Implementation of the Maximum Sustainable Yield under an Age-Structured Model

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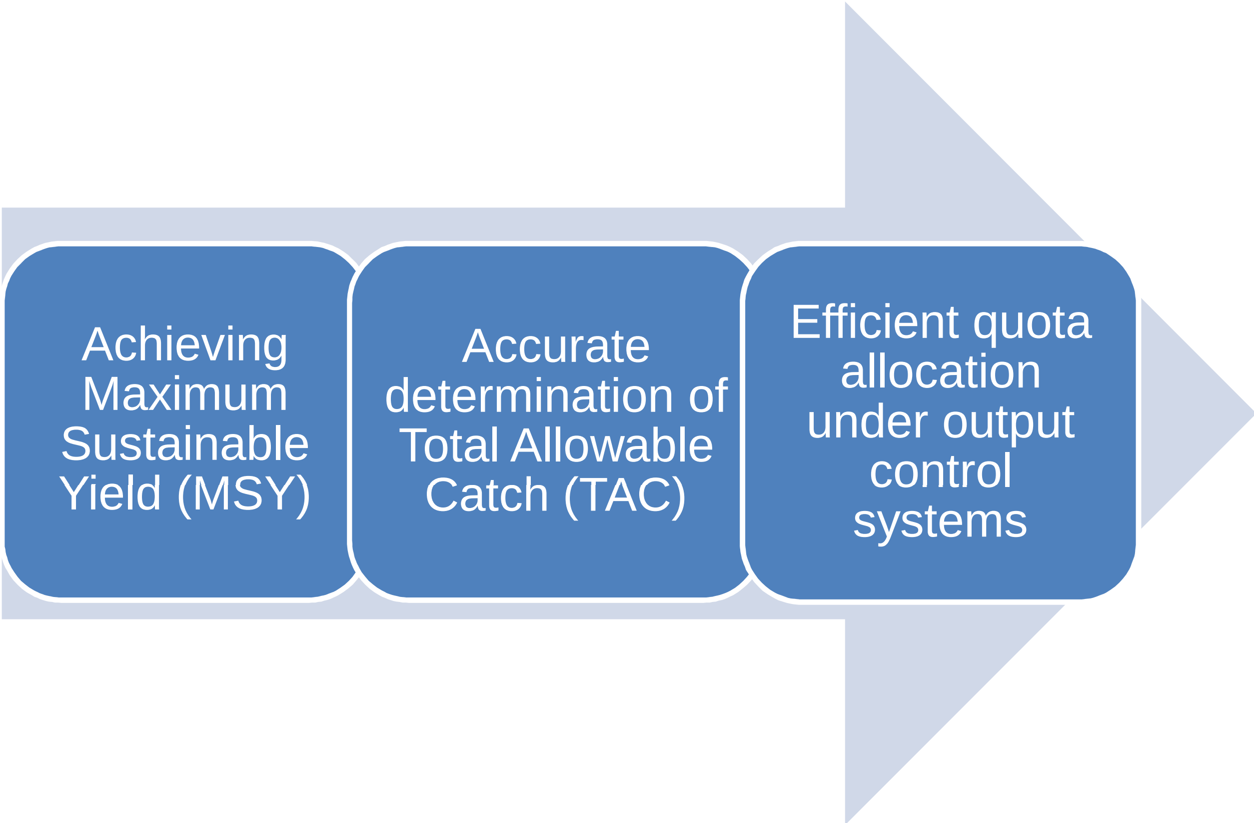
Overview



MECHANISM DESIGN for allocation of fishing rights

- We analyze the implementation of MSY approach under individual quota system.

- The main purpose of the study is to describe an effective design for quota allocation mechanism that guarantees sustainability of fish stocks and increases market efficiency.

Age-Structured Model

- The age-structured fish population model
  - Biological conditions are taken into consideration
  - More complex than simple biomass model
  - More realistic way of estimation

- In recent years, Clark (2010), Tahvonen (2009, 2010), Quaas et al. (2010) and Skonhoft et al. (2012) → Contributed to the literature of age-structured modeling for fisheries.

- Armstrong and Sumaila (2001), Björndal and Brasao (2006), Stage (2006), and Diekert et al. (2010) → Applications of age-structured model to different case studies.

- Age-structured fish population model developed by Skonhoft et al. (2012) is employed and fishing mortality rates at MSY are calculated using a simple Lagrangian method proposed by Skonhoft et al. (2012).

Main Results

- We designed a quota allocation mechanism that results in MSY level of fishing.

- We show that not only the fishing technology but also the estimated level of MSY is steering the optimal allocation of quotas.

- We also show that the optimal allocation of quotas does not have a bang-bang nature under imperfect fishing selectivity.

The Population Model

- Three cohorts of the fish population

  Juveniles, (age < 1)
  Young matures, (1 ≤ age < 2)
  Old matures, (2 ≤ age)

$$\square_0 < \square_1 < \square_2$$

$$\square_0 = 0, \quad \square_1 < \square_2$$

- Fixed fishing mortalities at the population equilibrium (steady-state outcomes) are taken into consideration.

$$(\square_{\square,\square+1} = \square_{\square,\square} = \square_{\square})$$

- The total biomass of the old mature fish is less than the total biomass of the young mature fish.

$$(\square_2 \, \square_2 < \square_1 \, \square_1)$$

Implementation of the Maximum Sustainable Yield

- The harvest function is,

$$\square = \square_1 \square_1 \square_1 + \square_2 \square_2 \square_2$$

The constraints for the maximization problem are,

$$\square_1 = \square_0 \, \square(\square_1, \square_2) \quad \text{(Recruitment constraint)}$$

$$\square_2 = \square_1 (1 - \square_1) \square_1 + \square_2 (1 - \square_2) \square_2 \quad \text{(Spawning constraint)}$$

- The Lagrange function and first order necessary conditions are as below:

$$\square = \square_1 \square_1 \square_1 + \square_2 \square_2 \square_2 - \square[\square_1 - \square_0 \, \square(\square_1, \square_2)] - \square[\square_2 - \square_1 (1 - \square_1) \square_1 + \square_2 (1 - \square_2) \square_2]$$

Table 3 Fishing mortality rates at MSY

	$\square_{\square}/\square_{\square_1}$	$\square_{\square}/\square_{\square_2}$	$\square_1$	$\square_2$
1) $\square = \square_1/\square_1 < \square_2/\square_2$	$= 0$	> 0	$0 < \square_1 < 1$	$= 1$
2) $\square_1/\square_1 < \square < \square_2/\square_2$	< 0	> 0	$= 0$	$= 1$
3) $\square_1/\square_1 < \square = \square_2/\square_2$	< 0	$= 0$	$= 0$	$0 < \square_2 < 1$

Catch Compositions & Fishing Technology

- Fishing technologies of fisherman 1 and fisherman 2 are denoted as $\square_1$ and $\square_2$, respectively.

- Under given catchability coefficients, we can simply write fishing technology of fisherman i as $\square_{\square} = \square^{2}_{\square}/(\square^{1}_{\square} + \square^{2}_{\square})$.

- We assume that until one of the fishermen's quota is exhausted, fishermen harvest the same total weight of fish at a given time duration.

Catch Compositions & Fishing Technology

- Our analysis focuses on the situation in which both fishermen target the old mature class.

  Coastal fleet 1 ⟶ lower level of fishing technology

  Coastal fleet 2 ⟶ higher level of fishing technology

Table 2 Cases on catch composition of fishermen

	Fishing technology level of fisherman 1	Fishing technology level of fisherman 2
Case 1	$\square_1 = 1$ (No bycatch)	$\square_2 = 1$ (No bycatch)
Case 2	$\square_1 = 1$ (No bycatch)	$0.5 < \square_2 < 1$ (Bycatch)
Case 3	$0.5 < \square_1 < 1$ (Bycatch)	$0.5 < \square_2 < 1$ (Bycatch)

Catch Compositions & Fishing Technology

- **Non-satiated behavior of fishermen :** Fishermen fulfill their remaining quotas through capturing untargeted (but revenue generating) fish after the targeted fish population is fully harvested.

  As a result, the fix ratio of the catch of targeted fish to untargeted fish derived by the catchability coefficients may no longer be valid.

- To illustrate:
  - Fisherman 1 has imperfect fishing selectivity and $\square_1 = 1, \square_2 = 0$ $\square\square\square \leq \square_2\,\square_2 + [(1-\square_1)/\square_1]\,\square_2\,\square_2$. In this case, fisherman 1 captures $\square$ tons of targeted fish where $\square = \square_1\square\square\square \leq \square_2\,\square_2$, and $[(1-\square_1)/\square_1]\,\square = (1-\square_1)\,\square\square\square$ tons of untargeted fish. The ratio derived from the catchability coefficients is provided in this case.

  - If TAC is determined above $\square_2\,\square_2 + [(1-\square_1)/\square_1]\,\square_2\,\square_2$, which is the cut-off level, then catch of the young mature fish of fisherman 1 will exceed its expected level derived by the catchability coefficients (under non-satiated behavior). The weight of catch of targeted fish by fisherman 1 will be equal to $\square_2\,\square_2$ and the rest of his catches will consist of $\square\square\square - \square_2\,\square_2$ weight of the young mature fish.

Quota Allocation Mechanism

Table 4 Quota allocation mechanism for Case 2

	The discounted biomass conditions	Fishing mortality rates at MSY	Optimal allocation of quotas at MSY
	i. $\square = \square_2 \square_2 \square_2 < \square_2 \square_2$		
	$\square_1/\square_1 < \square = \square_2/\square_2$	$\square_1 = 0$, $0 < \square_2 < 1$	$\square_1 = 1, \square_2 = 0$
	ii. $\square_2 \square_2 \leq \square = \square_1 \square_1 \square_1 + \square_2 \square_2 < \square_2 \square_2 + [(1 - \square_2)/\square_2] \square_2 \square_2$		
Case 2	$\square_1/\square_1 < \square < \square_2/\square_2$	$\square_1 = 0$, $\square_2 = 1$	$\square_1 = 1$, $\square_2 = 0$
$\square_1 = 1$, $0.5 < \square_2 < 1$	$\square = \square_1/\square_1$ $\square < \square_2/\square_2$	$\square^* \leq \square_1 < 1$ $\square_2 = 1$	$\frac{[\square_2 \square_2 - \square_2 \square]}{(1-\square_2)\square} \leq \square_1 \leq \frac{\square_2 \square_2}{(1+\square_2)\square}$ $\square_2 = 1 - \square_1$
		$0 < \square_1 < \square^* < 1$, $\square_2 = 1$	$\square_1 = \frac{[\square_2 \square_2 - \square_2 \square]}{(1-\square_2)\square}$, $\square_2 = 1 - \square_1$
	iii. $\square_2 \square_2 + [(1 - \square_2) / \square_2] \square_2 \square_2 \leq \square = \square_1 \square_1 \square_1 + \square_2 \square_2$		
	$\square = \square_1/\square_1 < \square_2/\square_2$	$0 < \square_1 < 1$, $\square_2 = 1$	$0 \leq \square_1 \leq \square_2 \square_2 / (1 + \square_2) \square$ $\square_2 = 1 - \square_1$

Numerical Illustration

Table 7 Parameters of a random fishery with a single fish stock

Parameter	Description	Given Values
[illegible]	Weight for the young mature fish	3.0 (kg/per fish)
[illegible]	Weight for the old mature fish	5.0 (kg/per fish)
[illegible]	Fishing mortality for the young mature fish (at MSY)	0.1
[illegible]	Fishing mortality for the old mature fish (at MSY)	1
[illegible]	Total population of the young mature fish	100,000
[illegible]	Total population of the old mature fish	45,000
[illegible]	Catchability coefficient (fisherman 1)	0.04 (1/effort)
[illegible]	Bycatch coefficient (fisherman 1)	0 (1/effort)
[illegible]	Catchability coefficient (fisherman 2)	0.032 (1/effort)
[illegible]	Bycatch coefficient (fisherman 2)	0.008 (1/effort)

Numerical Illustration

- TAC is set a level such that

$$\square = \square = \square_1 \square_1 \square_1 + \square_2 \square_2 \square_2 = 255 \text{ tonnes.}$$

- Fishing technologies are calculated as follows:

$$\square_1 = \square_1^2/\square_1^2 + \square_1^1 = 0.04/(0.04 + 0) = 1,$$

$$\square_2 = \square_2^2/\square_2^2 + \square_2^1 = 0.032/(0.032 + 0.008) = 0.8.$$

- Given the fact that the only fisherman who has imperfect fishing selectivity is fisherman 2, there is only one cut-off level for the TAC that can be written as:

$$\square_2 \square_2 + [(1 - \square_2)/\square_2] \square_2 \square_2 = 281.25 \text{ tonnes.}$$

Numerical Illustration

- MSY is higher than the total weight of the young mature fish ($w_2\ X_2$) and less than the cut-off level of $w_2\ X_2 + [(1 - j_2)/j_2]\ w_2\ X_2$.

- The optimal solution for this case was found as the following: (Case 2.2.b)

$$\frac{[\square_2\ \square_2 - \square_2\ \square\square\square\square]}{(1 - \square_2)\square\square\square\square} \leq \square_1 \leq \frac{\square_2\ \square_2}{(1 + \square_2)\square\square\square\square}$$

$$\square_2 = 1 - \square_1.$$

- The optimal quota shares computed by the equations above are, $\frac{21}{51} (\cong 0.4118) \leq \square_1 \leq \frac{225}{459} (\cong 0.4902)$ and $\frac{30}{51} (\cong 0.5098) \leq \square_2 \leq \frac{234}{459} (\cong 0.5882)$.

Numerical Illustration (Results)

- As a result, provided that $j_2 < 1$, a higher level of fishing technology of fisherman 2 will result in a higher quota level for fisherman 2. Furthermore, suppose that $?_1$ is found at a higher rate resulting in a TAC level in between the same cut-offs. In such a case, optimal quota share for fisherman 2 will be higher.

- What if quotas were distributed equally? $(?_1 = ?_2 = 0.5)$
  - Quota for fisherman 1 would not be used in full efficiency. A part of the quotas would be wasted.
  - Since TAC=MSY and all old mature fish would be catched, catch of young mature fish would be less than the desired level if there is waste of quota.

Numerical Illustration (Results)

The catch compositions of initial 125 tonnes of fishing for both fishermen:

Fishing levels	Old mature fish	Young mature fish
Fisherman 1 $(\square_1 = 1)$	125 tonnes	
Fisherman 2 $(\square_2 = 0.8)$	100 tonnes	25 tonnes

Remaining catches after all old mature fish are captured:

Fishing levels	Old mature fish	Young mature fish
Fisherman 1	-	-
Fisherman 2	-	2.5 tonnes

Numerical Illustration (Results)

$h_2^1\ ?_2\ ?_2 = 125$ tonnes $< ?_1\ ?_1\ ? = 127.5$ tonnes

$?_1^1\ ?_1\ ?_1 = 0\ (?_1 = 1)$,

$h_2^2\ ?_2\ ?_2 = 100$ tonnes $< ?_2\ ?_2\ ? = 102$ tonnes $(127{,}500 * 0.8)$

$?_1^2\ ?_1\ ?_1 = 27.5$ tonnes $> (1 - ?_2)\ ?_2\ ? = 25.5$ tonnes.

$?_2\ ?_2\ ?_2 = 225$ tonnes, $?_2 = 1$

$?_1\ ?_1\ ?_1 = 27.5$ tonnes < 30 tonnes. It is less than the MSY level of fishing.

- If quotas were distributed equally, MSY level of fishing would not be achieved.

Conclusion

- In the reform process of the CFP, the EU is seeking for an economically and socially viable, well-designed management system for EU fisheries.

- The EU promotes measures for achieving and sustaining MSY.

- In this study, we designed a quota allocation mechanism and we reached various results about the implementation of MSY under individual quota systems.

Conclusion

- Allocation of quotas (which depends on fishing technology and TAC level) does matter to achieve MSY conditions.

- The analysis shows that the optimal solution for allocation of quotas is highly dependent on MSY (=TAC) level.
  - At particular TAC levels, optimal quota levels will be also different.

- <u>Policy Implication 1)</u>
  - Fishing technologies and TAC levels should be analyzed together while distributing fishing quotas or assigning property rights to fishing agents.

Conclusion

- The initial allocation is usually determined by grandfathering. It is also possible to use auctions to determine the initial allocation of national quotas.

- We show that allocating the quotas according to grandfathering rule or auctioning may not provide economically and biologically viable solutions to achieve MSY harvesting condition.

- Policy Implication 2)

  - Technological structure of fishing industry and the structure of fish population should be considered in the process of distributing national quotas.


Thank you