is also deeply influenced by the rising SST. Hence, the fish stock along the coast of TW is:

$$S_t = S_m - H_m - \beta T,$$

where $T$ denotes the change in SST relative to the normal temperature, and $\beta$ is the impact factor of rising SST. We also assume that the remaining stock, $S_t$, is not negative and that the aggregate harvests for MC and TW are bounded; i.e., $0 \leq H_m \leq S_m$ and $0 \leq H_t \leq S_t$, respectively.

We assume that the unit cost of harvesting fish increases with congestion as the size of fleets expands and decreases with the stock size in each fishing ground. The unit cost of harvesting fish, $C_i^m$ and $C_j^t$ for $i = 1, 2, \ldots, n_m$ and $j = 1, 2, \ldots, n_t$ harvesters, respectively, can be written as:

$$C_i^m(h_m, H_m, S_m) = H_m - \alpha S_m$$

$$C_j^t(h_t, H_t, S_t) = H_t - \alpha S_t,$$

where $\alpha$ represents the coefficient of the stock effect. In order to keep the unit cost of harvesting positive, the coefficient $\alpha \in (0,1)$ is also imposed.

It is assumed that the inverse demand function for grey mullet is a linear function of the total harvest, $H$:

$$P = a - bH,$$

where $P$ is the price, $a$ is the choke price, and $b$ is the slope of the inverse demand function ($a > 0, b \geq 0$). Ruseski (1998), Naito and Polasky (1997), and Quinn and Ruseski (2001) assume that the market price of the harvested fish is constant because they are perfect substitutes (i.e., the demand for them is perfectly elastic and $b = 0$). Their analyses only focus on the rent for fishing and thus consumer preference is neglected. However, the constant market price assumption is not suitable when analyzing the grey mullet fishery. It is observed that the market price of grey mullet is variable in TW and that mullet roe has a unique characteristic flavor to the Taiwanese people. That is why we employ the negatively sloping demand function and treat the constant demand function as a special case.

In the third stage of the three-stage game developed here, each TW harvester chooses a harvest level to maximize his rent from the fishery, facing the harvest level chosen by the rival domestic and non-domestic fleets. In the second stage, each MC harvester chooses a harvest level to maximize his rent from the fishery, taking into account his influence on the harvest of TW but also facing the harvest level chosen by the rival MC fleets and the size of fleets chosen by the TW authority. In the first stage, only the TW authority chooses how many fleets are permitted to harvest in the TW fishing ground, with full knowledge of how fleet sizes influence the second- and third-stage equilibrium.

To solve for the backwards-induction outcome of this game, we first compute the equilibrium behavior of the fleets in the third stage, where the $j$-th fleet in the TW fishing ground chooses harvest level $h_j$ to maximize its individual rent, $\pi_j$, from the fishery:
Applying symmetry to the subsequent first-order conditions for $h_j^i$ (i.e., $h_j^i = h_i$ for all $j \in n_j$), then multiplying by $n_j$, yields the reaction function of the aggregate harvest level in the TW fishing ground to the aggregate harvest level of the fleets in the MC fishing ground as follows:

$$H_i(N; n_j) = \frac{n_j}{(1 + b)(1 + n_j)} \left[ a + \alpha(S_w - \beta T) - (\alpha + b)H_m \right].$$

(7)

Moving back to the second stage of the game, each harvester in the MC fishing ground wants to choose his harvest level, and looks ahead to determine how the harvesters in the TW fishing ground will respond. Thus, the $i$-th fleet in the MC fishing ground chooses harvest level $h_i^m$ to maximize its individual rent, $\pi_i^m$, from the fishery:

$$\max_{h_i^m \geq 0} \pi_i^m = [P - (H_m - \alpha S_m)]h_i^m.$$

(8)

Applying symmetry to the subsequent first-order conditions for $h_i^m$ (i.e., $h_i^m = h_m$ for all $i \in n_m$), then multiplying by $n_m$, yields the reaction function of the aggregate harvest level in the MC fishing ground to the size of fleets chosen by the TW authority as follows:

$$H_m^*(n) = \frac{n_m}{(1 + b)(1 + n)} \left[ (1 + b + n_m)(a + \alpha S_m) + bnT \alpha \beta \right] \Phi,$$

(9)

where $H_m^* = n_m h_m^*$ is the equilibrium aggregate harvest level for MC harvesters in the second stage and $\Phi = (1 + n_m)[(1 + b)^2(1 + n) - b(b + \alpha)n] > 0$. Substituting the harvest level in equation (9) into the aggregate harvest level of TW in equation (7), we have the first-stage equilibrium aggregate harvest level, that is:

$$H_1^*(n_j) = \frac{n_j}{(1 + b)(1 + n_j)} \left[ a + \alpha(S_m - \beta T) - \frac{n_m(a + b)(1 + b + n_m)(a + \alpha S_m) + bnT \alpha \beta}{\Phi} \right].$$

(10)

where $H_1^* = n_1 h_1^*$ is the aggregate equilibrium harvest level for TW. Then the harvest level chosen by the TW and MC harvesters in the third- and second-stage equilibrium is the function of the fleet size to be determined by the TW authority in the first stage.

We then examine the effect of a small increase in the fleet size in TW on its fishery, with a small increase in the fleet size in the downstream area leading to:

$$\frac{\partial H_1^*}{\partial n_i} = \frac{1}{(1 + n_i)} \left\{ \frac{n_m n_i b(\alpha + b)[(1 - \alpha)(a + \alpha S_m) - (1 + b)T \alpha \beta]}{\Phi \Omega} + h_i^* \right\} > 0$$

(11)
\[
\frac{\partial H^*}{\partial n_t} = -\frac{b(1 + b)n_m[(1 - \alpha)(a + \alpha S_m) - (1 + b)\theta\Omega]}{\Phi\Omega} < 0,
\]

where \( \Omega = (1 + b)^2(1 + n_t) - b(b + \alpha)n_t \). The results only hold when the slope of the demand function is not too large; i.e., \( b < (1 - \alpha)(a + \alpha S_m) - \alpha T/\alpha T \). Under this condition, it can be seen from equation (11) that the “direct effect” of a small increase in the fleet size for TW is positive.\(^6\) Harvesting by new entrants in the TW fishing ground reduces the size of the fish stock and increases the congestion cost in the fishery so that each harvester lowers his harvest level. However, the increased harvests of the new entrants more than offset the congestion-induced decrease in the harvests of those already in the TW fishing ground. It can also be seen from equation (12) that the “strategic effect” of a small increase in the fleet size of TW is negative. This is because the harvests of new entrants in the TW fishing ground increase the total amount of harvesting in the TW area, which decreases the market price of grey mullet accordingly. In turn, the MC harvesters reduce their harvests in response to the decrease in marginal revenue. Using equations (11) and (12), as well as the demand function in equation (5), the effects of an increase in fleet size in TW on the equilibrium total harvest level, \( H^* \), and the equilibrium market price, \( P^* \), are expressed as follows:

\[
\frac{\partial P^*}{\partial n_t} = -b \frac{\partial H^*}{\partial n_t} < 0,
\]

from which it can be found that the direct effect of a small increase in fleet size in TW dominates the strategic effect such that equation (13) holds.

Now consider the effects of a small increase in the size of the fleets in TW on their equilibrium rent in the third stage. Let the total rent of the TW harvesters be \( \Pi = n_t\pi_t \) and the unit harvesting cost function be \( C_t = C_t \) based on the symmetry condition for all TW harvesters. By differentiating the total rent \( \Pi = (P - C_t)H_t \) with respect to \( n_t \), and then substituting the first-order condition of equation (7), the effects of a small increase in the size of the fleets in TW are shown as:

\[
\frac{\partial \Pi^*_t}{\partial n_t} = \frac{h_t}{(1 + n_t)} \left[ (1 + b)(1 - n_t)h_t^* - 2(\alpha + b)n_t \frac{\partial H^*_m}{\partial n_t} \right].
\]

Notice that the first term in the square brackets of equation (14) is zero if \( n_t = 1 \) and negative if \( n_t > 1 \). The second term in the square brackets of (14) is positive, because the strategic effect of a small increase in the size of fleets in TW is negative; i.e., \( \partial H^*_m/\partial n_t < 0 \). In the absence of any strategic interaction between fleets in the upstream and downstream areas (e.g., \( n_m = 0 \)), having only a single fleet in the TW fishing ground would lead to an efficient level of harvest and maximum rent generation in the fishery. However, the existence of strategic interaction provides the TW authority with an incentive to increase the size of its fleets. In particular, when \( n_t = 1 \), a small increase in the size of fleets in the TW fishing ground unambiguously raises the equilibrium rent of TW. If \( n_t > 1 \), the effect is ambiguous.

\(^6\) As in similar results derived by Ruseski (1998) without considering the price effect.
We show that by considering imperfectly elastic demand, the size of domestic fleets can increase more than in a perfectly elastic demand setting when there is just one fleet in TW. It is observed from equation (14) that when $n_t = 1$ and the demand function is imperfectly elastic ($b \neq 0$), a small increase in the size of TW fleets can increase the domestic rent; i.e.,

$$\left. \frac{\partial \Pi_t}{\partial n_t} \right|_{n_t = 1, b \neq 0} = -(\alpha + b)h_t^* \frac{\partial H_m^*}{\partial n_t} > 0. \tag{15}$$

However, when $n_t = 1$ and the demand function is perfectly elastic ($b = 0$), the effect of a small increase in the size of fleets is nil; i.e.,

$$\left. \frac{\partial \Pi_t}{\partial n_t} \right|_{n_t = 1, b = 0} = 0, \tag{16}$$

since $\partial H_m^*/\partial n_t = 0$ when $b = 0$.

**Proposition 1:** An increase in the size of TW’s fleets increases the aggregate equilibrium harvest level for TW harvesters and increases the total equilibrium harvest level, but reduces the equilibrium market price and the aggregate equilibrium harvest level for MC harvesters.

Next, we examine the effects of increasing the fleet size for MC on the TW grey mullet fishery. A small increase in fleet size in the upstream area leads to:

$$\frac{\partial H_m^*}{\partial n_m} = \frac{h_m^*}{(1 + n_m)} > 0 \tag{17}$$

$$\frac{\partial H_t^*}{\partial n_m} = -\frac{n_t(\alpha + b)h_t^*}{(1 + b)(1 + n_m)(1 + n_t)} < 0. \tag{18}$$

It can be seen from equation (17) that the “direct effect” of a small increase in the fleet size for MC is positive. The harvests of new entrants increase the congestion cost in the MC fishing ground so that each harvester in that area reduces the size of his harvest. However, the increase in the harvests of the new entrants more than offsets the congestion-induced reduction in the harvests of harvesters already in the MC fishing ground. It can also be seen from (18) that the “strategic effect” of a small increase in the fleet size of MC is negative. Increasing the aggregate harvest in MC by means of new entrants in the MC fishing ground not only decreases the market price of grey mullet but also increases the unit harvesting cost faced by the TW harvester as a result of the depletion in stock. The former decreases the marginal revenue from harvesting, and the latter increases the marginal cost of harvesting. Hence, the small increase in fleet size in MC induces the TW harvesters to reduce their harvests. By using equations (17) and (18) and equation (5), the effects of an increase in fleet size in MC on the total equilibrium harvest level, $H^*$, and the equilibrium market price $P^*$ are:
Similar to the results in equation (13), a small increase in the fleet size in the MC fishing ground increases the equilibrium harvest and decreases the market price. Note that the upstream stock depletion effect as a result of expanding the fleet size reinforces the direct and strategic effect, while such an upstream depletion effect is absent in the results from the downstream harvest scenario.

Now let us consider the effect of a small increase in the MC fleet size on the total equilibrium rent of the TW harvesters in the third stage:

\[
\frac{\partial \Pi^*_t}{\partial n_m} = (P^* - C^*_t) \frac{\partial H^*_t}{\partial n_m} + H^*_t \left( \frac{\partial P^*}{\partial n_m} - \frac{\partial C^*_t}{\partial n_m} \right) < 0, \tag{20}
\]

since \((P^* - C^*_t)\) is assumed to be positive and \(\frac{\partial H^*_t}{\partial n_m} < 0\) from equation (18). Besides, the monetary effect of a small increase in the fleet size in MC is expressed as follows:

\[
\frac{\partial P^*}{\partial n_m} - \frac{\partial C^*_t}{\partial n_m} = - \frac{(\alpha + b)h^*_m}{(1 + n_m)(1 + n_t)} < 0. \tag{21}
\]

Hence, the small increase in the MC fleet size reduces the equilibrium rent of the TW harvesters. The analysis supports the serious concerns of TW harvesters that, in terms of their geographical superiority in the migratory path, MC harvesters can harvest first and reduce the fishing stock left for TW harvesters. The combined effect of MC’s geographical superiority and rapid expansion of its fleet has accelerated the erosion of the rent in the TW fishery. The effects of the increased fleet size in MC are summarized as follows:

**Proposition 2:** An increase in the size of the fleets in MC increases the aggregate equilibrium harvest level for MC harvesters and increases the total equilibrium harvest level, but reduces the equilibrium market price as well as the aggregate equilibrium harvest level for TW harvesters. In addition, the total rent of the TW harvesters also declines.

Finally, let us turn to the choice of fleet size by the TW authority in the first stage of the three-stage game. The TW authority can unilaterally choose its domestic fleet size by taking the size of the MC fleets as given. The choice of fleet size is made with the full knowledge of how fleet size influences first- and the second-stage equilibrium. The objective of the TW authority is to maximize the social welfare by choosing the fleet size in TW. The social welfare includes the consumer’s surplus \(\text{CS}\) in TW and the equilibrium rent accruing to TW harvesters, that is:

\[
\max_{n_t} W(n_t) = \text{CS} + \Pi^*_t, \tag{22}
\]

where \(\text{CS} = \int_0^{H^*} P(x)dx - P^*H^*\). Using equation (13), the effect of a small increase in fleet size on TW’s consumer surplus is:
\[ \frac{\partial CS}{\partial n_t} = bH^r \frac{\partial H^r}{\partial n_t} > 0. \]  

(23)

It can be seen that a small increase in the TW fleet has a positive effect on the consumer surplus, which means that the larger the fleet, the more grey mullet consumers will enjoy at a lower price. From equation (15), it is also known that when the size of fleets is one and the demand function is imperfectly elastic, a small increase in fleet size can increase the total equilibrium rent of the TW harvesters. By considering both of the positive effects from increasing fleet size, it can be inferred that the TW authority would choose an optimal fleet size greater than one.\(^7\)

Based on the model developed here, we consider two special cases with regards to choice of the optimal fleet size. The first one is to examine the assumption of perfectly elastic demand that is often used in the literature. If there are many other species that can perfectly substitute for grey mullet or there is well-developed grey mullet aquaculture that can compete with those captured in the wild, the demand function \( p = a - bH \) can be simply reduced to \( p = a \), and consumer surplus no longer plays a part in the social welfare. Without consumer surplus, optimal fleet size is completely determined by the rent of the fishery:

\[ \frac{\partial W}{\partial n_t} = \frac{\partial \Pi^*_n}{\partial n_t} = \frac{(1 - n_t)h^*_t}{1 + n_t} = 0. \]  

(24)

It is apparent that the optimal fleet size is \( n_t^* = 1 \), and because the TW authority cannot influence the market price through fleet regulation in this case, only one fleet will lead to an efficient harvest level and maximum rent in the fishery.\(^8\)

The second one is to discuss what the optimal fleet size will be if MC harvesters do not participate in the grey mullet fishery; i.e., \( n_m = 0 \) and only TW harvesters compete in the fishing ground. The first-order condition for \( n_t^* \) is:

\[ \frac{\partial W}{\partial n_t} = \frac{\partial CS}{\partial n_t} + \frac{\partial \Pi^*_n}{\partial n_t} \]

(25)

\[ = \left[ \frac{a + \alpha(S_m - \beta T)}{(1 + n_t)(1 + b)^2} \right] bH^r + \left[ \frac{a + \alpha(S_m - \beta T)}{(1 + n_t)(1 + b)^2} \right] (1 + b)(1 - n_t) = 0. \]

The optimal fleet size is \( n_t^* = 1 + b \). We have two implications from the result. First, the benefit to the consumer from increasing the fleet size, the first part of equation (25), is greater than the loss to the harvesters in terms of the rent obtained from the fishery, the second part of (25). This is because when the fleet is greater than one, one more addition to the fleets will decrease the rent of the TW harvesters. Secondly, it can be observed that optimal fleet size will increase with an increase in the slope of the demand function, because the steeper the demand function becomes, the more power the fishery will have to raise the market price. Hence, a larger fleet size

\(^7\) Optimal fleet size can be solved in reduced form, and is supposed to be a function of parameters specified in the model. To make our points clear, we do not adopt this approach.

\(^8\) We arrive at the same conclusion as Manson and Polasky (1997) in their “no demand–side distortion” case.
will be required by the TW authority to offset the increase in price through fleet expansion. Here we have the following proposition:

**Proposition 3:** The optimal fleet size in TW is greater than one when MC harvesters harvest in the upstream area and the demand function for grey mullet in TW is not perfectly elastic. In particular, when the demand function is perfectly elastic, the optimal fleet size is 1; when there are no harvesters in the upstream area, the optimal fleet size is \(1 + b\).

### The Effects of Rising SST

Consider the effects of rising SST on the TW grey mullet fishery. The effects are shown as follows:

\[
\frac{\partial H^*}{\partial T} = \frac{bn_n \alpha \beta}{\Phi} > 0 \tag{26}
\]

\[
\frac{\partial H^*}{\partial T} = - \frac{n \alpha \beta}{(1+b)(1+n)} \left[ 1 + bn_n(\alpha + b) \right] < 0 \tag{27}
\]

\[
\frac{\partial H^*}{\partial T} = - \frac{n \alpha \beta}{(1+b)(1+n)\Phi} \left[ (1+n_n)(1+n_m) + b^2 + b(2+n_m) + bn_n + 2 - \alpha \right] < 0 \tag{28}
\]

\[
\frac{\partial P^*}{\partial T} = -b \frac{\partial H^*}{\partial T} > 0. \tag{29}
\]

Rising SST reduces the fish stock migrating to the TW fishing ground and increases the marginal cost of harvesting. Consequently, rising SST results in a decreased harvest level in TW and a corresponding increase in market price. The rising market price will motivate MC harvesters to increase their harvest, which will further prevent the spawning fish stock from migrating southward. Increasing the harvest in the upstream area induced by the rising SST strengthens the negative stock effect and causes the marginal cost of the harvest to increase further, so that the harvest in TW declines even more. In equilibrium, the total harvest declines and the market price increases. In addition, the effect of the rising SST on the equilibrium rent in the TW fishery is shown as:

\[
\frac{\partial \Pi^*}{\partial T} = (P^* - C^*) \frac{\partial H^*}{\partial T} + H^* \left( \frac{\partial P^*}{\partial T} - \frac{\partial C^*}{\partial T} \right) < 0, \tag{30}
\]

since \((P^* - C^*)\) is assumed to be positive and \(\frac{\partial H^*}{\partial T} < 0\) from equation (27). Furthermore, the monetary effect of increasing SST is expressed as follows:

\[
\frac{\partial P^*}{\partial T} - \frac{\partial C^*}{\partial T} = - \frac{\alpha \beta}{(1+n)\Phi} \left[ (1+n_n)(1+n_m)(1+2b) + b^2(1+n_m + n_n) - bn_n \right] < 0. \tag{31}
\]
Therefore, the effect of the rising SST on the equilibrium rent in the TW fishery is negative. This shows that the increase in rent from raising the market price is dominated by the decrease in rent from the increased cost of harvesting due to the rising SST. The effect of rising SST on the equilibrium rent in the MC fishery is:

\[
\frac{\partial \Pi^*_m}{\partial T} = \frac{2bn_\alpha \beta H^*_m}{(1 + b)(1 + n_t)(1 + n_m)} > 0. \tag{32}
\]

Because of the increase in market price and the expansion in harvests of the MC harvesters due to the rising SST, the rent of the MC harvesters increases in equilibrium.

Now consider the effect of rising SST on the consumer surplus:

\[
\frac{\partial CS}{\partial T} = bH^* \frac{\partial H^*}{\partial T} < 0. \tag{33}
\]

Because the rising SST reduces the total equilibrium harvest, the consumer is worse off. By combining equations (30) and (33), it can be concluded that the effect of rising SST on the social welfare in TW is negative. We summarize the effects of rising SST as follows:

**Proposition 4:** An increase in the SST increases the aggregate equilibrium harvest level for MC harvesters and increases the equilibrium market price, but reduces the aggregate equilibrium harvest level for TW harvesters and the total equilibrium harvest. In addition, the total rent of the TW harvesters and the consumer surplus enjoyed by the people of TW also decrease.

If the SST rises significantly such that the grey mullet no longer migrates to the TW fishing ground, i.e. \(S_t = 0\), the collapse of the TW grey mullet fishery is unavoidable. Should such a time come, TW will either import captured grey mullet from MC or develop grey mullet aquaculture.

**Conclusion**

This paper develops a three-stage game theoretic model to examine the grey mullet fishery in TW. Faced with fleet expansion upstream and decreased fish stock due to global warming, we show that the authority in TW can increase its rent from the fishery as well as its consumer surplus by expanding its fleet size. We also show that the rising SST will harm the social welfare of the people in TW, but will benefit the harvesters in MC.

Political hostility between the two sides of the Taiwan Strait is the main obstacle to managing the grey mullet stock sustainably. If this political obstacle persists, non-cooperative fishing may continue. As a result, the grey mullet resource will be the first victim of the strategic behavior of the two rivals, and the fisheries in TW and MC will be the next. Non-cooperative fishing only results in the prisoner’s dilemma.

\[\text{It can be expressed algebraically that when } T \geq (S_m - H_m)/\beta = T_0, \text{ where } T_0 \text{ is the critical point, grey mullet would disappear from the TW fishing ground.}\]
References


Huang, C.S. 2005. Taiwan Fisheries Research Institute, Kaohsiung, Taiwan. Interviews.


