CONSIDERATIONS FOR TAC TARGETS IN A SINGLE GEAR, MULTIPLE SPECIES FISHERY

- A CASE STUDY OF THE LARGE PURSE SEINE FISHERY FOR MACKEREL (*SCOMBER JAPONICUS*) AND JACK MACKEREL (*TRACHURUS JAPONICUS*) -

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ABSTRACT

This paper provides a Total Allowable Catch (TAC) assessment model for a single gear, multi-species fishery in South Korea. To estimate appropriate Allowable Biological Catch (ABC) of mackerel and jack mackerel caught by the large purse seine fleet in the territorial waters of South Korea, the model uses an extended Beverton-Holt yield per recruit model and a biomass-based cohort analysis. The extended Beverton-Holt yield per recruit model adds two terms [a relative bycatch index (w_i) and a relative instantaneous fishing mortality index (a_i)] to the original Beverton-Holt model [1]. The reason for adding new terms is because bycatch of those species caught by the large purse seine can affect the instantaneous fishing mortality and the recruitment of each species. In conclusion, this paper suggests that the current ABC level of mackerel needs to be lowered to prevent overfishing of jack mackerel with the small stock due to bycatch.

Keywords: TAC assessment model, Multi-species, Single fishing gear, Korean TAC system, Allowable Biological Catch, Mackerel, Jack mackerel

INTRODUCTION

The territorial waters of South Korea are in a temperate marine zone. More than 200 species are found there. Off-shore and in-shore fisheries of South Korea involve approximately 37 fishing gears. These species have been caught by several fishing gears in the adjacent Korean waters, and so most Korean fisheries have involved multi-species and multi-fishing gears. South Korea has enforced Total allowable Catch (TAC)-Based Fisheries Management since 1999 (Table I) and also has a plan to gradually extend TAC species. In particular, multi-species[i] with high commercial value will be added to the list of TAC species in the near future [2,3]. Hence, assessment models of TAC set-up suitable to multi-species fisheries of South Korea will be needed.

The current Korean TAC assessment model is based on an Allowable Biological Catch (ABC) estimation designed to ensure that Spawning Stock Biomass (SSB) remains at or above the precautionary biomass level [4]. Data used in the analysis depend upon biological information for individual species and its past catching history [5]. Particularly, the current TAC assessment model[ii] has only considered a single species and a single fishing gear and also has excluded interactions[iii] among multi-species and fishing gears. Therefore, it can overestimate or underestimate ABCs of the targeted TAC species, because it treats as exogenous variables such as biological, technical and economic interactions and environmental factors. For example, the catch proportions of most TAC species has been lower than their TAC levels. Nonetheless, due to the decrease in stock and catch per unit effort (CPUE) of TAC species [3,6], their TAC levels have continually and slightly decreased as shown in Table I. This can be an evidence of what TAC levels have been overestimated for their species. Basically, the main reason for this overestimation would be that the current Korean TAC assessment model has not appropriately reflected various interactions that can occur among multi-species and multi-fishing gears. For example, the TAC of the sardine has especially been higher than its catch proportion since the TAC system began in 1999. Environmental factors such as a sudden rise of water temperature has been rarely reflected in the TAC of the sardine (Table I). In addition, in most Korean TAC species with high bycatch rate, the TACs used since 1999 appear to have been inadequate to conserve the resource which may reflect the omission of bycatches (Table II).

Table I: The Current Korean TAC System: 9 Species and 5 Fisheries

Fishery	Species	1999		2000		2001		2002		2003	
		TAC (ton)	Catch Proportion (%)*	TAC (ton)	Catch Proportion (%)	TAC (ton)	Catch Proportion (%)	TAC (ton)	Catch Proportion (%)	TAC (ton)	Catch Proportion (%)
Large Purse Seine	Mackerel	133,000	115	170,000	49	165,000	96	160,000	79	158,000	74
	Jack Mackerel	13,800	47	13,800	68	10,600	90	10,600	100	11,000	100
	Sardine**	22,660	42	22,600	3	19,000	0.6	17,000	0	13,000	0
Off-Shore Trap	Red Snow Crab	39,000	65	39,000	78	28,000	69	28,000	64	22,000	92
	King Crab	-	-	-	-	-	-	1,220	78	1,000	61
Diver	Purplish Washington Clam	-	-	-	-	9,500	64	9,000	59	9,000	52
	Fun Mussel	-	-	-	-	4,500	33	2,500	57	2,500	65
Village	Cheju Island Top Shell	-	-	-	-	2,150	90	2,058	96	2,150	91
Off-Shore Gill Net Trap	Blue Crab	-	-	-	-	-	-	1,550	97	13,000	38
Total		208,460	93	245,400	51	238,750	81	231,928	72	231,650	70

Source: Ryu, J., Nam, J., and Gates J. M., 2006. Limitations of the Korean Conventional Fisheries Management Regime and Expanding Korean TAC System toward Output Control System, Marine Policy 30: 510-522.

Therefore, this paper provides an extended TAC assessment model considering technical interactions[iv] to re-estimate TAC levels for multi-species (i.e., mackerel and jack mackerel) caught by a single fishing gear (i.e., large purse seine).

The purposes of the paper are first to set up a TAC assessment system considering technical interactions, as an auxiliary and precautionary means, for overcoming limitations of the current TAC assessment model, and for rational operation of the Korean TAC system, secondly, to develop an extended TAC assessment model for estimating accurate TAC of multi-species selected. Finally, the paper from results analyzed suggests policy directions for the Korean TAC system.

The paper is organized as follows. Section 2 introduces the theoretical approach of TAC assessment about multi-species and a single fishing gear with a technical interaction based on a modified Beverton-Holt yield per recruit model and a surplus production model. Section 3 provides the basic structure of an extended TAC assessment model. Section 4 analyzes the optimal ABC level of the single gear-multi-species case using the extended yield per recruit model and biomass-based cohort analysis and also discusses and compares the ABC level analyzed by the extended model to that estimated the current Korean TAC assessment model. Section 5 contains concluding remarks about implications and limitations of Korean TAC system for single gear-multi-species assessment.

THEORTICAL APPROACH OF TAC ASSESSMENT FOR A SINGLE GEAR, MULTISPECIES FISHERY

Most analyses of multi-species fisheries have ignored the effects of joint catch under an assumption that the each unit of effort is applied directly to each species. This assumption is reasonable of the bycatch component of a species is small relative to the targeted catch of the species [7]. However, Korean fisheries have experienced high bycatch rate among the targeted TAC species (Table II).

Table II: Bycatch Rate (b_i) of Korean TAC Species (Unit: %)

Fishery	Species	1980	1985	1990	1995	2000	2001	Average
Large Purse Seine	Mackerel	3.4	8.8	4.4	20.3	25.3	12.7	12.5
	Jack Mackerel	50.4	19.0	27.9	38.7	26.8	38.8	33.6
	Sardine	14.5	9.1	4.4	3.4	2.1	4.7	6.4
Off-shore Trap	Red Snow Crab	-	-	-	35.5	23.2	30.7	29.8
Diver	Fun Mussel	-	-	47.3	79.4	57.2	69.3	63.3
Village	Cheju Island Top Shell	29.8	37.1	46.9	58.8	62.5	63.9	49.8
Off-shore gill net trap	Blue crab	91.9	98.3	89.2	44.3	63.5	78.7	77.6

Source: Ryu, J. *et al*., 2002. A Study on Annual Expansion Program of TAC Target Species, Ministry Of Maritime Affairs and Fisheries (MOMAF), 167 pp.

Analyses which do not consider technical interactions such as the bycatch component, can cause a bias in TAC estimation by each species. Nevertheless, the Korean TAC assessment has used the single species Beverton-Holt yield per recruit model[v] in most TAC species [1,5]. A theoretical limitation of this model is whether or not the instantaneous fishing mortality (F) within the model is accurately reflecting each species' bycatch. Our conclusion is that the instantaneous fishing mortality from bycatches can differentially affect yields per recruit. Hence, for multi-species fisheries with high bycatch rates of target species, more accurate estimates of yield per recruit by species can be obtained by adding additional terms within the model. Specifically, an extended Beverton-Holt yield per recruit model for a single gear, multi-species adds two terms [i.e., a relative bycatch index (w_i) and a relative instantaneous fishing mortality index (a_i)] to the original Beverton-Holt model. The reason for adding new terms is that bycatch of mackerel and jack mackerel caught by the large purse seine can affect the instantaneous fishing mortality and recruitment of each species. The new terms capture the changes in fishing mortality and stock of each species due to bycatches. As previous literatures with related to our theoretical approach, Murawski provided a detailed account of a single fishery and multi-species yield per recruit model which is quite similar conceptually to that presented by Beverton and Holt. Murawski also extended the model to examine the case where several fisheries exploit differing mixtures of the same stocks and applied both the single and multiple fisheries models to the Georges Bank otter trawl fishery [8,9]. Daan and Pascoe have developed a model where the catch of one species is a function of the effort applied to that species as well as the effort targeted on other species in the fishery [10,32]. That is, there were separate target and bycatch catchability coefficients [7]. Seo and Zhang [27] provided a multi-species yield per recruit model which uses individual catch rate of the multi-species (hair tail, small yellow croaker, white croaker and pomfret) caught by the Korean pair trawl fishery [11].

In addition, Anderson [12,31] developed a theoretical two species model where the catch of one species was a function of the effort directed at that species as well as the effort directed at the other species. This approach based on the surplus production model [13,14] provides a strong theoretical basis for the extended Beverton-Holt single gear, multi-species yield per recruit model. A theoretical multi-species and single fishing gear model can be interpreted as shown in the following Fig. 1.

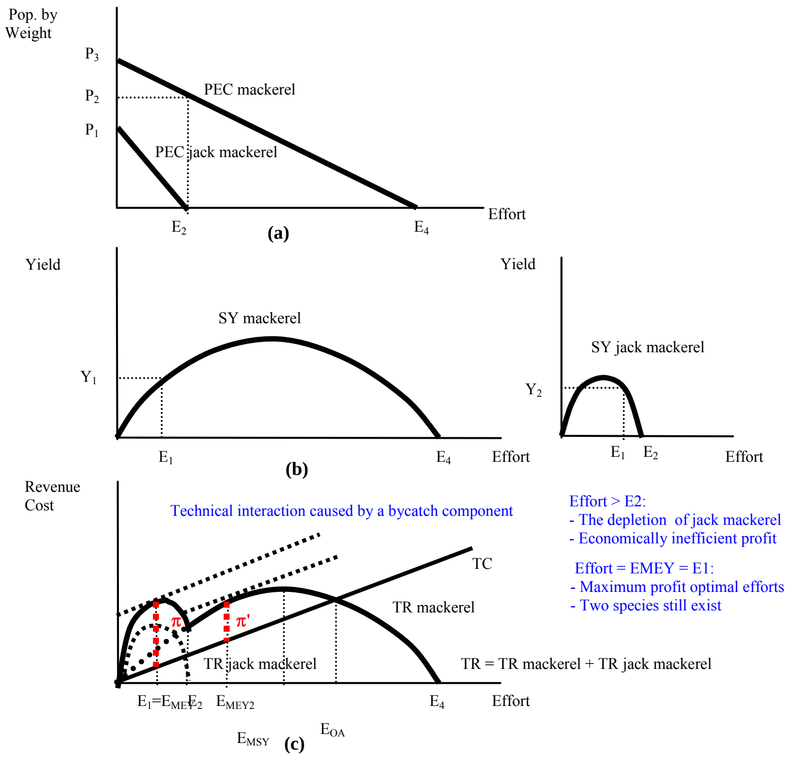


Figure1. A Theoretical Approach on Mackerel and Jack Mackerel caught by the large purse seine with Technical Interaction

Yields caught of either type of fish depend upon the effort used and the size of the respective population. Each species will have a population equilibrium curve (PEC), as shown in Fig. 1(a). Since the two populations are independent, the curves are derived from the relevant intersection between individual fishing effort and equilibrium population such that the equilibrium population size decreases as fishing effort increases. Thus, in the absence of fishing effort, mackerel has an unexploited equilibrium population size of P_3. Similarly, the natural equilibrium size of jack mackerel is P_1. As effort increases, a new equilibrium is reached at a lower population size due to the increase in catch.

Particularly, when fishing effort reaches E_2, the stock species B is destroyed at zero but that of mackerel is at P_2. If fishing effort reaches E_4, the population of mackerel is depleted as well. When each species is at a sustainable yield such as the Fig. 1(b), the total sustainable yield is the sum of the two sustainable yields. For instance, when fishing effort of both species is E_1, the equilibrium yields of those are Y_1 and Y_2 respectively. Therefore the total sustainable yield (Y_1+Y_2) at this level of fishing effort comprises those two quantities as shown in the Fig. 1(c), and the revenue earned by multiplying relative prices by the sustainable yields will depend upon the prices of the two species and the size of each catch.

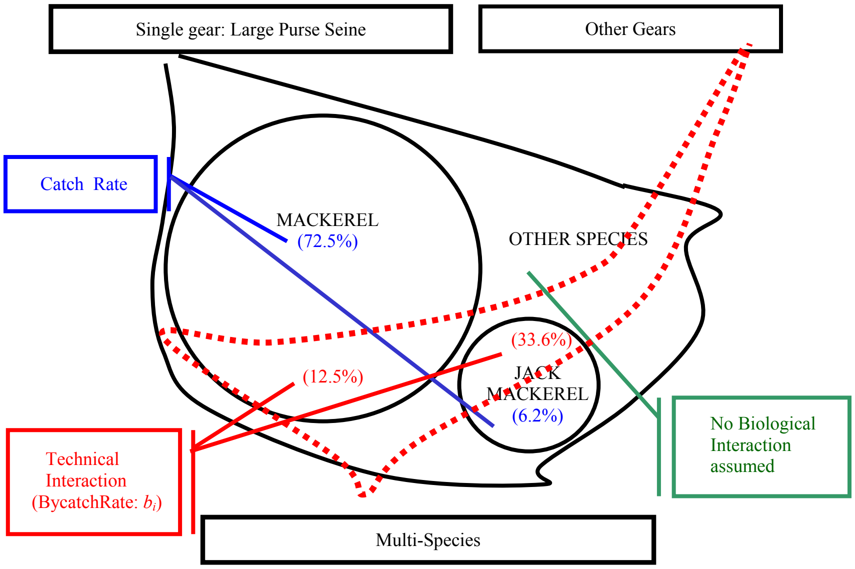
Economically, E_{MEY1} or E_1 is more efficient than E_{MEY2}, E_{MSY}, and E_{OA} because although fishing effort is less, profit (π) of E_{MEY1} is the highest given the total cost (TC). In addition, biologically, in E_{MEY1}, both species are still remaining but in E_{MEY2} or E_3. At that point with $E_{MEY2,}$ jack mackerel is completely depleted. Therefore total revenue arises entirely from the catch of mackerel. Thus, in this theoretical multi-species and single fishing gear example, E_{OA} at open-access fishery and E_{MSY} regulation destroy jack mackerel that could have been of value to another sector of society (i.e. social welfare loss) such as sports or recreational fishing. E_{MEY2} regulation also destroys jack mackerel [12,31].

In conclusion, in a fishery with two technically-related species, exclusive focus on harvests one species mackerel without considering the bycatches of the other species, may result in depletion of one or both species. Thus, although two species are biologically independent, bycatch between two species due to fishing activity of the single fishing gear can result in depletion of the bycatch species.

AN EXTENDED TAC ASSESSMENT MODEL

As a case study, multi-species and a single fishing gear with technical interaction are applied to mackerel and jack mackerel caught by a large purse seine in Korean waters. The large purse seine fleet has averaged 72.5 percent mackerel and 6.2 percent jack mackerel from 1994 to 2003 [15]. The extended TAC assessment model uses an extended Beverton-Holt single gear, multi-species yield per recruit model and biomass-based cohort analysis.

Model's Basic Structure



Source: Ministry of Maritime Affairs and Fisheries (MOMAF), 2004. http://fs.fips.go.kr/index.jsp: Catch rate and Bycatch rate (b_i)

Figure 2. The Basic Structure of Multi-Species by a Single Gear

The model assumes that i) two species are independent each other so that there is no biological interactions between the species, ii) the mackerel and the jack mackerel have caught by large purse seine, a fishing gear selected are limited to mackerel, and jack mackerel and other species (e.g., sardine, squid, hairtail) caught by the gear are ignored in this analysis, iii) there is a technical interaction in that the large purse seine on the one target stock creates fishing mortality on other stocks, and iv) bycatch rate, percentage of the two species caught by other gears (e.g., large bottom trawl, large trawl) is also considered. The basic structure of multi-species and single fishing gear is illustrated in Fig. 2.

Analysis Method

***An Extended Beverton-Holt Single Gear, Multi-species Yield Per Recruit Model*:**
To estimate more accurately, annual fishing mortalities (year^{-1}) such as F_{ABC} for the study fishery, the extended Beverton-Holt yield per recruit model is transformed to Eq.1. The extended model uses a relative bycatch index (w_i) and a relative instantaneous fishing mortality index (a_i) in order to consider technical interactions like bycatch component.

$$Y/R = \sum_{i=1}^{s} w_i a_i F \exp(-M_i(t_{ci} - t_{ri})) \cdot W_{\infty i} \sum_{n=0}^{3} \frac{U_n \exp[-nK_i(t_{ci} - t_{0i})]}{a_i F + M_i + nK_i} \cdot (1 - \exp[-(a_i F + M_i + nK_i)(t_{Li} - t_{ci})]) \qquad \text{(Eq. 1)}$$

where s represents the number of species, w_i represents a relative bycatch index of i species (bycatch rate of i species / average bycatch rate of all species targeted), a_i represents a relative instantaneous fishing mortality index (= $F_i / \overline{F_w}$) of i species, F represents an instantaneous fishing mortality rate, $\overline{F_w}$ represents a weighted average instantaneous fishing mortality rate of s species, M_i represents an instantaneous natural mortality coefficient of i species, t_{ci} represents mean age (years) at first capture of i species, t_{ri} represents mean age (years) at recruitment to the fishing area of i species, $W_{\infty i}$ represents asymptotic weight parameter of i species, U_n represents summation parameters ($U_0=1$, $U_1=-3$, $U_2=3$, $U_3=-1$), K_i represents the Brody growth coefficient of i species, t_{0i} represents hypothetical age the fish of i species would be zero length, and t_{Li} represents the maximum age (years) of i species.

The weighted average instantaneous fishing mortality rate ($\overline{F_w}$) which reflects a bycatch component implies the ratio of the sum of the products of instantaneous fishing mortality (F_i) coefficient of i^{th} species and its bycatch rate (b_i), divided by sum of the bycatch rates (b_i) of i^{th} species. $\overline{F_w}$ can be expressed by

$$\overline{F_w} = \frac{\sum_{i=1}^{s} b_i F_i}{\sum_{i=1}^{s} b_i} \qquad \text{(Eq. 2)}$$

where s represents the number of species ($i = 1, 2, \cdots, S$). The bycatch rate of i^{th} species, b_i can be estimated from its target fisheries and total annual catch.

$$b_i = 1 - C_k / T \qquad \text{(Eq. 3)}$$

where C_k represents an annual catch caught by k fishery (gear) for a TAC target species i, T represents an annual total catch caught by all fisheries (gears) for a TAC target species i. The Bycatch rate (bi) implies the proportion of the TAC target species i which is not caught by k fishery (gear) for the annual total catch. The level of fishing mortality at $F_{0.1}$ is defined formally for a given recruitment age as that level of F where [16].

$$\left.\frac{d(Y/R)}{dF}\right|_{F=F_{0.1}} = \left.\frac{(0.1)d(Y/R)}{dF}\right|_{F=0.0} \qquad \text{(Eq. 4)}^{vi}$$

From Eq. 1 and Eq. 4, $F_{0.1}$ can be estimated. In addition, F_{MAX} can be estimated by the highest level (g) of the extended Beverton-Holt yield per recruit, obtained from changes in instantaneous fishing mortality. Here, F_{MAX} means the rate of fishing mortality that produces the maximum yield per recruit. This is the point beyond which growth overfishing is usually said to begin. This paper will have more to say later on this point.

***An Extended Spawning Stock Biomass Per Recruit Model*:**
A spawning stock biomass per recruit model (SSB/R or SPR) has received much attention as a means to preserve reproductive potential of the population [17]. The SSB/R was introduced by Shepherd [18], Campbell [19], Sissenwine and Shepherd [20], Prager *et al.* [21] and Gabriel *et al.* [22]. In order to estimate $F_{x\%}$ of mackerel and jack mackerel caught by large purse seine, the extended spawning stock biomass per recruit model is used.

$$\left.\frac{SSB}{R}\right|_{F=0} = \sum_{t=t_r}^{t_\lambda} m_t \cdot \exp[-M(t_c - t_r)] \cdot W_\infty \sum_{n=0}^{3} \frac{U_n \exp[-nK(t_c - t_0)]}{(M + nK)} \cdot (1 - \exp[-(M + nK)(t_L - t_c)]) \qquad \text{(Eq. 5)}$$

where *SSB* represents the spawning stock biomass, *R* represents recruit, t_λ represents maximum age, and m_t represents mature proportion by age *t*: mackerel ($m_1=0.02$, $m_2=0.68$, $m_3=0.95$, $m_4=0.96$, $m_5=1{,}00$), jack mackerel ($m_1=0.15$, $m_2=0.40$, $m_3=0.80$, $m_4=0.95$, $m_5 = 1{,}00$) [5]. When $F=F_{0.x}$, SSB/R is as follows.

$$\left.\frac{SSB}{R}\right|_{F=F_{o.x}} = \sum_{t=t_r}^{t_\lambda} m \cdot \exp[-M(t_c - t_r)] \cdot W_\infty \sum_{n=0}^{3} \frac{U_n \exp[-nK(t_c - t_0)]}{(F+M+nK)} \cdot (1 - \exp[-(F+M+nK)(t_L - t_c)]) \qquad \text{(Eq. 6)}$$

% SSB/R or % SPR means the proportion of SSB/R $_{F=F\,0.x}$ divided by SSB/R $_{F=0}$ in absent of fishing effort. To find X%, it can be derived as Eq. 7.

$$\frac{SSB\ /R\big|_{F=Fo.x}}{SSB\ /R\big|_{F=0}} = X\,\% \qquad \text{(Eq. 7)}$$

where $F_{0.\mathrm{x}}$ means instantaneous fishing mortality of each level such as $F_{0.1}$, $F_{0.2}$, or $F_{0.3}$.

***A Biomass-Based Cohort Analysis Model*:**

In order to estimate biomass (B_{ij}) by cohort (age) of *j* species, in year *i*, and instantaneous fishing mortality (F_{ij}) of *j* age-species, in year *i*, the biomass-based cohort analysis is employed as Eq. 8 [23]. However, in this model, the result of each species' biomass (B_{ij}) estimated from Baik, *et al.* [5] is directly used.

$$B_{ij} = B_{i+1\,j+1} e^{(M-G_j)} + C_{ij} e^{(\frac{M-G_j}{2})} \qquad \text{(Eq. 8)}$$

where B_{ij} represents biomass in weight by cohort (age) of *j* age-species , in early of year *i*, C_{ij} represents catch in weight by cohort (age) of *j* age-species in year *i*, *M* represents an instantaneous natural mortality rate, and G_j represents an instantaneous growth rate of *j* age-species. For last year and maximum age, the biomass-based cohort analysis can be estimated from Eq. 9.

$$B_{ij} = C_{ij} \frac{(F_{ij} + M - G_j)}{F_{ij}(1 - e^{-(F_{ij}+M-G_j)})} \qquad \text{(Eq. 9)}$$

Where, F_{ij} represents an instantaneous fishing mortality of *j* age-species, in year *i*. The instantaneous fishing mortality (F_{ij}) of *j* age-species, in year *i* can be estimated from Eq. 10.

$$F_{ij} = \ln(\frac{B_{ij}}{B_{i+1\,j+1}}) - M + G_j \qquad \text{(Eq. 10)}$$

The instantaneous growth rate (G_j) of *j* age-species can be estimated from Eq. 11.

$$G_j = \ln(\frac{W_{j+1}}{W_j}) \qquad \text{(Eq. 11)}$$

where, W_{j+1} represents weight of $j+1$ age-species, and W_j represents weight of *j* age-species.

***Estimation Equation for Annual Allowable Catch (ABC)*:**

To estimate TAC (ABC) for multi-species, ABC estimation equation for Tier 1-3 information available within Korean ABC estimation model [5] is used.

$$ABC = \sum_{i=0}^{t_\lambda} \frac{B_{ij} F_{ABC}}{M + F_{ABC}} (1 - e^{-(M + F_{ABC})}) \qquad \text{(Eq. 12)}$$

where ABC represents annual allowable catch of species and t_λ represents maximum age. Finally, in order to compare the current Korean TAC (ABC) with TAC (ABC) for a single gear, multi-species fisheries, this paper applies F_{ABC} for the two models and calculate the associated TACs (ABCs). In addition, TAC (ABC) of each species for large purse seine is calculated by TAC (ABC) by each species and recent average catch rate of each species caught by the large purse seine.

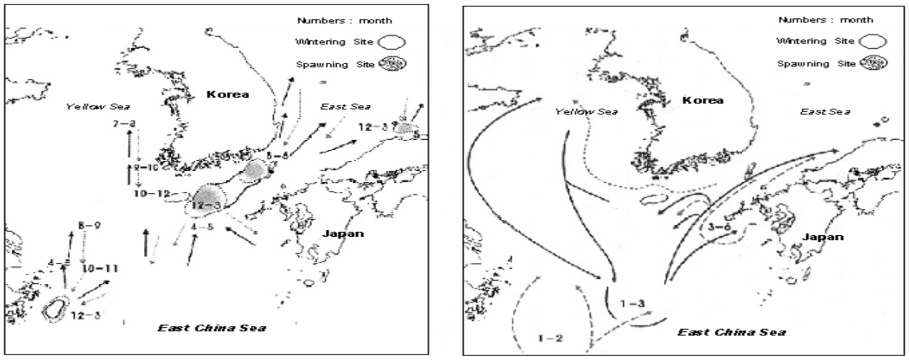
ABC of Each Species Caught by Large Purse Seine
= ABC of Each Species X Recent Average Catch Rate (2000-2003**)**

ANALYSIS AND RESULTS

This section analyzes the optimal TAC level for the study fishery and compares the TAC level for the extended model with that of the current Korean TAC assessment model.

Target Species and Gear

Mackerel caught in Korean territorial waters belongs to two different stocks – East China Sea and Tsushima stocks. The main spawning areas of these stocks are near the East China Sea (Dec.–Mar.), Cheju Island (Dec.–Mar.) and Tsushima Island (May–June). Mackrel mainly inhabits the Yellow, the East China and the East Seas and the southern waters of S. Korea. Jack mackerel inhabits the Yellow and the East China Seas, the southern waters of S. Korea and the western waters of the Kyushu region. The main spawning areas of jack mackerel are near the middle of the East China Sea (Feb.–Mar.), the western of the Kyushu region (Apr.–Mar.), and Cheju Island (June-Aug.). These two species live in almost the same places as shown in Fig. 3. These two species are caught by large purse seines and have high potential for bycatches. Major species (i.e. mackerel, jack mackerel, sardine, squid) caught by large purse seines have been regarded as major species and a main fishing gear within the current Korean TAC system. Therefore, the multi-species, large purse seine fishery can be an appropriate empirical model for our comparisons of alternative TAC models without considering the technical interaction for multi-species.



(a) Mackerel **(b) Jack mackerel**

Source: National Fisheries Research and Development Institute (NFRDI) 2005. http://www.nfrda.re.kr/sea-fish-info/fis/fdata5.html

Figure 3. Migrations of Mackerel and Jack Mackerel

Analysis Data

***Selection of Major Target Species Caught by Large Purse Seine*:**
In order to compare TAC for each species between two models, sardine, hairtail, and squid were excluded in this model, because sardine had low bycatch and catch rates and hairtail and squid did not belong to TAC target species until 2005. Therefore, mackerel and jack mackerel that have high catch rate and bycatch rate are used in this model. These two species occupy, on average, around 80% of total catches of the large purse seine fleet during the past 10 years. In addition, the average bycatch rate of these two species shows mackerel (0.18) and jack mackerel (0.46) respectively (Table. II and III).

***Biological Parameters of Target Species*:**
To compare the current Korean F_{ABC} of each mackerel and jack mackerel and F_{ABC} for these two species, the extended TAC model uses same biological parameters estimated from National Fisheries Research and Development Institute (NFRDI) in 2004 except instantaneous fishing mortality (F_i) of jack mackerel. The reason for this is that $F_{current}$ of jack mackerel last year was much higher than that of jack mackerel in recent past years. Thus $F_{current}$ of jack mackerel is assumed as 0.6. in this model (Table IV). The instantaneous fishing mortality (F_i) can be estimated from the Ricker Formula, $F_{current} = 1 - exp\ (-F_i)$.

Table III: Catches and Percentage Composition of Major Target Species Caught by the Large Purse Seine Fleet: 1994-2003

(Unit: Ton and %)

Year	Gear	Large Purse Seine				
	Species	Mackerel	Jack Mackerel	Sardine	Others	Sum
1994	Catches	197,761	35,036	35,335	42,835	310,967
	%	0.64	0.11	0.11	0.14	1.00
1995	Catches	159,820	7,521	13,078	47,576	227,995
	%	0.70	0.03	0.06	0.21	1.00
1996	Catches	386,877	10,790	15,837	39,833	453,337

	%	0.85	0.02	0.03	0.09	1.00
1997	Catches	139,293	12,867	6,844	25,785	184,789
	%	0.75	0.07	0.04	0.14	1.00
1998	Catches	148,892	15,296	5,661	35,188	205,037
	%	0.73	0.07	0.03	0.17	1.00
1999	Catches	155,728	7,913	16,791	49,495	229,927
	%	0.68	0.03	0.07	0.22	1.00
2000	Catches	109,025	14,288	2,161	54,514	179,988
	%	0.61	0.08	0.01	0.30	1.00
2001	Catches	177,935	10,729	123	43,034	231,821
	%	0.77	0.05	0.00	0.19	1.00
2002	Catches	126,519	18,965	8	36,357	181,849
	%	0.70	0.10	0.00	0.20	1.00
2003	Catches	113,121	13,558	14	31,969	158,662
	%	0.71	0.09	0.00	0.20	1.00
Average	Catches	171,497	14,696	9,585	40,659	236,437
	%	0.725	0.062	0.041	0.172	1.000

Source: Ministry of Maritime Affairs and Fisheries (MOMAF), 2004. http://fs.fips.go.kr/index.jsp

Table IV: Biological Parameters of Selected Major Species

Species	Parameters											
	M	t_0	t_c	t_L	W_i	a_i	m_i	W_∞	L_∞	K	F_i	$F_{current}$
Mackerel	0.52	-0.428	1.01	10	0.542	0.513	0.125	2249.55	51.67	0.299	0.40	0.33
	(%)	(age)	(age)	(age)	(%)	(%)	(%)	(g)	(cm)		(%)	(yr^{-1})
Jack mackerel	0.53	-0.809	0.53	7	1.458	1.181	0.336	1047.17	429.9	0.248	0.92	0.60
	(%)	(age)	(age)	(age)	(%)	(%)	(%)	(g)	(mm)		(%)	(yr^{-1})

Source: Baik *et al.*, 2004. Stock Assessment and Fishery Evaluation Report of Year 2005 TAC – based Fisheries Management in the Adjacent Korean Water, National Fisheries Research and Development Institute (NFRDI). 237pp.

Note: M = an instantaneous natural mortality coefficient
t_0 = hypothetical age when the fish would be zero length
t_c = mean age (years) at first capture
t_L = maximum age (years) of each species
W_i = a relative bycatch index of *i* species (= *bi / AVG bi of two species targeted*)
a_i = a relative instantaneous fishing mortality index ($=F_i/\overline{F_i}$)
b_i = bycatch rate of species i
W_∞ = asymptotic weight parameter
L_∞ = asymptotic length parameter
K = the Brody growth coefficient
F_i = an instantaneous fishing mortality rate of *i* species
$F_{current}$ = the current levels of fishing mortality.

Results

Estimation of F_x and $F_{x\%}$:

We analyze how $F_{x\%}$ changes from the change in F_i of current Korean TACAM and extended TACAM. We estimate appropriate $F_{x\%}$ and $F_{0.x}$ of two models in order to compare the current Korean TACAM and the extended TACAM. This model provides F_{MAX}, F_{ABC} and $F_{0.1}$ as F_x and $F_{50\%}$, $F_{40\%}$, $F_{35\%}$, $F_{30\%}$ and $F_{25\%}$ as $F_{x\%}$ (Table V). $F_{0.1}$ at current mean age at first capture estimated by current TAC assessment model was mackerel (0.17/year) and Jack mackerel (0.18/year) respectively, but $F_{0.1}$ at current mean age at first capture estimated by the extended TAC assessment model was 0.16/year. F_{MAX} estimated by current TAC assessment model was mackerel (0.69/year) and Jack mackerel (0.58/year) respectively, but F_{MAX} estimated by the extended TAC assessment model was 0.86/year. $F_{x\%}$ at lower bound F_{ABC} estimated by current TAC model was mackerel (30%) and jack mackerel (35%), but $F_{x\%}$ at lower bound F_{ABC} estimated by multi-species model was 50%. $F_{x\%}$ at upper bound F_{ABC} estimated by current TAC model was mackerel (25%) and jack mackerel (30%), but $F_{x\%}$ at upper bound F_{ABC} estimated by multi-species model was 40% (Table V).

Table V: Comparison of F_x and $F_{x\%}$ between Two Models (Unit: Year $^{-1}$ and g)

Species	F_{MAX}	$F_{50\%}$	$F_{40\%}$	$F_{35\%}$	$F_{30\%}$	$F_{25\%}$	$F_{0.1}$	F_{ABC}	Y/R(g) at F_{ABC}
Current TACAM for Mackerel	0.69	0.18	0.23	0.26	0.30	0.35	0.17	0.30 - 0.35	84.0 - 88.1
Current TACAM for Jack mackerel	0.58	0.16	0.21	0.24	0.27	0.31	0.18	0.24 - 0.27	30.4 - 31.7
TACAM for Multi-Species	0.86	0.27	0.38	0.45	0.53	0.64	0.16	0.27 - 0.38	77.7 - 88.5

Estimations of Y/R (YPR) and SSB/R (SPR):

We analyze how Y/R and SSB/R change from the change in respective F_x and $F_{x\%}$ within the models. We estimate appropriate F_{ABC} through the relationship between Y/R and F_x and between SSB/R and $F_{x\%}$. We compare Y/R and SBB/R at F_{ABC} of the two models. F_{ABC} estimated by current TAC assessment model was mackerel (0.30/year – 0.35/year) and Jack mackerel (0.24/year – 0.27/year) respectively, but F_{ABC} estimated by the extended TAC assessment model was 0.27/year – 0.38/year. At this point, yield per recruit (Y/R) for individual species by current TAC assessment model was estimated as mackerel (84.0g – 88.1g) and Jack mackerel (30.4g – 31.7g) respectively.

Yield per recruit (Y/R) by multi-species model was estimated as 77.7g – 88.5g. In addition, X% of spawning stock biomass per recruit (SSB/R) for individual species by current TAC assessment model was mackerel (25% – 30%) and jack mackerel (30% – 35%) respectively, but X% of that by multi-species model was 40% – 50% (Table VI).

Table VI: Comparison of Y/R and SSB/R between Two Models (Unit: g and Year $^{-1}$)

Species	Y/R at F_{MAX}	Y/R at $F_{50\%}$	Y/R at $F_{40\%}$	Y/R at $F_{35\%}$	Y/R at $F_{30\%}$	Y/R at $F_{25\%}$	Y/R at $F_{20\%}$	F_{ABC} (Year $^{-1}$)	Y/R at F_{ABC}
Current TACAM for Mackerel	96.10	65.18	75.76	79.73	84.00	88.09	90.90	0.30 - 0.35	84.0 - 88.1
Current TACAM for Jack Mackerel	35.91	24.32	28.17	30.41	31.71	33.07	34.27	0.24 - 0.27	30.4 - 31.7
TACAM for Multi-species	99.76	77.71	88.53	92.76	95.95	98.43	99.69	0.27 - 0.38	77.7 - 88.5

Table VII: Symbol Descriptions of Each Model

Symbol	Descriptions	Unit
Mac YPR C-T	Mackerel's Yield Per Recruit: Current Korean TACAM	g
Jac YPR C-T	Jack Mackerel's Yield Per Recruit: Current Korean TACAM	g
Mac %SPR C-T	Mackerel's % Spawning Stock Biomass-Per-Recruit: Current Korean TACAM	%
Jac %SPR C-T	Jack Mackerel's % Spawning Stock Biomass-Per-Recruit: Current Korean TACAM	%
Multi YPR E-T	Mackerel and Jack Mackerel's Yield Per Recruit: Extended TACAM	g
Multi %SPR E-T	Mackerel and Jack Mackerel's % Spawning Stock Biomass-Per-Recruit: Extended TACAM	%

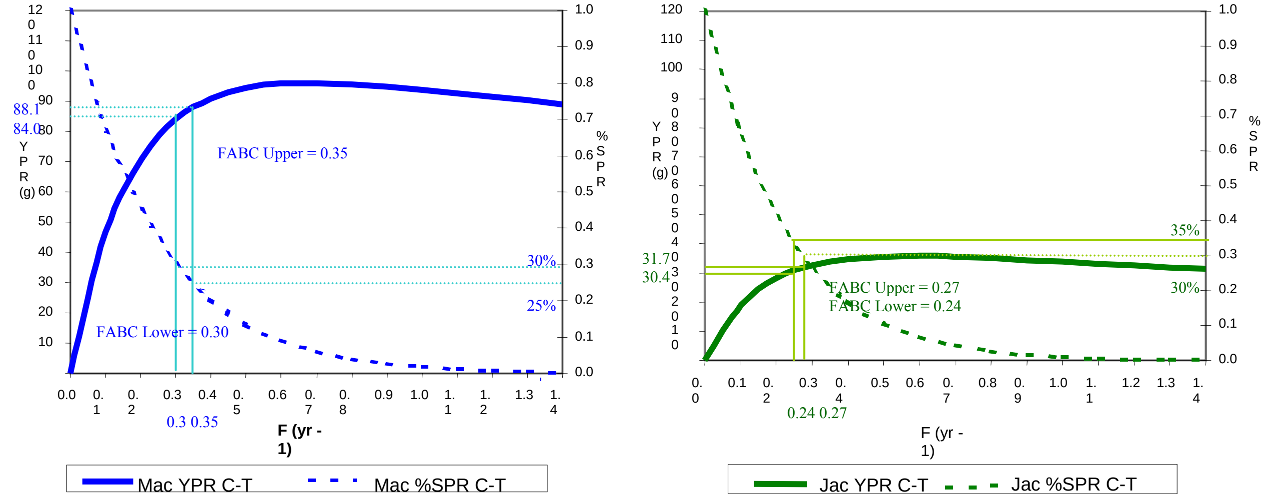


Figure 4. Current Korean TACAM for Mackerel and Jack Mackerel

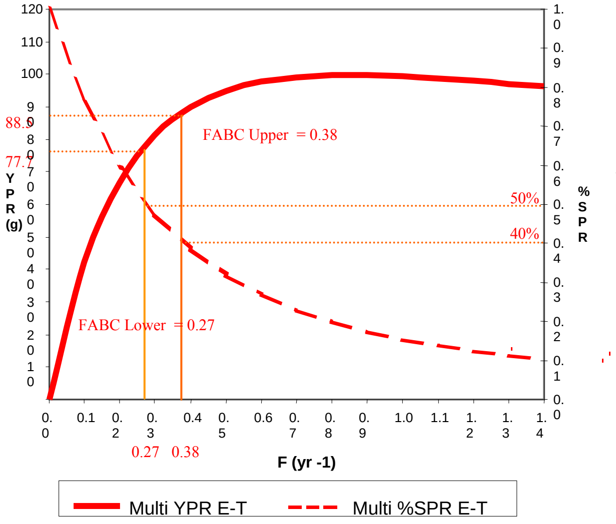


Figure 5. Extended TACAM for Mackerel and Jack Mackerel

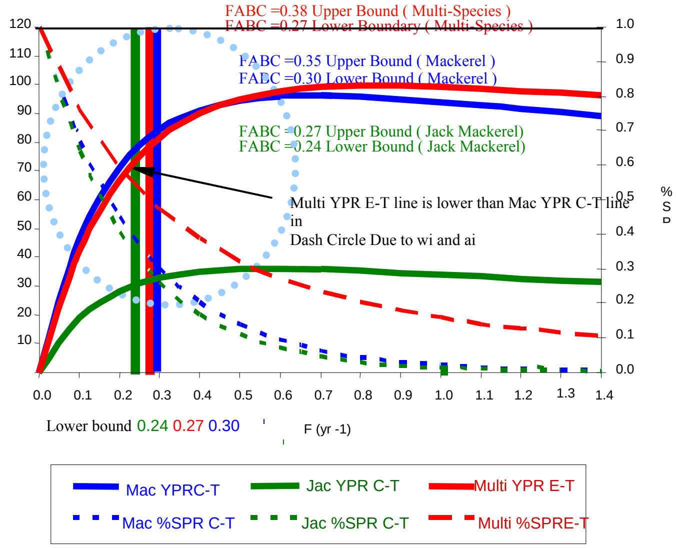


Figure 6. Comparison of YPR and %SPR between Two Models

Before explaining in detail for these results, we need to mention about an upper bound of F_{ABC} for multi-species estimated by the extended TAC assessment model. The upper bound of F_{ABC} for multi-species is meaningless, because the relative bycatch index (w_i) and the relative instantaneous fishing mortality index (a_i) of mackerel with comparatively abundant stock and lower bycatch rate cause a positive effect to the extended Beverton-Holt single gear, multi-species yield per recruit model. In other words, yield per recruit of mackerel obtained from w_i and a_i of mackerel is much greater than that of jack mackerel obtained from w_i and a_i of jack mackerel. As a result, the upper bound of F_{ABC} for multi-species can be overestimated. Therefore, in the extended TAC assessment model designed to protect small bycatch species like jack mackerel, the upper bound of F_{ABC} for multi-species does not have significant meaning. For this reason, we focus only on the` lower bound of F_{ABC} for multi-species.

In the case of mackerel, the lower bound F_{ABC} level (0.27: red bar) of TAC for multi-species was lower than lower bound F_{ABC} level (0.30: blue bar) of Mackerel estimated by the current Korean TAC assessment model. This is because w_i and a_i imposed, decrease the yield per recruit in the extended Beverton-Holt model. As shown in Fig. 6, red Multi YPR E-T curve for multi-species is lower than blue Mac YPR C-T curve for each mackerel within a dash-circle, meaning a valid annual fishing rate range.

To protect jack mackerel's stock, the large purse seine should less catch mackerel. If F_{ABC} is set up at 0.3 level, due to bycatch, jack mackerel's stock can fall. Especially, based on the lower bound F_{ABC} level (0.24: green bar) and the lower level (30,41g) of current yield per recruit (Y/R) of jack mackerel, we can know that the jack mackerel stock is not enough. Hence if F_{ABC} of mackerel is reduced as the lower bound level (0.27) in the multi-species model, the associated bycatch reduction would be expected to improve the jack mackerel stock.

In addition, we suggest that jack mackerel be caught at the lower bound F_{ABC} level (0.24). The reason for this is that the extended TAC model just is an auxiliary and precautionary means of the current Korean TAC assessment model for protecting bycatch species with small stock. Thus the lower bound (0.24) of jack mackerel estimated by the current model should be maintained as a conservation measure. As shown in above, to prevent the depletion of small stock species, F_{ABC} (0.3 level) of the mackerel targeted by the large purse seine can be overestimated. Therefore, in an aspect of small stock's conservation, lower bound F_{ABC} level (0.27) of TAC for multi-species also should be considered when the TAC of each species is set up.

***ABC Estimation*:**
The recent average catch rate of mackerel and jack mackerel caught by the large purse seine is 87% and 72% respectively. ABC of each species caught by the large purse seine was estimated by multiplying recent (2000-2003) average catch rate to the single species ABC (Table VIII).

Table VIII: Comparison of ABC between Two Models

Species	Mackerel by current Korean TACAM		Jack Mackerel by current Korean TACAM		Mackerel of TACAM for Multi-Species	
	Total Catch (100%)	Large Purse Seine (87%)	Total Catch (100%)	Large Purse Seine (72%)	Total Catch (100%)	Large Purse Seine (87%)
$F_{critical}$	F25%, F30%		F30%, F35%		F40%, F50%	
ABC (Ton)	147,348 - 191,706	128,192 - 166,784	7,712 - 9,884	5,552 - 7,116	134,350 - 205,488	116,884 - 178,774
F_{ABC}(Year^{-1})	0.30 - 0.35		0.24 - 0.27		0.27 - 0.38	

ABC levels of mackerel and jack mackerel that can be caught by large purse seine in 2005 estimated by the current Korean TAC assessment model were 128,192 – 166,784 and 5,552 – 7,116 respectively. ABC level of mackerel that can be caught by large purse seine in 2005 estimated by the extended TAC assessment model was 116,884 – 178,774. Appropriate ABC of mackerel that can be caught by large purse seine based on lower bound F_{ABC} (0. 27) of multi-species is less than that of mackerel estimated by current Korean TAC assessment model. This result fundamentally corresponds to the theoretical approaches mentioned to section 2.

CONCLUSION

This paper provided a type of TAC assessment model for multi-species and a single fishing gear. In order to overcome several limitations with the current Korean TAC assessment model, the study suggested theoretical approaches with related to technical interactions among multi-species. The extended TAC assessment model for multi-species and a single fishing gear used the extended Beverton-Holt yield-per-recruit model, in based on biological parameters of NFRDI (2004) in order to examine whether or not the current TAC level of mackerel and jack mackerel within TAC target species is appropriate. As a result, this paper estimates that the current TAC level of mackerel has been somewhat overestimated and suggests that the mackerel TAC level needs to be lowered to prevent overfishing of the small stock of jack mackerel due to the bycatch rate.

The extended TAC assessment model for multi-species and a single fishing gear compensates or backs up ABC estimation by species of a single fishing gear by computing ABC for multi-species. For example, average fishing mortality among multi-species due to bycatch can partially reduce a bias of fishing mortality that a single species and single fishing gear assessment does not detect. Thus, the extended TAC assessment model can be adopted as an auxiliary and precautionary means, for overcoming limitations of the current TAC assessment model and for rational operation of the Korean TAC system. Conversely, this implies that the extended TAC assessment model has a limit of estimating each ABC by each species, because it does not provide an appropriate fishing mortality rate (F_{ABC}) for individual species. It just offers a certain fishing mortality combined by multi-fishing gears, considering bycatch inflicted by fishing gears. Henceforth, when the Korean government adds multi-species with high commercial value to its TAC system, the Korean government needs to allocate optimal amounts of target species by fishing gear (or vessel) considering technical interactions such as bycatch rate as well as biological interactions like the predator-prey relationship.

In conclusion, the results obtained for this case study accord with a prior expectation in the sense that target TACs are lower when bycatch is taken into account. It also suggests the feasibility of the approach. Conversely, in view of the modest difference in TACs from the existing versus generalized model, it could be argued that these differences are well within the precision of model capabilities and that the gains from the added complexity are not worth the cost. While this rationale is comforting, should be tested under a range of input scenarios to determine how robust the robustness of results.

The use of F_{ABC} based on round weight of fish harvested may be questioned as a policy target for several reasons. First, F_{ABC} does not adequately consider the costs of harvest. As F goes to F_{MSY}, the marginal cost of additional harvests explodes toward infinity. The harvests of the marginal entrant are subsidized by reduced yields of existing fishermen. Secondly, along the sustainable Beverton-Holt yield curve, percentage change in total yields is equal to percentage change in numbers of fish caught times percentage change in mean weight per fish harvested ($\%\Delta H = \%\Delta N \times \%\Delta M$). At maximum yield per recruit, $\%\Delta N$ and $\%\Delta M$ are equal in absolute magnitude but of opposite sign. However, in the study fishery, price per g increases with fish size so that maximum revenue per recruit occurs at an F lower that F_{MAX} of yield per recruit [24]. It is arguable that maximum revenue per recruit is the point at which overfishing begins, rather than F_{MAX} of yield per recruit. More investigations of this economic discussion are needed. Thirdly, the importance of revenue considerations for profitability as producers' surplus, is obvious. However, the fish size-price premia imply significant gains in consumers' surplus form F value lower than the usual F_{ABC}.

Finally, we hope that the extended TAC assessment model will be corresponded to suggestions of Conroy [25] and Box [26] cited below. "*All model results, regardless of how well the model has been constructed, should be viewed as indicative rather than as fact*" [25]. "*All models are wrong, but some are useful!. Models are best used to compare alternative policies. Certainty is not given to us; Even a virgin fishery can collapse due to exogenous events, so how much precaution is enough?*" [26].

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ENDNOTES

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[i] Among multi-species (e.g., hairtail, flounder, puffers, redlip croaker, conger eel) with high commercial value, squid (Todarodes pacificus) is officially added to the list of TAC species in 2006.

[ii] The current Korean TAC assessment model, which does not consider technical interactions such as the bycatch component, uses the single species Beverton-Holt yield per recruit model for most TAC species [1].

[iii] Interactions – a) Biological interaction is the interaction between fish stocks, and within fish stocks, caused by predation and food competition, b) Economic interaction is the competition between fleets, e.g. between an industrial fishery and an artisanal fishery. The more one fleet catches of the limited resource the less will be left for its competitors. c) Technical interaction means that the fishery on one stock creates fishing mortality on other stocks because the fishery is either a multi-species fishery or because of inevitable by-catches [28].

[iv] Here, as a case study, this paper just provides a type of multi-species and a single gear with a technical interaction considering a bycatch component, but hereafter, this case study needs to provide several types like a single species and multi-gears, and multi-species and multi-gears considering three interactions.

[v] Beverton and Holt [1] developed, as yield-per recruit model, a theory of fishing of Baranov [29] using the von Bertalanffy curve [30] which described growth in fish length. The single species Beverton and Holt yield per recruit model can be described as

$$Y / R = F \exp(-M(t_c - t_r)) \cdot W_\infty \sum_{n=0}^{3} \frac{U_n \exp[-nK(t_c - t_0)]}{F + M + nK} \cdot (1 - \exp[-(F + M + nK)(t_L - t_c)])$$

where *Y/R* represents yield per recruit in weight (g), *F* represents instantaneous fishing mortality coefficient, *M* represents instantaneous natural mortality coefficient, U_n represents summation parameters (U_0=1, U_1=-3, U_2=3, and U_3=-1), t_c represents mean age (years) at first capture, t_r represents mean age (years) at recruitment to the fishing area, W_∞ represents asymptotic weight, t_0 represents hypothetical age the fish would be zero length, *K* represents the Brody growth coefficient, and t_L represents the maximum age (years).

[vi] This equation is used in a 1st order Taylor Series approximation to project yield. This approximation is only valid for "small" F value. For "large" F values, higher order terms would be needed. For the case study F is relatively low. $F_{0.1}$ means that the slope of the yield per recruit curve for the $F_{0.1}$ rate is only one-tenth the slope of the curve at its origin.