EYD

Ekonomik Yaklaşım Derneği / Association

***Ekonomik Yaklaşım* 2018, 29(108): 1-21**

www.ekonomikyaklasim.org
doi: 10.5455/ey.16696

MEY Harvesting Strategies in an Overlapping Generations Fishery Population Model[1]

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04 Temmuz 2017'de alındı; 04 Mayıs 2018'de kabul edildi.
26 Ekim 2018'den beri erişime açıktır.

Received 04 July 2017; accepted 04 May 2018.
Available online since 26 October 2018.

Araştırma Makalesi/Original Article

Abstract

In order to maintain fisheries sustainable in both biological and economic terms, the institutions that are responsible for the regulation and supervision of fisheries need to set target levels of harvesting. Thus, characterizing the optimal levels of exploitation carries a particular significance in the design of fishery management systems from a policy-making point of view. This paper investigates maximum economic yield (MEY) harvesting strategies for different bio-economic environments to develop a management system that can be implementable in real world fisheries. Fish population dynamics are modeled as a specific type of age-structured

[1] This research was supported by the Turkish Scientific and Technical Research Council (TÜBİTAK) Grant No. 3501-114K957. All errors are ours.

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models, i.e., overlapping generations (OLG) model. Using this framework, we represent the observed transition path of the whole population and different age classes to a steady state. We also contribute to the modeling studies in the literature, which provide important tools for policy-makers, by revealing how the indicators in the sector (i.e. profits, effort of fleets, optimal harvest rates etc.) respond to the changes in modeling approach and underlying assumptions.

Keywords: Bio-economics, Maximum Economic Yield, Fisheries Management, Overlapping Generations.
JEL Codes: *D04, D47, D78, Q22.*

Özet

Ardışık Nesiller Balık Popülasyon Modelinde MEM Avlanma Stratejileri

Biyolojik olarak sürdürülebilir ve ekonomik olarak karlı bir balıkçılık sektörü hedefi için bu sektörün regülasyon ve denetimden sorumlu kurumların etkin avlanma oranlarını belirlemesi gerekmektedir. En iyi avlanma stratejileri politikasının geliştirilmesi bu sektörün sürdürülebilirlik yönetimi için önemlidir. Bu çalışmada birçok farklı biyoekonomik kurulum altında Maksimum Ekonomik Mahsül (MEM) avlanma stratejileri detaylı bir şekilde çözülerek gerçek yaşam balıkçılık sektörü için yönetim sistemleri geliştirilmiştir. Biyoekonomik modelin biyolojik kısmında balık popülasyonu bir yaşa bağlı balık popülasyon modeli olan ardışık nesiller modeli kullanılarak modellenmiştir. Bu teorik çerçeve kullanılarak balık popülasyon dinamikleri ve her bir neslin ya da tüm biyokütlenin durağan duruma geçişleri detaylı bir şekilde incelenmiştir. Literatürdeki teorik modelleme çalışmalarına bir katkı olarak da avlanma stratejileri ve ekonomik göstergelerin farklı modelleme yaklaşımlarına ve varsayımlarına göre değişimleri gösterilmiştir.

Anahtar Kelimeler: Biyoekonomi, Maksimum Ekonomik Mahsül, balıkçılık yönetimi, ardışık nesiller modeli.
JEL Kodları: D04, D47, D78, Q22.

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MEY Harvesting Strategies in an Overlapping Generations Fishery Population Model
https://doi.org/10.5455/ey.16696

1. Introduction

The institutions that are responsible for the regulation and supervision of fisheries need to set some target levels of harvesting in order to truly guarantee sustainable fisheries in both biological and economic terms. Some of these institutions (or management systems) try to implement maximum sustainable yield (MSY) harvesting conditions, while others try to implement MEY harvesting conditions as their primary management objectives for fisheries. MSY harvesting conditions are found by solving a constrained optimization problem, where the priority is in maximizing the total harvest of fishing fleets, subject to the biological constraints related to a given fish stock. On the other hand, MEY harvesting conditions are found by prioritizing maximum total profit of fishing fleets, subject to the biological constraints related to a given fish stock.

Countries usually take biological, economic and political objectives into consideration when managing their fisheries (Hilborn, 2007). There is still an ongoing debate over which target level is more appropriate for a management system. For example, the *European Common Fisheries Policy* aims to implement MSY for all economically valuable fish stocks, while MEY is the primary management target for Australian Commonwealth fisheries defined by the *Australian Fisheries Management Act* (Dichmont et al., 2010). That is why both concepts are important, and characterizing MSY and MEY levels of exploitation in different bio-economic models carries a particular significance in the design of fishery management systems.

This paper aims to construct a dynamic bio-economic model and find MEY optimal harvesting strategies by incorporating both biological and economic aspects of the issue. We concentrate on MEY harvesting strategies since the characterization of MSY harvesting strategies has been well studied in the literature. Optimal harvesting strategies are derived in the literature with different biological and economic assumptions for age-structured fisheries (Tahvonen, 2009; Tahvonen et al., 2013; Skonhoft et al., 2012; Quaas et al., 2013; Skonhoft and Gong, 2014, 2016; Holden and Conrad, 2015; Kanık and Küçükşenel, 2016; Kanık and Küçükşenel, 2017). Past studies characterized optimal harvesting conditions and determined the effects of different types of gear selectivity, timing of harvest or environmental stochasticity on an optimal harvest. Moreover, MEY was developed as an equilibrium concept and fisheries are not in equilibrium in reality (Dichmont et al., 2010). This paper differs in that the calculation of harvest rates and the total biomass in the ecosystem is performed with numerical solution of a system of nonlinear equations in a more realistic bio-economic model with endogenous fish market prices. We also analyze the convergence process of fisheries to MEY. Our analyses make several contributions to bio-economic modeling and fisheries management literature in terms of modeling, simulation and solution techniques which can be utilized in policy making processes. First and foremost, we model fish population using a 4-period *Overlapping Generations (OLG) Model* which is a more complex age-structured model and also more suitable for modeling real-life fishery population dynamics. We also provide a complete characterization and solution of the MEY harvesting problem in both static and dynamic environments. Lastly, we relax the exogenous price assumption, and repeat the characterization and solutions in the presence of endogenous prices.The rest of the paper is organized as follows. Section 2 describes the bio-economic model. In Section 3, the optimization problem to find MEY harvesting strategies for both static and dynamic environments is formulated. We first assume that fish prices are constant. Then, we relax this assumption by assuming variable prices. We close the paper with a discussion and some concluding remarks in Section 4.

2. OLG Population Model

Pursuit of an optimal harvesting strategy for a sustainable fishery sector necessitates an analysis of fish population dynamics. This paper uses an OLG model to represent the age structure of the fish population. Although previous studies provided a decent insight of population dynamics and target harvest rates, there are some improvable points in general formulation of age-structured models commonly used in the literature (Reed, 1980; Botsford, 1981; Gurtin and Murphy, 1981; Getz and Haight, 1989). The most important one is related to population dynamics of the oldest fish cohort. In the age-structured models, the oldest cohort is subject to natural mortality and fishing mortality. There exist some survivors in the old cohort since mortality rates are not usually equal to one. This implies that some fish in the oldest cohort can live forever if they are lucky enough in each season. The second reason for employing OLG is the *"timing"* of the recruitment process. In the age structured models, young mature and old mature contribute to the recruitment process, and juveniles join the population at the same period. Namely, classical age-structured models does not allow for spawning period. However, in our OLG setup, we allow for a one-period long spawning process.

Under our setting, fish[5] in the ecosystem has *4* different age-classes; in each period *t*, there are fish of ages *0*, *1*, *2* and *3*. Age *0* fish are the juveniles that are the ones who have not reached adult forms yet and assumed to have no economic value due to their size and weight. Juveniles do not contribute to recruitment as well since they are not matured yet. Age *1* and *2* fish are the young matures and old matures respectively and they are the spawning stock. Age *3* are living the last period of their life-cycle just before the natural death. Figure 1 is a timeline that summarizes the life-span of a cohort of fish population in our setting.

Each year, new fish join the population through Beverton-Holt recruitment function by the previous periods' young and old matures, given in Equation 1.

$$X_{0,t+1} = Rec(t+1) = \frac{a(X_{1,t}+\beta X_{2,t})}{b+X_{1,t}+\beta X_{2,t}} \quad (1)$$

In the recruitment function, a stands as a scaling parameter that corresponds to the maximum number of recruits per spawning fish, β stands as a fertility parameter to differentiate the fertilities of the young and old matures and b is the shape parameter.

Juveniles, who can survive in their environment for a period, take the adult form in the following period and become young matures. In Equation 2, s_0 is the survival rate of the juveniles from one period to another.

$$X_{1,t} = X_{0,t-1}s_0 \quad (2)$$

[5] This structure mainly inspired from salmon population but the model can be modified in terms of number of periods and parameters to implement for other species as well.

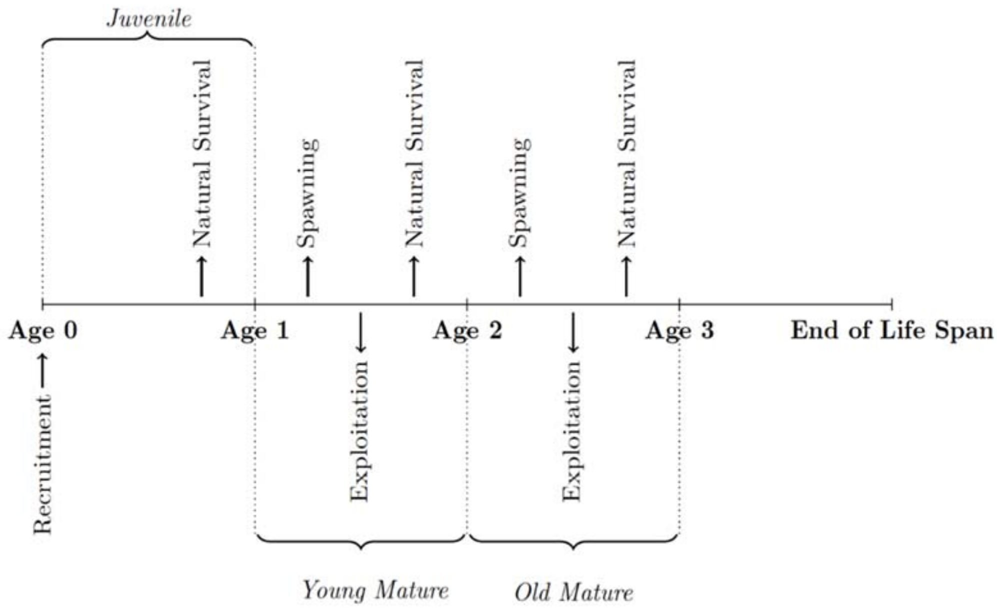

Figure 1 Life-Span of a Cohort

Young matures and old matures are subject to two different forms of mortality: natural mortality and exploitation. In this setting, we assume that the exploitation happens after spawning in each period which is the actual practice.

$$X_{2,t} = X_{1,t-1} s_1 (1 - h_{1,t-1}) \tag{3}$$

$$X_{3,t} = X_{2,t-1} s_2 (1 - h_{2,t-1}) \tag{4}$$

Equations 3 and 4 together show the evolution of the young and old mature fish population where s_1 and s_2 are the natural survival rates of young and old matures for a period, respectively and h_1 and h_2 are the total harvesting rates of the corresponding age groups.

3. Maximum Economic Yield

In this section, maximum economic yield harvesting strategies are analyzed in static and dynamic environments within our OLG setup. We assume without loss of generality that there are two types of fleets. Fleets are characterized by their fishing selectivities. There are two types of selectivities: perfect fishing selectivity and imperfect fishing selectivity. Under perfect fishing selectivity, fleet i catches only the age class i it targets, and by-catch amount is negligibly small. Under imperfect fishing selectivity on the other hand, by-catch amount is at considerable levels while fleets still catch the targeted age class as well. A summary of parameters and corresponding values used in both static and dynamic problems is given in Table 1.

3.1 Static Problem

This is a one-shot solution concept for MEY problem. Neither past nor future periods are taken into account by the social planner i.e., the planner maximizes the economic yield of a specific period in which she is living based on the number of fish of each cohort at that specific period. This period has an important characteristic, of which the variables of interest are constant through time (unlike dynamic problem concept). In other words, static problem yields the steady state values for the dynamic problem.

3.1.1 Perfect Fishing Selectivity

Economic yield here refers to economic profit which is the difference between the revenue from the total biomass harvested and total cost (Euro/kg). Main problem in static environment is given by Equation 5.

$$Max\ \Pi_t \tag{5}$$

which can be rewritten as

$$\max \sum_i [p_i h_i - C_i] \tag{6}$$

Static problem is given in Equations 5 and 6, where p_i is the constant price of fish of age i (Euro/kg) and similarly h_i and C_i are the rate harvested and total cost. Total profit is the sum of profits earned by exploitation of the two cohorts which have economic value.

Harvest is assumed to be a function of fishing effort and have the form of Equation 7 as in Grafton et al. (2010) under perfect fishing selectivity case.

$$h_i = q_i(b_i)^{\mu} E_i \tag{7}$$

Table 1 Parameters[6]

Symbol	Definition	Value
a	Scaling parameter in recruitment function	1500 (number of fish)
β	Fertility parameter in recruitment function	1.5
b	Shape parameter in recruitment function	500 (number of fish)
s_0	Natural survival rate of juveniles from one period to another	0.6
s_1	Natural survival rate of young matures from one period to another	0.7
s_2	Natural survival rate of old matures from one period to another	0.7
w_0	Weight of juveniles	1 (kg/fish)
w_1	Weight of young mature	2 (kg/fish)
w_2	Weight of old mature	3 (kg/fish)
w_3	Weight of the oldest fish	3 (kg/fish)
p_1	Price of young mature	1 (Euro/kg)
p_2	Price of old mature	1 (Euro/kg)
c_1	Effort cost of fleet 1	0.25 (Euro/effort)
c_2	Effort cost of fleet 2	0.25 (Euro/effort)
μ	Stock effect in harvest function	0.08
η	Marginal product of fishing effort	0.2
q_1	Catchability coefficient of fleet 1	0.05 (1/effort)
q_2	Catchability coefficient of fleet 2	0.05 (1/effort)
$\tilde{q}_1$	Catchability coefficient of fleet 1 bycatch	0.01 (1/effort)
$\tilde{q}_2$	Catchability coefficient of fleet 2 bycatch	0.01 (1/effort)
r	Interest rate	0.10

In Equation 7, μ is the stock effect that is analogous to the sensitivity of the amount of harvest to the size of corresponding fish population, η is the marginal product of fishing effort, q_i is the catchability coefficient and b_i is the biomass index such that $0 \leq b_i \leq 1$ which is given by Equation 8.

[6] Scaling, fertility and shape parameters, natural survival rates and weights for young and old mature fish are taken from Skonhoft et al. (2012). Other parameters are authors' choice for which sensitivity analyses are available upon request.

$$b_i = \frac{\sum x_i w_i}{X_i w_i} \qquad i = 0, 1, 2, 3 \qquad (8)$$

Cost, C_i, is a linear function of fishing effort, given by Equation 9 where c_i is the constant cost of per unit effort.

$$C_i = c_i E_i \qquad (9)$$

3.1.2 Imperfect Fishing Selectivity

Under imperfect selectivity, maximization problem remains the same except the harvest function. Now, fleet *i* harvests age *i* and unintentionally age *j* fish as well. In order to incorporate this setup into our model, the method used in Skonhoft et al. (2012) is employed in which there exists an unintended catchability parameter $\tilde{q}_i$, which leads to an unintended harvest of fish of age *i* notated as $\tilde{h}_i$ given in Equation 10.

$$\tilde{h}_i = \tilde{q}_i (b_i)^{\mu} E_j^{\eta} \qquad (10)$$

Total harvest of age *i* fish is then, equal to the sum of intended and unintended catches given in Equation 11.

$$h_i^{total} = h_i + \tilde{h}_i \qquad (11)$$

3.1.3 Results for the Static Problem

In the static setting, MEY is found by maximizing profit with respect to biological constraints given by Equations 1, 2, 3 and 4 and economic constraints given by Equations 7 and 9 in perfect selectivity case and Equations 10 and 9 in imperfect selectivity case. Results are summarized in Table 2.

Table 2 MEY - Static Solution

	h_1	h_2	E_1	E_2	*Profit*
Perfect	0.0198	0.0197	0.0159	0.0158	0.0316
Imperfect	0.0238	0.0236	0.0159	0.0158	0.0395

Under the static solution concept, young matures and old matures are exploited in similar rates by spending a similar amount of effort for each age class. Moreover, unintended catches increase the profitability of the fishing sector.[7] Also, it is notable that the solutions in the static problem yields the steady state values for the dynamic problem.

3.2 Dynamic Problem

Dynamic problem in this setting is more applicable to the real-life problem, due to the fact that a social planner is more likely to consider all future impacts of a policy. In this problem, the aim of the social planner is to maximize the discounted sum of current and all future profits made by the fishery sector. Contrary to the static problem, in this subsection, variables have two indices i and t which indicate cohort and time, respectively.

In the dynamic problem of finding MEY harvesting strategies under perfect and imperfect fishing selectivity, sum of discounted profits made by the representative agent by exploiting (Equation 5') is maximized where the discount rate is noted by *r*:

$$max \sum_t \frac{\Pi_t}{(1+r)^t} \tag{5'}$$

which can be written as:

[7] The reasoning is discussed in the dynamic problem section in detail in which we obtained parallel results.

$$\sum_t \sum_{i=0}^{i=3} \frac{[p_{i,t}h_{i,t} - C_{i,t}]}{(1+r)^t} \quad (6')$$

Economic constraints are the same as in the static problem however they are now in time-variant form, given below:

$$h_{i,t} = q_i(b_{i,t})^{\mu} {E_{i,t}}^{\eta} \quad (7')$$

$$b_{i,t} = \frac{X_{i,t}w_i}{\sum_i X_{i,t}w_i} \quad (8')$$

$$C_i = c_i E_{i,t} \quad (9')$$

$$\tilde{h}_{i,t} = \tilde{q}_i(b_{i,t})^{\mu} {E_{j,t}}^{\eta} \quad (10')$$

$$h_{i,t}^{total} = h_{i,t} + \tilde{h}_{i,t} \quad (11')$$

Incorporating unintended catches in the dynamic problem changes harvest conditions and hence biological constraints as well. Biological constraints regarding recruitment and juveniles remain the same as in Equations 1 and 2, while conditions for young and old matures take the following forms:

$$X_{2,t} = X_{1,t-1}s_1(1 - h_{1,t-1} - \tilde{h}_{1,t-1}) \quad (12)$$

$$X_{3,t} = X_{2,t-1}s_2(1 - h_{2,t-1} - \tilde{h}_{2,t-1}) \quad (13)$$

Therefore, the dynamic problem is the maximization of total discounted profit defined in Equation 6' with respect to economic and biological constraints defined under perfect and imperfect fishing selectivities, given in Equations 7'-13.

3.2.1 Results for the Dynamic Problem

Under both perfect and imperfect fishing selectivities, fish population in all age classes increases with respect to the initial benchmark state which implies that the total biomass in the ecosystem increases. Total profit in both cases increases with the calculated harvest rates, as well. Table 3 summarizes fish population dynamics given optimal harvest rates. Under perfect fishing selectivity case, steady state is achieved in 14 years. Also, the robustness of the results are satisfied, since the solutions for static problem (both perfect and imperfect fishing selectivity cases) coincide with the steady state values of dynamic problem.

Table 3 MEY under perfect fishing selectivity

Year	X_0	X_1	X_2	X_3	h_1X_1	h_2X_2	π
1	750	400	250	120	7.9317	4.9254	0
2	912	450	274	172	8.8775	5.3566	0.0314
3	949	547	309	188	10.878	6.044	0.0316
4	1003	569	375	212	11.2482	7.4046	0.0316
5	1040	602	390	257	11.8843	7.6771	0.0315
6	1055	624	413	268	12.3164	8.1458	0.0316
7	1070	633	428	283	12.477	8.4482	0.0316
8	1077	642	434	294	12.651	8.5641	0.0316
9	1082	646	441	298	12.7249	8.7074	0.0316
10	1085	649	443	303	12.7816	8.7452	0.0316
11	1086	651	445	304	12.821	8.7859	0.0315
12	1088	652	447	305	12.8391	8.8269	0.0316
13	1089	653	447	307	12.8585	8.8254	0.0316
14	1089	653	448	307	12.8574	8.8464	0.0316
15	1089	653	448	307	12.8574	8.8464	0.0316
.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.
20	1089	653	448	307	12.8574	8.8464	0.0316
.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.
50	1089	653	448	307	12.8574	8.8464	0.0316

The effort levels exerted by both types of fleets is plotted with respect to time in Figure 2. In MEY harvesting solution, the level of effort exerted by fleet 1 that exploits young mature fish is less than the effort exerted by fleet 2 that exploits the old mature fish on the steady state. This is intuitive in the sense that age 1 fish will have economic value in the next time period while age 2 will not have any value at all. Thus, fleet exploiting the old mature fish should exert a higher effort in the steady state.

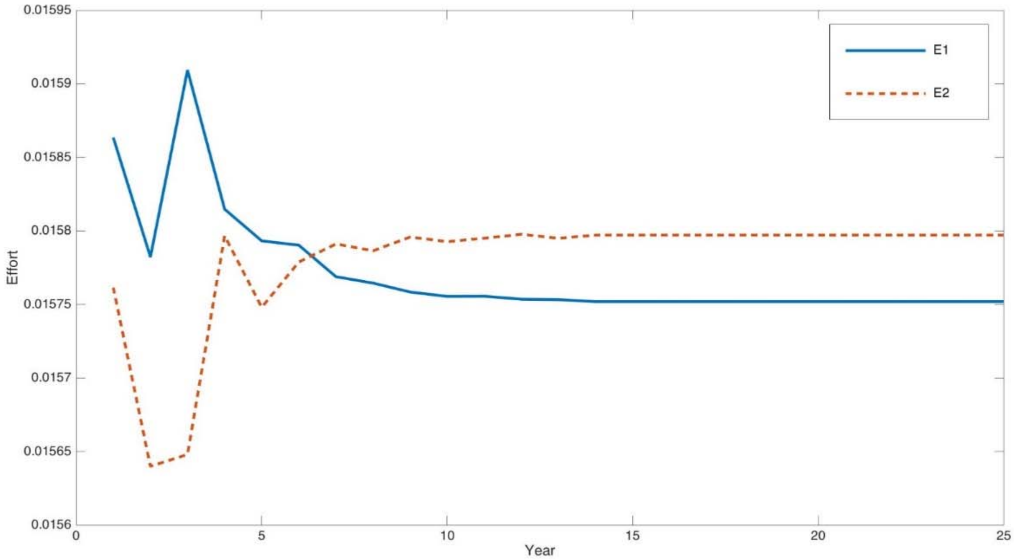

Figure 2 Effort levels under perfect fishing selectivity

Table 4 summarizes the dynamics of the solution under imperfect fishing selectivity case. Steady state is achieved in 15 years under imperfect fishing selectivity.

Figure 3 reveals effort levels exerted by two fleets under imperfect fishing selectivity case. Similar to perfect fishing selectivity case, effort level of fleet 2 exceeds the one of fleet 1 in the steady state, as expected and explained earlier.

Our results support the intuitive reasoning as imperfect fishing selectivity yields higher profit than the perfect fishing selectivity mainly due to the fact that *"joint production replaces a single good production with zero additional production cost"* (Skonhoft et al., 2012).

Table 4 MEY under imperfect fishing selectivity

Year	X_0	X_1	X_2	X_3	h_1X_1	h_2X_2	π
1	750	400	250	120	9.516	5.9118	0
2	912	450	273	171	10.652	6.4054	0.039
3	948	547	308	187	13.049	7.2325	0.039
4	1003	569	374	211	13.499	8.8613	0.04
5	1040	602	389	256	14.262	9.1888	0.039
6	1055	624	411	266	14.783	9.726	0.04
7	1069	633	426	281	14.977	10.0884	0.04
8	1077	641	433	291	15.161	10.2536	0.039
9	1081	646	438	296	15.276	10.3738	0.039
10	1084	649	442	299	15.344	10.471	0.039
11	1086	650	444	302	15.364	10.5187	0.039
12	1087	652	444	303	15.413	10.517	0.039
13	1087	652	446	305	15.412	10.5676	0.039
14	1088	652	446	305	15.409	10.566	0.039
15	1088	653	446	305	15.435	10.5656	0.039
.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.
20	1088	653	446	305	15.435	10.5656	0.039
.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.
50	1088	653	446	305	15.435	10.5656	0.039

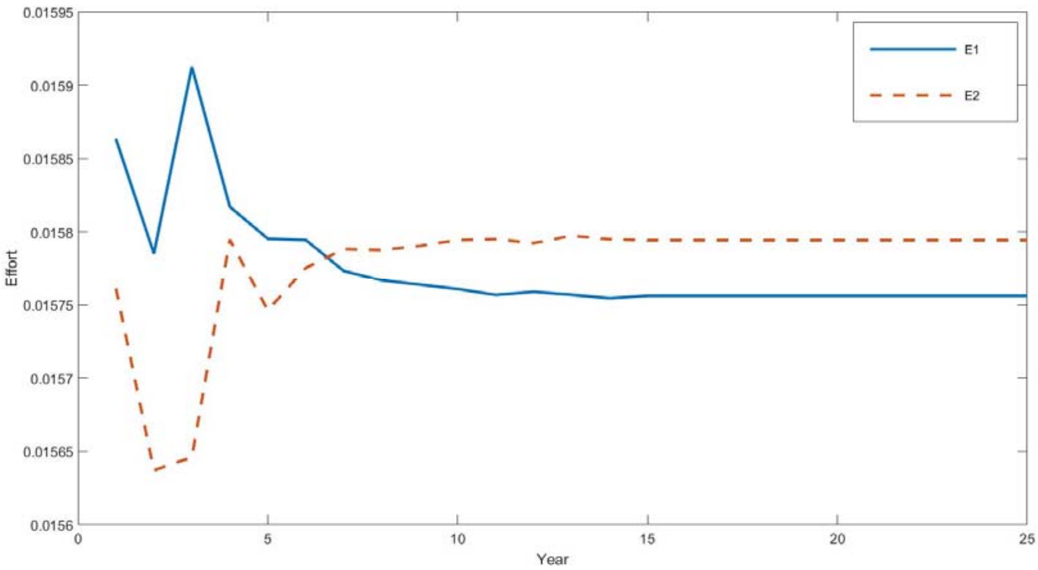

Figure 3 Effort levels under imperfect fishing selectivity

3.3 An Extension: Relaxing the Constant Price Assumption

Modeling and simulation studies in this particular topic try to converge real life-cycle patterns of agents without making the modeling processes unsolvably complex. Costs and prices are the most important determinants of the MEY problem and must be carefully investigated and modeled. This subsection attempts to handle this problem by relaxing the constant price assumption. Demand is assumed to be inelastic and the supply function is given in Equation 14 where ζ is the intercept term and θ is the slope coefficient.

$$p_{i,t}^{eqm} = \zeta_{i,t} + \theta_i Q_{i,t}^{s} \tag{14}$$

In Equation 14, $Q_{i,t}^{s}$ equal to the total biomass harvest of the corresponding age class *i,* at the corresponding period *t*. The price is measured in terms of *Euro Cent*. Note that our intercept term is dependent on age and time which will behave as the shifter parameter of the supply function. Shifter parameter has the form given in Equation 15.

$$\zeta_{i,t} = -\rho_i w_i X_{i,t} \tag{15}$$

Intercept term is negatively correlated to biomass of the corresponding fish population. As the quantity of fish available for exploitation decreases, equilibrium price tends to increase which leads to higher quantity supplied through the supply function; and vice versa. Under imperfect fishing selectivity, the only difference will be the formulation of quantity supplied, Q^s, that is now the total biomass harvested by intended and unintended catch; given in Equation 16.

We keep the rest of the model unchanged and new additional parametrization added to Table 1 given in Table 5.[8]

[8] Parameters for the supply function is chosen by the authors and the sensitivity analysis for these parameters is available upon request.

Table 5 Additional parameters for MEY with endogenous prices

Symbol	Definition	Value
θ	Slope term in supply function	0.8
ρ	Shifter coefficient of the supply function	0.03

The impact of relaxing the constant price assumption is twofold. Since the objective function now depends on the endogenous price, agents are being effected from the prices and they are responsible from the resulting price as well, in a way that their decisions in fact is determining the actual price level. Here, we do not allow for any information asymmetry of any kind; i.e., agents are fully aware of the consequences of their effort and harvest decision and they can accurately estimate the available biomass in the ecosystem as in the previous cases. Table 6 summarizes the fish population dynamics, price formation process and the total profit of the industry with endogenous prices under perfect fishing selectivity.

As summarized in Table 6, with the proposed strategy, total biomass in the ecosystem and total profit earned by the agents increase as in the previous cases, and the ecosystem achieves its steady state in 16 years. Steady state price of fish per kilogram is approximately € 1.5.

Figure 4 reveals effort levels exerted by both fleets under perfect fishing selectivity case with endogenous prices. It is seen that fleets behave in a similar way, but the effort levels are different. Effort level exerted by fleet 1 exceeds that of fleet 2. Table 7 summarizes dynamics of fish population under imperfect fishing selectivity with endogenous prices. Again, the biomass of the ecosystem increases with the optimal harvest rates and steady state is achieved in 15 years. Steady state price of per kilogram fish is almost € 0.5.

Table 6 Perfect Fishing Selectivity with Endogenous Prices

Year	X_0	X_1	X_2	X_3	h_1X_1	h_2X_2	p_1(cent)	p_2(cent)	π
1	750	400	250	120	23.31	14.136	21.9757	13.8856	0
2	912	450	266	167	27.147	15.004	37.7145	18.0603	8.3775
3	944	547	299	177	35.635	17.495	88.9719	33.6467	21.0321
4	998	566	361	199	36.998	22.834	97.1005	79.8818	32.0827
5	1033	599	374	239	39.759	23.758	118.574	89.478	38.7865
6	1048	620	395	247	41.634	25.645	133.973	110.823	46.8658
7	1062	629	408	261	43.079	26.81	139.915	124.945	51.4085
8	1069	637	414	269	43.426	27.798	146.03	131.559	54.3066
9	1073	641	419	273	43.426	28.07	149	137.502	56.3532
10	1076	644	422	276	43.691	28.254	151.316	141.046	57.7052
11	1078	646	424	278	43.77	28.248	152.873	143.472	58.6267
12	1080	647	425	279	43.959	28.248	153.655	144.695	59.0918
13	1080	647	426	280	43.956	28.343	153.517	145.953	59.3575
14	1080	648	426	280	44.047	28.34	154.436	145.947	59.5636
15	1080	648	426	280	44.045	28.435	154.436	145.947	59.5636
16	1080	648	426	280	44.044	28.434	154.436	145.947	59.5636
.	.	.	.	.	.	.	.	.	.
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20	1080	648	426	280	44.044	28.434	154.436	145.947	59.5636
.	.	.	.	.	.	.	.	.	.
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50	1080	648	426	280	44.044	28.434	154.436	145.947	59.5636

Table 7 Imperfect Fishing Selectivity with Endogenous Prices

Year	X_0	X_1	X_2	X_3	h_1X_1	h_2X_2	P_1 (cent)	P_2 (cent)	π
1	750	400	250	120	28.27	17.402	21.232	19.265	0
2	912	450	260	163	32.756	18.3	25.41	20.519	1.254
3	940	547	292	169	43.006	21.796	35.99	26.03	1.955
4	995	564	353	189	45.355	27.971	38.728	35.36	2.502
5	1029	597	363	228	48.791	29.036	42.246	37.016	2.74
6	1043	617	384	234	51.201	31.358	44.902	40.7	3.051
7	1057	626	396	247	52.256	32.654	46.05	42.73	3.206
8	1064	634	402	254	53.175	33.325	47.041	43.799	3.308
9	1068	638	407	258	53.656	33.878	47.57	44.677	3.379
10	1071	641	409	261	53.998	34.103	47.937	45.038	3.415
11	1073	643	411	262	54.239	34.33	48.203	45.403	3.446
12	1074	644	412	264	54.352	34.439	48.324	45.574	3.461
13	1074	644	413	264	54.365	34.55	48.344	45.751	3.471
14	1075	645	413	265	54.361	34.548	48.338	45.745	3.469
15	1075	645	413	265	54.47	34.551	48.453	45.753	3.476
.	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	.
20	1075	645	413	265	54.47	34.551	48.453	45.753	3.476
.	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	.
50	1075	645	413	265	54.47	34.551	48.453	45.753	3.476

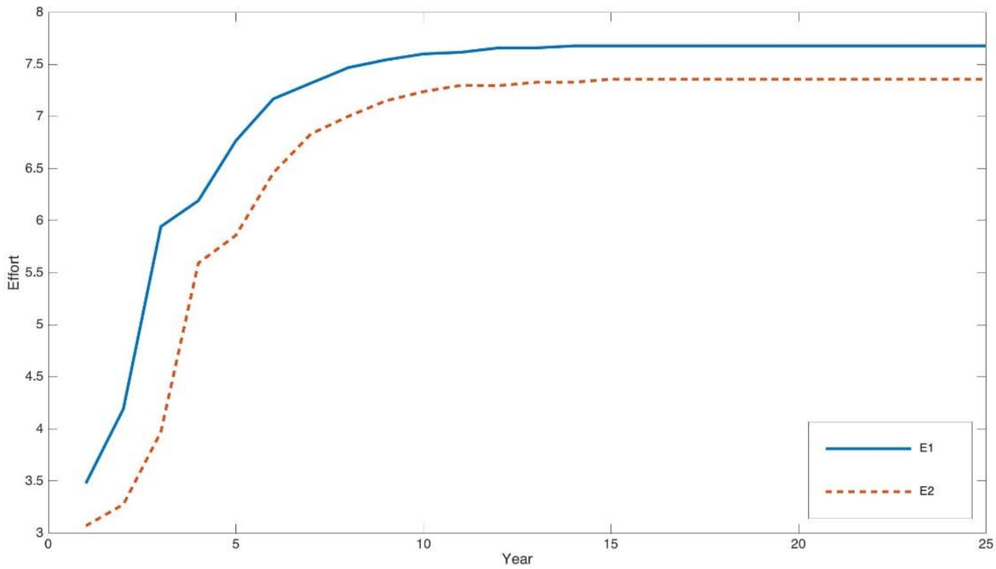

Figure 4 Effort levels under perfect fishing selectivity with endogenous prices

Figure 5 reveals the effort levels exerted by both fleets under imperfect fishing selectivity with endogenous prices. It is observed that effort level exerted by fleet 1 is always higher than the effort level exerted by fleet 2.

Our analyses with endogenous prices show that prices and thus profits resulted in perfect fishing selectivity case is significantly higher than the imperfect fishing selectivity case. Our results in endogenous prices seem to contradict with the outcomes of the exogenous price model. However, notice that the relaxation of constant price assumption concerns a methodological contribution and thus the results of the endogenous price case are not comparable to those of fixed price assumption. The two are completely different models as the basic assumption they are built upon are different. However, these differences in the outcomes of the models still carry an important information and point out the fact that modeling techniques and underlying assumptions are very important. Since the designed policies heavily depend on these models, models converging to real life-cycle dynamics should be developed and used.

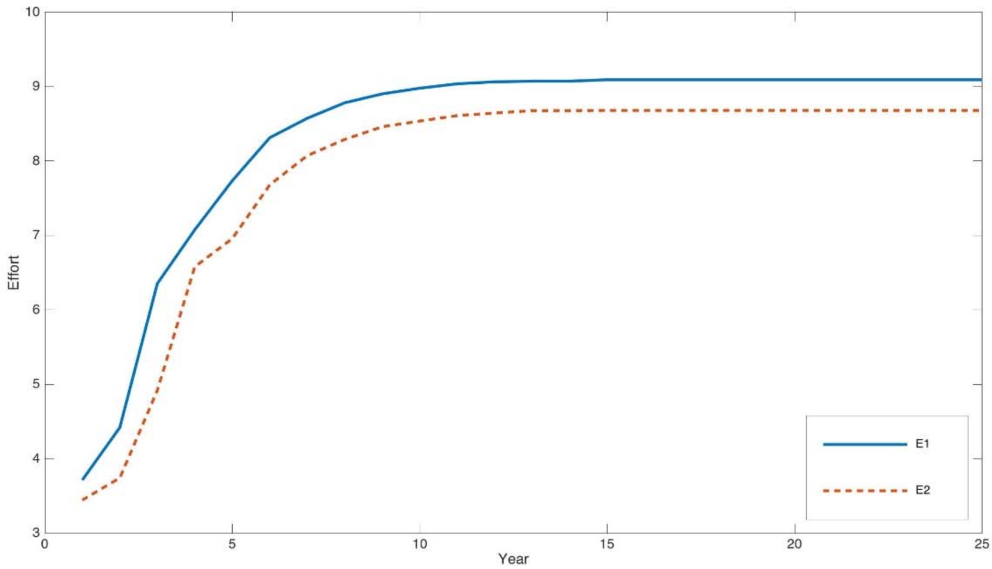

Figure 5 Effort levels under imperfect fishing selectivity with endogenous prices

4. Conclusion

This paper attempts to model the dynamics of a fish population as well as come up with new methods to find optimal harvesting strategies. The proposed modeling and solution techniques provide a general framework for analyzing the effects fishery management targets on the fishery sector. Our analyses make several contributions to bioeconomic modeling and fisheries management literature in terms of modeling, simulation and solution techniques which can be utilized in policy making processes such as quota implementation.

This study contributes to the literature in the sense that calculation of optimal harvest rates (and also other variables, such as biomass in the ecosystem, profitability etc.) are performed with numerical solution of a system of nonlinear equations. To do so, we construct a realistic bioeconomic model which is a 4-period overlapping generations model for a single-type fish population, with the representative agent assumption for all agents in the modeled economy/ecosystem; i.e., a single agent represents the population of its own kind in all properties. With the proposed modeling strategy, we also provide a complete characterization and solution of the MEY harvesting problem in both static and dynamic environments, under both perfect and imperfect selectivities. We do not only analyze final situation but also the convergence process to a steady state. The constant price assumption in the analysis of the maximum economic yield problem is also relaxed, and endogenous prices are then incorporated into the model. Note that we hesitate to draw any comparisons between the results of the two models as the relaxation of this assumption cause the generated model losing its fundamental connections with the previous ones. By this extension, we highlight the importance of the assumptions that models are built upon in this literature. This is also important in the sense that if the underlying assumptions alter the findings of the model this much, policy makers using these modeling approaches should be even more careful about evaluation.

Future research on this topic might be fitting the results of the model to real data to see which models present the dynamics of the population best. Introducing stochastic environmental processes into the model in order to correspond with and further converge onto a solution that more accurately models real life practices might also enrich the analyses. Another extension might be the introduction of variety in terms of types of fish, in order to enrich the modeled ecosystem and to make inferences about a population which carries its internal exploiting dynamics in terms of a predator-prey relationship.

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