The Economic Gains to Accounting for Fisheries Induced Evolution

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The economic gains to accounting for fisheries induced evolution

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Abstract:

Ecologists warn that the rapid evolution occurring as a result of high-intensity commercial fishing could have significant economic and ecological effects. So far, fishery managers do not take this rapid evolution (called fisheries-induced evolution or FIE) into consideration when determining fishery policy. I model the interactions between the genetics, population structure, and economics of the fishery in order to determine how beneficial altering the fishery managers decision framework to include fisheries induced evolution would be to fishery profit and yield.

My model is based on North-East Arctic Cod, which are long lived and for which an abundance of information exists, including proof of FIE. I compare the steady state reached by a ‘myopic’ fishery manager who sets effort and mesh size policy while ignoring evolution, to the steady state reached by a fishery manager who dynamically optimizes his strategy with the knowledge of how evolution will respond. This paper shows that accounting for evolution can increase steady state profits by 29-34%, however this benefit decreases and is eventually eliminated as the discount rate increases from zero. An important auxiliary benefit to accounting for evolution is the effect optimal management has on fishery biomass, maturation rates, and yield.

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Introduction

For decades, ecologists have documented the rapid evolution that is occurring to fish stocks as a result of high-intensity commercial fishing. (Law and Grey 1989, Enberg et al. 2012). This evolution of economically relevant life-history traits in fish, which occurs due to the intense harvesting pressure from commercial fisheries, may irreversibly diminish fisheries yields and ecological services within decades (Conover and Munch 2002, Heino et al. 2002, de Roos et al. 2006, Jørgensen et al. 2007). In this paper, I model the complex interactions between the genetics, population structure, and economics of the fishery in order to determine what economic gains can be achieved by incorporating this rapid evolution (called fisheries-induced evolution, or FIE) into the fishery management decision process.

Commercial fisheries harvest fish populations aggressively, removing large portions of the population every year and targeting the bigger and older fish of the population. This occurs both as a consequence of selective fishing gear used combined with intense fishing pressure, which is thought to outstrip natural forces of selection by up to 400% (Jørgensen et al. 2007, Swain et al. 2007) As a result of this artificial selection by the fishery, fish that mature at a young age and fish that are small for their age contribute a disproportionate amount of offspring to the subsequent generation. By this mechanism each generation will mature a little earlier, and grow a little more slowly, than the previous. North East Arctic Cod, for example, typically matured between 10-11 years of age in the 1930s, but by the 1990s the mean maturation age had dropped to approximately 7 years (Heino et al. 2002). This effect, known as fisheries-induced evolution, creates a potential trade-off between harvest rates and stock size since early maturation and slower growth will affect population growth rates.

Early maturation affects fishery profitability through population growth rate, which is given by the ratio of the natural log of the number of eggs that the average fish in a population expects to produce in a lifetime to the average time between generations. When the average fish matures early, they get a 'head start' on procreation, which increases the number of years during which they can reproduce and decreases the average time between consecutive generations. Both of these effects would, all things being equal, increase population growth rate.

Since sexually immature fish grow at a faster rate than sexually mature fish (Quince et al. 2008), a given fish will be smaller at any given age than any fish that matures later in life. As the maturation rate increases, and so the average age of maturation decreases, the average rate of individual growth will decrease as well. The effect of slower individual growth on the expected number of offspring in a lifetime (and thus population growth rate) is not obvious since small fish are more likely to escape harvest, but they also produce less eggs at any given age because egg production is correlated to body size.

While price per kilogram does not vary by size in all fisheries, in fisheries such as cod, tuna, and halibut (among others), large fish sell for a higher price per kilogram on the market than small fish (Norges Råfisklag 2014, Fry n.d.). If large fish generate more revenue more per pound than small fish, fishery induced evolution may result in a decrease in fishery value even if the population growth rates do not decrease significantly, since early maturing fish are smaller at any given age, which may decrease the average fish size in the population.

The management of fisheries-induced evolution has received little attention in the resource economics literature. In contrast, the evolution of pesticide resistance has received greater attention, due to the extremely rapid rate at which evolution in pests occurs as well as the dichotomous nature of the genes involved in pesticide resistance (one is either resistant or not). Unfortunately, key assumptions and simplifications made in such models applied to pesticide resistance evolution cannot be readily transferred to the fisheries context. Guttormsen et al. (2008) presented the first economic model to
examine the effect of selective harvesting on fishery genetics. They assumed the evolving trait is composed of a single gene that produces a discrete number of possible trait values\(^1\) in order to observe the effect selective harvesting has on the frequency of schooling behavior in a pelagic fish population. This paper assumes that the evolving trait is composed of many genes that combine to produce a continuous spectrum of possible trait values.

In related work, Eikeset et al. (2013) modeled fisheries-induced evolution with a simulation-based model to attempt to determine how managing an evolving fish stock differs from the management of a stock that is not evolving, and to compare the net present value associated with each scenario. Zimmermann and Jørgensen (2015) perform a similar comparison to Eikeset et al (2013), but with a model that includes mesh size as a control variable, which has been shown to be crucial when managing age-structured populations (Diekert et al. 2010b), and assumes selectivity is constrained by gear type, as opposed to knife edge selectivity. While there are differences in their results and conclusions, both papers find that the existence of fisheries induced evolution has only a small impact on the net present value of the fisheries. This result was striking and perhaps somewhat controversial, as the prediction put forth by the ecological literature on fisheries induced evolution was that the economic consequences would be severe (Jørgensen et al. 2007). It is important to note, however, that neither model permits the fishery manager to respond to evolution, but instead assumes that the manager must choose a single management strategy that is to be followed in perpetuity.

In this paper, I determine whether including fishery-induced evolution in the fishery management decision has a significant impact on the profitability of a fishery. I compare the steady state reached by a myopic fishery manager who uses effort and mesh size to maximize annual profits while assuming evolution does not occur, subject only to a sustainability condition, to the steady state reached by a fishery manager who dynamically optimizes the net present value of the fishery with the ability to forecast how evolution will respond to fishing pressure. My model assumes the fishery manager has perfect control of the fishery and is able to use both annual effort and mesh size as control variables. I assume the fishery uses trawlers to harvest fish, which constrains the fishery managers ability to control the selectivity pattern imposed on the population by harvest.

In order to calculate the steady state of the myopic fishery manager I make the common assumption that evolution is fitness-maximizing, conditional on the management strategy. As both the fishery and evolution are maximizing their objective functions (fitness and profit, respectively), subject to the action of the other, I can model the steady state that will be reached by that myopic fishery as a Nash equilibrium: in the steady state fitness cannot improve through evolution, given the annual level of effort and the mesh size that is used to harvest from the population, and the fishery manager cannot increase profits by adjusting effort or mesh size, given the population characteristics. While modeling evolution as a Nash game is not unprecedented in the biological literature, this will be the first bioeconomic application that I know of. In contrast, the steady state reached by the dynamically optimizing fishery manager is characterized by the steady state which maximizes the discounted net present value of the fishery, treating the rate of maturation as a stock to be managed along with population size. By comparing these two outcomes I am able to estimate the effect ignoring fisheries-induced evolution has on fishery profits.

My model is built to approximate the Atlantic cod (\textit{Gadus morhua}) fishery in Norway. Northeast Arctic (NEA) cod, the worlds largest and most valuable stock of Atlantic cod, is primarily fished by Norwegian gillnets and Russian and Norwegian trawlers (each comprising roughly 30% of the total catch) (The Norwegian Ministry of Trade, Industry and Fisheries 2013). The NEA cod fishery

\(^1\)Modeling a trait as the product of a single gene that produces a discrete number of possible trait values is referred to as Mendelian genetics. Modeling a trait as the product of many genes that combine to produce a continuous spectrum of possible trait values is referred to as quantitative genetics.
managers utilize many controls, including minimum mesh size, total allowable catch (which is set annually, jointly by Russia and Norway), and individually distributed quotas. The NEA cod fishery has a minimum mesh size of 130mm for trawlers and a minimum mesh size of 165mm for gillnets (ICES 2010). NEA cod sell on an increasing price gradient (large fish sell for more per pound than small fish), which means that fisheries-induced evolution towards slower growth may be particularly damaging for this fishery (Norges Råfisklag 2014). NEA cod live 8 to 13 years, and are observed to grow up to be roughly 110 cm long and weigh up to 10 kg in the wild (although the record length and weight reported far exceed that; fishbase 2015).

I find that the benefit to incorporating fisheries induced evolution into the management decision framework is very sensitive to the discount rate of the dynamically optimizing fishery manager. At the extreme, when the discount rate of the dynamic fishery manager is 0%, fishery profit is increased by 29%. As the discount rate increases, the difference in steady state profit decreases and becomes negative once the discount rate surpasses 4%. Since the myopic fishery manager has a zero discount rate sustainability constraint, these results suggest that incorporating fisheries induced evolution in fishery management may be very beneficial.

In Section 1, I describe the theoretical model used to calculate the steady state. In Section 2, I present preliminary results and show that the economic impact of accounting for fishery-induced evolution generally depend on the discount rate, but can be rather large. In Section 3 I discuss the results and their implications, and future directions.

1 The Model

My goal is to use the simplest model that incorporates the complexities of evolution and still allows me to estimate the profit gain to including fisheries induced evolution in the fishery managers decision framework. To accomplish this I exploit the fitness-maximizing nature of evolution and model the steady state of a fishery manager that maximizes annual profit, subject to a sustainability constraint, while assuming no evolution occurs as a Nash equilibrium between the fishery and evolution. At that steady state, evolution has maximized fitness given the annual effort and mesh size used by the fishery, and the fishery manager has maximized annual profit given the maturation rate that evolution has reached. I compare this result, which is the result of what I call the ‘myopic’ fishery, to the steady state profit of the ‘dynamic’ fishery, which is dynamically optimized to maximize the net present value of the fishery while taking evolution into account. By focusing on these two outcomes I am able to compare what steady state profit would be in a scenario where evolution is perfectly understood and forecasted to the steady state profit of a management scenario where evolution not accounted for.

1.1 The fishery

In this sub-section I describe the economic characteristics of the fishery such as the price structure, harvest rates, and fishing costs.

I consider model two possible scenarios: one where cod sells for a constant price per kilogram and another which uses the minimum prices mandated by the Norwegian Fishermens Sales Organization on sales of NEA Cod (Norges Råfisklag 2014).
Figure 1: Gear retention probability versus fish length for various gear types

Trawler gear retention for various mesh sizes. As a trawler pulls through the water, fish that are not small enough to swim through the mesh are caught. Increasing mesh size increases the size that fish need to be in order to escape, and also decreases the steepness with which the size of the fish affects the likelihood it is caught.

If the price per kilogram is constant:

\[ p_{a,i} = p_{\text{constant}} \]  

and, if the price per kilogram is following the sales organization minimum price schedule:

\[ p_{a,i} = \begin{cases}  
  p_1 & \text{if } w_{a,i} < 1 \text{ kg} \\
  p_2 & \text{if } w_{a,i} < 2.5 \text{ kg} \\
  p_3 & \text{if } w_{a,i} < 6 \text{ kg} \\
  p_4 & \text{if } w_{a,i} > 6 \text{ kg} 
\end{cases} \]  

where \( p_{a,i} \) is the price per kilogram of a fish age \( a \) that matured at age \( i \), and \( w_{a,i} \) is the corresponding weight of that fish, defined by equation (6) in the following section. Harvest is a function of effort (in tonnage days) and mesh size (in millimeters). The fishery manager is assumed to have perfect control over the fishery effort and mesh size. Harvest rate is described as probability a fish of age \( a \) that matures at age \( i \) will be caught given effort level \( E \) and mesh size \( m \). The probability a fish is harvested is determined by the probability a fish comes in contact with the fishing gear and the probability a fish is caught by the gear (conditional on coming in contact with it). The instantaneous probability a fish comes in contact with the gear depends on the level of effort exerted, which is modified by \( q \), the catchability coefficient. The annual probability is approximated using an exponential approximation. Having come in contact with the gear, the probability a fish is caught by the gear depends on the mesh size and the body size of the fish. The larger the fish or the smaller the mesh size, the more
likely a fish will be caught in the gear.

\[ H(E, m, a, i) = (1 - \exp(-qE)) \cdot h(m, a, i) \]  

(2)

\( H(E, m, a, i) \) is the likelihood a fish of age \( a \) that matures at age \( i \) is caught and \( h(m, a, i) \) is the probability a fish gets caught in the fishing gear, conditional on having come in contact with the gear. The functional form of \( h(m, a, i) \) depends on the type of gear used. Trawlers pull large nets through the water, catching anything and everything too large to swim through the mesh. This creates a sigmoidal gear retention function (Figure 1), which can be described using the equation:

\[ h_{\text{trawl}}(m, a, i) = \left(1 + \exp\left(-\tau_1 \frac{a}{m} - \tau_2 m + \tau_3 \right)\right)^{-1} \]

where \( m \) is mesh size in millimeters, and \( \tau_1 \) through \( \tau_5 \) are constants that determine the shape and magnitude of gear retention.

Cost is assumed to increase linearly with effort (measured in tonnage days) and there is no fixed cost, nor is there any direct cost to changing mesh size. In reality there is likely some cost associated with decreasing mesh size for trawlers, since that would increase resistance and thus the amount of fuel necessary to drag the net through the water.

\[ C(E) = cE \]  

(3)

Using equations (1) and (3), the single-period profit equation is:

\[ \pi(E, m, y) = \left[ \sum_{a=3}^{A} \sum_{i=3}^{a} p_{a,i} N_{a,i} w_{a,i} \cdot H(E, m, a, i) \right] - C(E) \]  

(4)

Where \( N_{a,i} \) is the number of fish at age \( a \) that matured at age \( i \), which is defined by equations (9) through (14), in the following section.

1.2 The biology

In order to model the evolution of an earlier maturation schedule, the fishery must have a well-defined age structure. NEA Cod spend their first two years of life as larva and pelagic juveniles. In their third year of life, they are recruited to the fishery through a density-dependent process. Each year thereafter, they move to the next age-class so long as they survive natural mortality and fishing mortality. Age of maturation depends on many factors, including genetic predisposition, and can be modeled as a function that can shift towards or away from the origin as a result of evolution. Evolution is a fitness maximizing process and, following convention, I use population growth rate as my models metric of fitness.

I use a Beverton-Holt recruitment relationship to determine the number of (age 3) cod entering the
Figure 2: Length at age and maturity. The red line indicates the length a fish would theoretically be if they reached the age on the x-axis without maturing. The colored lines indicate the growth trajectories for different ages of maturation. Once a fish is mature, they grow asymptotically towards the maximum fish length ($L_\infty$).

Fishery annually.

$$R(E, m, y) = \frac{\rho_1 \cdot SSB(E, m, y)}{1 + \rho_2 \cdot SSB(E, m, y)}$$

where $SSB$ is the spawning stock biomass, which is the cumulative weight of all mature individuals in the population, and $\rho_1$ and $\rho_2$ are constants, where $R$ is equal to $\rho_1/\rho_2$ as $SSB$ approaches infinity.

The spawning stock biomass is given by the sum of the body mass of all mature individuals.

$$SSB(E, m, y) = \sum_{a=3}^{A} \sum_{i=3}^{a} N^{a,i}(E, m, y) \cdot w^{a,i}$$

$N^a$ is the number of fish aged $a$, mat$_a$ is the probability a fish of age $a$ is mature, and $w^{a,i}$ is the weight of a fish of age $a$ that matured at age $i$ in metric tons. Weight can be calculated from length at age using a species-specific allometric relationship.

$$w^{a,i} = \omega_1 \cdot (l^{a,i})^{\omega_2}$$

$l^{a,i}$ is the length of a fish of age $a$ that matured at age $i$ (in centimeters), $\omega_1$ is a scaling coefficient that accounts for the density of the fish (in kilogram per cubic centimeter), and $\omega_2$ is a shape parameter for the body form of the fish species. The value of $\omega_2$ is generally approximately equal to 3, as it
converts the length of the fish into a three dimensional volume. Long, thin fish tend to have \( \omega_2 \) values under 3 while thick fish generally have \( \omega_2 \) values over 3 (Brodziak 2012).

The rate at which fish grow in length is dependent upon whether they are mature or immature. Immature fish use excess energy to grow in size, while mature fish must redirect some of this energy to reproductive growth. Length at age is calculated using a piecewise approximation of the von Bertalanffy growth function, as was used in Baskett et al. (2005). Immature fish grow linearly at the maximum growth rate, as the majority of their energy is invested in bodily growth. After maturation, fish grow asymptotically towards the maximum fish length (\( L_\infty \)). This relationship is given below, and depicted in Figure 2.

\[
l_{a,i} = \begin{cases} 
  akL_\infty & \text{if } a \leq i \\
  L_\infty(1 - c_i \exp{ak}) & \text{if } a > i 
\end{cases}
\]  

(7)

where \( k \) is a constant, \( i \) is the age at which the fish matures, and \( c_i \) satisfies

\[
c_i = (1 - ik) \exp{ik}
\]

to ensure that \( l_{a,i} \) is a continuous function.

Before any fish can reproduce, they must survive natural mortality and harvest. Natural mortality is estimated to occur at an annual rate of

\[
\Phi_a = \begin{cases} 
  1 - \exp(-\varphi_1) & \text{if } a = 3, ..., 14 \\
  1 - \exp(-\varphi_2) & \text{if } a = 15 
\end{cases}
\]

Where \( \varphi_1 \) and \( \varphi_2 \) are instantaneous natural mortality rates, which generally are difficult to estimate for an active fishery. \( \varphi_1 \) is assumed to be 0.2 for all fish of all ages, although I adopt the convention used by Diekert et al. (2010b) who increase instantaneous natural mortality for the oldest age group in order to account for senescence.

The number of eggs laid per cod increases geometrically with body length according to the relationship:

\[
b^{a,i} = \beta_1 \cdot (l_{a,i})^{\beta_2}
\]

\( \beta_2 \) is a constant and, like \( \omega_2 \), converts body length (in centimeters) to body volume (in cubic centimeters) and is thus generally approximately equal to 3. \( \beta_1 \) gives the expected number of eggs (technically called oocytes) laid per cubic centimeter of body volume. In order for a fish to lay eggs it must be sexually mature. The likelihood a fish is mature depends on its age and the genetically-determined maturation schedule, which I assume shifts according to the evolving parameter, \( y \). As the evolving parameter increases in value, fish mature at increasingly younger ages (Figure 3).

\[
\text{mat}^i(y) = \frac{\zeta_1}{\zeta_2 + \exp{-i(\zeta_3 + y)}}
\]

(8)

\( \zeta_1, \zeta_2, \) and \( \zeta_3 \) are constants that describe a sigmoidal curve fit to the 2009 maturation schedule (ICES 2010). The slope of the curve is determined by \( \zeta_3 \), and so the evolving parameter \( y \) will determine the rate at which fish evolve once they enter the fishery. Evolution affects only the slope of the curve,
which imposes the realistic assumption that only immature fish enter the fishery. One caveat is that if fish evolved to mature later, then it is possible that not all fish would be mature by age $A$, which would complicate the formulas required to describe the system. Since evolution is only pushing maturation earlier, this is not something I worry about. Also note that, no matter the value of $y$, no fish enter the fishery sexually mature.

In order to more easily describe the population structure, I will define

$$M_i(y) = \frac{\text{mat}_i(y) - \text{mat}_{i-1}(y)}{1 - \text{mat}_{i-1}(y)}$$

as the probability of maturing at age $i$, conditional on being immature at age $i-1$ and given $y$.

Using $H(E, m, a, i)$, recruitment ($R$), natural mortality ($\phi^a$), and the probability of maturation ($M^i$), the number of fish in each size class can be calculated. The number of fish at age $A$ is a combined sum of the fish that survive age $A - 1$ and of fish that survive another year in the oldest age group.

To increase legibility, I will denote $\Psi^{a,i}(E_t, m_t)$ as the probability a fish survives age $a$, given maturation age $i$:

$$\Psi^{a,i}(E_t, m_t) = (1 - \phi^a)(1 - H(E_t, m_t, a, i))$$
\[ N_{t+1}^a = R(N_{t-1}^{a,4}, N_{t-1}^{5,4}, \ldots, N_{t-1}^{A,A}) \]  
\[ N_{t}^{a,+} = N_{t-1}^{a,+} \cdot \Psi^{-1,+,y}(E_{t-1}, m_{t-1}) \cdot (1 - M^a(y_{t-1})) \quad \forall \quad a < A \]  
\[ N_{t}^{a,a} = N_{t-1}^{a,a} \cdot \Psi^{-1,a}(E_{t-1}, m_{t-1}) \cdot M^a(y_{t-1}) \quad \forall \quad a < A \]  
\[ N_{t}^{a,i} = N_{t-1}^{a,i} \cdot \Psi^{-1,i}(E_{t-1}, m_{t-1}) \quad \forall \quad i < a < A \]  
\[ N_{t}^{A,i} = N_{t-1}^{A,i} \cdot \Psi^{A,i}(E_{t-1}, m_{t-1}) + N_{t-1}^{A,i} \cdot \Psi^{A,A}(E_{t-1}, m_{t-1}) \quad \forall \quad i < A \]  
\[ N_{t}^{A,A} = N_{t-1}^{A,A} \cdot \Psi^{A,+,y}(E_{t-1}, m_{t-1}) \cdot M^A(y_{t-1}) + N_{t-1}^{A,A} \cdot \Psi^{A,A}(E_{t-1}, m_{t-1}) \]  

where \( N^{a,i} \) indicates the number of fish of age \( a \) that mature to age \( i \) and \( N^{a,+} \) indicates the fish of age \( a \) that are immature. \( R \) is recruitment, defined in equation (5). The number of fish that are recruited each year (\( R \) or \( N^{3,+} \)) is a function of all of the mature fish the previous year. The number of immature fish in age class \( a \) (\( N^{a,a} \)) is given by the number of immature fish in age class \( a - 1 \) during the previous year (\( N^{a-1,a-1} \)) minus those who died of natural causes, those who were fished, and those who matured that year. The number of fish in age class \( a \) that matured the previous year (\( N^{a,a-1} \)) is given by the number of immature fish aged \( a - 1 \) the previous year (\( N^{a-1,a-1}+ \)) who matured that year, minus those who died of natural causes, those who were fished. The number of fish in age class \( a \) that matured at age \( i \) (\( N^{a,i} \)) is given by the number of fish that were age \( a - 1 \) the previous year that matured at age \( i \) and survived natural death and fishing.

Evolution is assumed to be a fitness maximizing process, using \( y \) as a control variable. One of the most commonly used measures of fitness (\( W \)) is population growth rate (\( r \)). Since my model works with discrete-time population growth, I use the discrete time approximation of population growth rate as my fitness metric (Lande 1982).

\[ W(E, m, y) = \exp\{r(E, m, y)\} \]

Population growth rate (\( r \)) is defined as:

\[ r(E, m, y) = \frac{\ln R_0(E, m, y)}{G(E, m, y)} \]

where \( R_0 \) is the net reproductive rate, or the expected number of offspring left by each female, and \( G \) is the generation time and is itself a function of \( R_0 \).

\[ R_0(E, m, y) = \sum_{a=3}^{A} \left\{ \sum_{i=3}^{a} \left[ \text{mat}_i \cdot b^{a,i} \cdot \prod_{j=3}^{i} (1 - H(E, m, a, j)) \right] \cdot (1 - H(E, m, a, i))^{a-i} \cdot \prod_{k=3}^{a} (1 - \Phi_k) \right\} \]

The expected number of offspring left by each female is a sum across all ages and across all possible ages of maturation. For each age and age of maturation combination the fish must have survived to that age and must be mature at that age. The number of eggs produced, conditional on having survived and being mature, is a function of fish size, which can be calculated directly from age and age at maturation. As \( y \) increases, the maturation curve shifts to the right and \( \text{mat}_i \) increases for all \( i \). Earlier maturation results in smaller fish that are more likely to escape fishing gear (since \( H(E, m, a, i) \) is decreasing in \( i \)), but produce less eggs at any given age (since \( b(i, a) \) is increasing in \( i \)).

Generation time is the sum of the expected number of offspring at each age, weighted by that age,
divided by the net reproductive rate.

\[ G(E, m, y) = \frac{\sum_{a=3}^{A} a \cdot \left\{ \sum_{i=3}^{a} \left[ mat_i \cdot b^{a-i} \cdot \prod_{j=3}^{i} (1 - H(E, m, a, j)) \cdot (1 - H(E, m, a, i))^{a-i} \cdot \prod_{k=3}^{a} (1 - \Phi_k) \right] \right\}}{R_0} \]

Generation time will respond more moderately to changes in the maturation schedule, however changes in generation time affect fitness more than changes in net reproductive rate.

In order for the dynamically optimizing fishery manager to manage the stock through time, he must be able to predict how the evolutionary state will move from year to year. This can be done using the breeders equation (Lush 1937):

\[ B(y_t) = y_{t+1} - y_t = \sigma^2 \frac{1}{\bar{r}(E_t, m_t, y_t)} \frac{\partial \bar{r}(E_t, m_t, y_t)}{\partial y_t} \]  \hspace{1cm} (15)

Where \( \bar{r}(y_t) \) is the average fitness of the a population with mean genetic value \( y_t \) and a variance of \( \sigma^2 \):

\[ \bar{r}(E_t, m_t, y_t) = \int_{i=-\infty}^{\infty} pr(i) \exp\{r(E_t, m_t, i)\} di \hspace{1cm} s.t. \hspace{1cm} i \sim N(y_t, \sigma^2) \]

### 1.3 The Myopic Steady State

The myopic fishery manager knows the population growth function but assumes that the fishery characteristics (growth rate, size at age, etc) are fixed. He will update the fishery effort and mesh regulations as a response to evolution, in order to profit maximize, but will not forecast the evolutionary response to the level of effort and the mesh size chosen. Evolution is essentially updating the fish age at maturation as a response to changes in mesh and effort, in order to maximize fitness. Thus, the fishery manager and evolution will reach a steady state where their best response curves intersect, and neither can improve their objective by changing strategy.

Since we are solving for the steady state \( y_t = y_{t-1} = y, E_t = E_{t-1} = E \) and \( m_t = m_{t-1} = m \). Given any genetic state \( y \), the myopic fishery manager solves:

\[ \{E, m\} = \text{arg max}_{E, m} \pi(E, m, y) \]  \hspace{1cm} (16)

subject to the sustainability constraint:

\[ \Delta N^{a,i} = N_t^{a,i} - N_{t-1}^{a,i} = 0 \hspace{1cm} \forall \hspace{1cm} a = 1, ..., A; i = 1, ..., a \]  \hspace{1cm} (17)

where \( \pi(E, m, y) \) is defined by equation (4) and \( N_t^{a,i} \) is defined by (9) through (14).

In response to the chosen levels effort and mesh size, evolution maximizes fitness:

\[ y = \text{arg max}_y \exp\{r(E, m, y)\} \]
Thus the myopic steady state occurs at the Nash equilibrium between the fishery manager and evolution, where the fishery manager has maximized annual profit, subject to the population characteristics (and any change in effort or mesh size would result in a decrease in annual profit), and evolution has maximized fitness, subject to the annual harvest pattern (and any change in $y$ would decrease fitness).

1.4 The Dynamically Optimized Steady State

The dynamically optimizing fishery manager maximizes the discounted net present value of the stream or profits from the fishery. To do this, the fishery manager maximizes profits, taking the user cost of each stock as well as of the evolving parameter into account. One way to write this maximization is as a Hamiltonian:

The fishery manager is solving:

$$H = \pi(E_t, m_t, y_t) + \lambda_{3,+}(\Delta N_{t}^{3,+}) + \lambda_{4,3}(\Delta N_{t}^{4,3}) + \lambda_{4,+}(\Delta N_{t}^{4,+}) + \ldots + \lambda_{A,A}(\Delta N_{t}^{A,A}) + \mu(\Delta y_t)$$

where

$$\Delta N_{a,i} = N_{t}^{a,i} - N_{t-1}^{a,i},$$

and $N_{t}^{a,i}$ is defined by (9) through (14), and

$$\Delta y = B(E_{t-1}, m_{t-1}, y_{t-1})$$

where $B$ is described in (15).

The steady state reached by the dynamic fishery manager can then be characterized by the Pontryagin conditions associated with the Hamiltonian:

$$\frac{\partial H}{\partial E} = 0$$

$$\frac{\partial H}{\partial m} = 0$$

$$\delta \lambda_{a,i} - \frac{\partial H}{\partial N_{a,i}} = 0 \quad \forall \quad a = 1, \ldots, A; \quad i = 1, \ldots, a$$

$$\Delta N_{a,i} = 0 \quad \forall \quad a = 1, \ldots, A; \quad i = 1, \ldots, a$$

$$\delta \mu - \frac{\partial H}{\partial y} = 0$$

$$\Delta y = 0$$
<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
<th>Units</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_{\text{constant}}$ price per kilogram (when constant)</td>
<td>1.70</td>
<td>USD · kg$^{-1}$</td>
<td>Norges Råfisklag (2014)</td>
</tr>
<tr>
<td>$p_1$ Price per kg for fish smaller than 1kg</td>
<td>1.32</td>
<td>USD · kg$^{-1}$</td>
<td>Norges Råfisklag (2014)</td>
</tr>
<tr>
<td>$p_2$ Price per kg for fish between 1kg and 2.5kg</td>
<td>1.55</td>
<td>USD · kg$^{-1}$</td>
<td>Norges Råfisklag (2014)</td>
</tr>
<tr>
<td>$p_3$ Price per kg for fish between 2.5kg and 6kg</td>
<td>1.78</td>
<td>USD · kg$^{-1}$</td>
<td>Norges Råfisklag (2014)</td>
</tr>
<tr>
<td>$p_4$ Price per kg for fish larger than 6kg</td>
<td>2.11</td>
<td>USD · kg$^{-1}$</td>
<td>Norges Råfisklag (2014)</td>
</tr>
<tr>
<td>$q$ Catchability coefficient</td>
<td>1.94 · 10$^{-8}$</td>
<td>tonnage day$^{-1}$</td>
<td>Diekert et al. (2010b)</td>
</tr>
<tr>
<td>$\tau_1$ Retention parameter 1</td>
<td>-2.2</td>
<td>-</td>
<td>Kvanne (2005)</td>
</tr>
<tr>
<td>$\tau_2$ Retention parameter 2</td>
<td>0.499</td>
<td>-</td>
<td>Kvanne (2005)</td>
</tr>
<tr>
<td>$\tau_3$ Retention parameter 3</td>
<td>16.105</td>
<td>-</td>
<td>Kvanne (2005)</td>
</tr>
<tr>
<td>$\tau_4$ Retention parameter 4</td>
<td>0.112</td>
<td>-</td>
<td>Kvanne (2005)</td>
</tr>
<tr>
<td>$\tau_5$ Retention parameter 5</td>
<td>4.335</td>
<td>-</td>
<td>Kvanne (2005)</td>
</tr>
<tr>
<td>$c$ Cost per unit effort</td>
<td>8.93</td>
<td>USD · tonnage day$^{-1}$</td>
<td>Diekert et al. (2010a)</td>
</tr>
<tr>
<td>$\rho_1$ Recruitment parameter 1</td>
<td>5.1 · 10$^6$</td>
<td>individuals</td>
<td>Diekert et al. (2010b)</td>
</tr>
<tr>
<td>$\rho_2$ Recruitment parameter 2</td>
<td>9.3 · 10$^{-3}$</td>
<td>kg$^{-1}$</td>
<td>Diekert et al. (2010b)</td>
</tr>
<tr>
<td>$\omega_1$ Density of individual cod</td>
<td>7.40287 · 10$^{-3}$</td>
<td>kg · cm$^{-\omega_2}$</td>
<td>ICES (2010) *</td>
</tr>
<tr>
<td>$\omega_2$ Volume parameter</td>
<td>3.050</td>
<td>-</td>
<td>ICES (2010) *</td>
</tr>
<tr>
<td>$\varphi_1$ Instantaneous rate of natural mortality</td>
<td>0.2</td>
<td>-</td>
<td>ICES (2010) *</td>
</tr>
<tr>
<td>$\varphi_2$ Instantaneous rate of natural mortality for senescent fish</td>
<td>0.5</td>
<td>-</td>
<td>ICES (2010) *</td>
</tr>
<tr>
<td>$k$ Growth rate modifier</td>
<td>0.25</td>
<td>-</td>
<td>Diekert et al. (2010b)†</td>
</tr>
<tr>
<td>$L_\infty$ Maximum cod length</td>
<td>100</td>
<td>-</td>
<td>Diekert et al. (2010b)†</td>
</tr>
<tr>
<td>$\beta_1$ Eggs laid per volume of fish</td>
<td>0.805</td>
<td>eggs · cm$^{-\beta_2}$</td>
<td>Marshall et al. (1998)</td>
</tr>
<tr>
<td>$\beta_2$ Volume approximation given length</td>
<td>3.36</td>
<td>-</td>
<td>Marshall et al. (1998)</td>
</tr>
<tr>
<td>$\zeta_1$ Maturation schedule parameter 1</td>
<td>3.159 · 10$^{-5}$</td>
<td>-</td>
<td>ICES (2010) ‡</td>
</tr>
<tr>
<td>$\zeta_2$ Maturation schedule parameter 2</td>
<td>3.218 · 10$^{-5}$</td>
<td>-</td>
<td>ICES (2010) ‡</td>
</tr>
<tr>
<td>$\zeta_3$ Maturation schedule parameter 3</td>
<td>1.634</td>
<td>-</td>
<td>ICES (2010) ‡</td>
</tr>
</tbody>
</table>

Table 1: Summary of model parameters.

* I used a linear regression to fit the log-transformed model using a linear regression and applied the appropriate bias-correction as described by Brodziak (2012) to ICES (2010) data on NEA cod. I used the five year (2006 to 2010) average of weight at age and length at age data and attained an $r^2$ of 1.00.

† I fit the piecewise Von Bertalanffy model from equation (7) to the length at age and maturity at age information in Diekert et al. (2010b), and attained an $r^2$ of 0.9466.

‡ I fit the sigmoidal curve in equation (8) to the 2009 population maturation rates by age (maturation ogives) in the ICES (2010) data and attained an $r^2$ of 0.9959.
2 (Preliminary) Results

These results are preliminary. I am currently working on including more age classes, as the NEA Cod fishery requires a minimum of 6 age classes (post recruitment) to be calibrated properly. The results below use a growth rate approximation which allowed me to get results with only 4 age classes. The parameters reported in table 1 are the ones used to generate the preliminary results.

How the dynamic fishery manager behaves in comparison to the myopic fishery depends greatly on the discount rate the dynamic fishery manager. In the extreme case, when the dynamic fishery manager does not discount the future at all, the dynamic fishery exerts approximately 25.30% less effort than the myopic fishery (22.78 million tonnage days versus 28.54 million) and uses a somewhat smaller mesh (142.9mm versus 147.7mm). This results in very large (28.91%) increase in annual profit (2.03 billion USD versus 1.44 billion USD).

\[
\begin{array}{cccccccccc}
\delta =0.00 & \delta =0.01 & \delta =0.02 & \delta =0.03 & \delta =0.04 & \delta =0.05 & \delta =0.06 & \delta =0.07 \\
Effort & -25.30\% & -3.62\% & 1.95\% & 4.59\% & 6.50\% & 8.15\% & 9.67\% & 11.08\% \\
Mesh & -3.35\% & -0.15\% & -0.82\% & -1.35\% & -1.80\% & -2.21\% & -2.61\% & -2.99\% \\
Profit & 28.91\% & 19.08\% & 6.30\% & 1.63\% & -0.10\% & -1.06\% & -1.71\% & -2.20\% \\
\end{array}
\]

Table 2: Effort, mesh size, and annual profit of the dynamic fishery's steady state, relative to the myopic fishery's steady state (price per kilogram constant). The number in each cell indicates the percent difference in dynamic steady state effort, mesh size, and profit, relative to the myopic steady state value of the same parameter for the same age group. \( \delta \) refers to the discount rate of the dynamic fishery manager.

\[
\begin{array}{cccccccccccc}
Age & \delta =0.00 & \delta =0.01 & \delta =0.02 & \delta =0.03 & \delta =0.04 & \delta =0.05 & \delta =0.06 & \delta =0.07 & \text{Myopic} \\
3 & 0.00 & 0.00 & 0.01 & 0.01 & 0.01 & 0.01 & 0.01 & 0.01 & 0.01 \\
4 & 0.26 & 0.53 & 0.76 & 0.82 & 0.85 & 0.86 & 0.86 & 0.86 & 0.85 \\
5 & 0.98 & 1.00 & 1.00 & 1.00 & 1.00 & 1.00 & 1.00 & 1.00 & 1.00 \\
6 & 1.00 & 1.00 & 1.00 & 1.00 & 1.00 & 1.00 & 1.00 & 1.00 & 1.00 \\
\end{array}
\]

Table 3: Steady state maturation rates for myopic and dynamic fisheries at the steady states (price per kilogram constant). The number in each cell indicates the fraction of the population that is mature at a given age. \( \delta \) refers to the discount rate of the dynamic fishery manager.

As the discount rate increases, saving for the future becomes less important so the dynamic fishery manager chooses to use more effort (table 2). Since effort increases as the discount rate increases steady state population biomass and yield decrease (tables 4 and 5), and steady state maturation occurs earlier in response to the increased fishery pressure (table 3).

Mesh size responds nonmonotonically to the discount rate, though it primarily decreases with the discount rate (table 2). While it may appear that a decrease in mesh size is a result of the fishery manager caring less for the future, this is most likely not the case. When mesh is small enough (that all second and third year fish that come in contact with the net will be caught), a further decrease in mesh actually results in fish maturing later in life (figure 4)\(^2\). This is because as mesh size decreases the difference in the likelihood that an early maturing fish will be caught, relative to the likelihood a late maturing fish will be caught, decreases. If the late maturing fish is already retained in the fishing gear with a probability of 1 (which is larger at a given age than an early maturing fish), a decrease in mesh size cannot increase the probability an old fish is caught. The probability an early maturing fish

\(^2\)Note that when mesh size is large enough that increasing the mesh size affects the likelihood the largest age classes are caught, decreasing mesh size results in fish that mature earlier, in order to increase the likelihood that reproduction occurs before capture.
Figure 4: The effect of mesh size on the fitness maximizing value of $y$ for various levels of effort. When mesh size is sufficiently small (less than 160mm, approximately) the slope of the maturation curve ($y$) increases in response to an increase in mesh size. This is because a decrease in mesh size in this range does not affect the probability an large (age 5+) fish is caught, but does increase the probability a small fish (age 4) is caught, decreasing the relative benefit of early maturation to fitness. When mesh size is sufficiently large, the slope of the maturation curve ($y$) decreases in response to an increase in mesh size. This is because a decrease in mesh size in this range decreases the probability a large fish (age 5 or 6) is caught, as well as the probability a small fish (age 4) is caught, overall increasing the benefit of early maturation to fitness.

is retained, however, increases. This decrease in the difference in catch rates reduces the evolutionary incentive to mature earlier.

This evolutionary response to fishing is what drives the difference in profit between the dynamic and the myopic fishery. A dynamic fishery manager with a discount rate of 1-2% uses a very similar amount of effort as the myopic fishery. At those same discount rates, the dynamic fishery receives 6-19% more in annual profit than the myopic fishery. While the myopic fishery is simply responding to evolution, the dynamic fishery is able to anticipate evolutions response to fishing pressure, and so it chooses a smaller mesh size because it is aware that this will in fact cause the fish to mature later and thus be larger on average, increasing net fishery yield.

When the discount rate is low (0-2%) the dynamic fishery results in population with a larger biomass (table 4). Despite this, no matter what the discount rate, the dynamic fishery always produces a higher yield than the myopic fishery (table 5).

At low discount rates, the long run benefit of accounting for evolution is quite apparent; there are more fish that can be caught at a higher rate and the resulting annual profits are significantly higher. If the discount rate of the manager is high, however, the dynamically optimizing fishery manager will necessarily receive a higher net present value of the fishery, but the long run steady state will result in a fishery that is less productive and less profitable than that of a myopic fishery manager.
Table 4: Steady state biomass by age for myopic and dynamic fisheries at the steady states (price per kilogram constant). The number in each cell indicates the biomass (in million metric tons) of a given age group. $\delta$ refers to the discount rate of the dynamic fishery manager.

<table>
<thead>
<tr>
<th>Age</th>
<th>$\delta = 0.00$</th>
<th>$\delta = 0.01$</th>
<th>$\delta = 0.02$</th>
<th>$\delta = 0.03$</th>
<th>$\delta = 0.04$</th>
<th>$\delta = 0.05$</th>
<th>$\delta = 0.06$</th>
<th>$\delta = 0.07$</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>0.10</td>
<td>0.09</td>
<td>0.09</td>
<td>0.09</td>
<td>0.09</td>
<td>0.09</td>
<td>0.09</td>
<td>0.09</td>
</tr>
<tr>
<td>4</td>
<td>0.65</td>
<td>0.64</td>
<td>0.64</td>
<td>0.64</td>
<td>0.64</td>
<td>0.64</td>
<td>0.64</td>
<td>0.64</td>
</tr>
<tr>
<td>5</td>
<td>1.45</td>
<td>1.25</td>
<td>1.06</td>
<td>1.00</td>
<td>0.98</td>
<td>0.96</td>
<td>0.95</td>
<td>0.94</td>
</tr>
<tr>
<td>6</td>
<td>2.18</td>
<td>1.79</td>
<td>1.59</td>
<td>1.50</td>
<td>1.44</td>
<td>1.39</td>
<td>1.35</td>
<td>1.31</td>
</tr>
</tbody>
</table>

Table 5: Steady state yield by age for of dynamic fisheries at the steady state, relative to the myopic fishery’s steady state (price per kilogram constant). The number in each cell indicates the percent difference in dynamic steady state yield for a given age, relative to the myopic steady state yield for that age. ‘net’ refers to the net yield of the dynamic fishery, versus the net yield of the myopic fishery, which is not a sum of the percent differences by age since yield is on the order of hundred metric tons for fish age 3, and over half a million metric tons for fish age 6 (so the effect of a 1% increase in yield of 4 year old fish impacts net yield three-fold more than a 1% increase in yield of 1 year old fish). $\delta$ refers to the discount rate of the dynamic fishery manager.

<table>
<thead>
<tr>
<th>Age</th>
<th>$\delta = 0.00$</th>
<th>$\delta = 0.01$</th>
<th>$\delta = 0.02$</th>
<th>$\delta = 0.03$</th>
<th>$\delta = 0.04$</th>
<th>$\delta = 0.05$</th>
<th>$\delta = 0.06$</th>
<th>$\delta = 0.07$</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>1.18%</td>
<td>-1.60%</td>
<td>5.94%</td>
<td>11.08%</td>
<td>15.36%</td>
<td>19.42%</td>
<td>23.39%</td>
<td>27.30%</td>
</tr>
<tr>
<td>4</td>
<td>13.64%</td>
<td>-1.00%</td>
<td>9.22%</td>
<td>16.74%</td>
<td>23.14%</td>
<td>29.28%</td>
<td>35.32%</td>
<td>41.32%</td>
</tr>
<tr>
<td>5</td>
<td>57.37%</td>
<td>41.38%</td>
<td>16.04%</td>
<td>9.88%</td>
<td>9.24%</td>
<td>9.89%</td>
<td>11.03%</td>
<td>12.39%</td>
</tr>
<tr>
<td>6</td>
<td>20.43%</td>
<td>10.58%</td>
<td>0.79%</td>
<td>-2.98%</td>
<td>-5.06%</td>
<td>-6.73%</td>
<td>-8.23%</td>
<td>-9.63%</td>
</tr>
<tr>
<td>net</td>
<td>31.50%</td>
<td>19.49%</td>
<td>5.98%</td>
<td>2.10%</td>
<td>0.93%</td>
<td>0.41%</td>
<td>0.15%</td>
<td>0.02%</td>
</tr>
</tbody>
</table>

Tables 6 through 9 show the results of the above experiment repeated, but with a price gradient (as exists in NEA cod). Qualitatively the results do not change, however the differences are larger. This likely occurs for two reasons. Firstly, if large fish are more valuable to the fishery the cost to mis-management and excess evolution is higher. Secondly, there is incentive for the myopic fishery to use larger nets since, if no evolution occurs as a result of harvest, increasing the value of the oldest age group will increase the incentive to reduce harvest from all but the oldest age class (Diekert et al. 2010b).

Table 6: Effort, mesh size, and annual profit of the dynamic fishery’s steady state, relative to the myopic fishery’s steady state (price per kilogram increasing). The number in each cell indicates the percent difference in dynamic steady state effort, mesh size, and profit, relative to the myopic steady state value of the same parameter for the same age group. $\delta$ refers to the discount rate of the dynamic fishery manager.

<table>
<thead>
<tr>
<th>$\delta$</th>
<th>$\delta = 0.00$</th>
<th>$\delta = 0.01$</th>
<th>$\delta = 0.02$</th>
<th>$\delta = 0.03$</th>
<th>$\delta = 0.04$</th>
<th>$\delta = 0.05$</th>
<th>$\delta = 0.06$</th>
<th>$\delta = 0.07$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Effort</td>
<td>-25.39%</td>
<td>-3.26%</td>
<td>2.52%</td>
<td>4.65%</td>
<td>6.35%</td>
<td>7.88%</td>
<td>9.28%</td>
<td>10.59%</td>
</tr>
<tr>
<td>Mesh</td>
<td>-4.09%</td>
<td>-0.50%</td>
<td>-0.98%</td>
<td>-1.36%</td>
<td>-1.74%</td>
<td>-2.13%</td>
<td>-2.51%</td>
<td>-2.89%</td>
</tr>
<tr>
<td>Profit</td>
<td>33.73%</td>
<td>21.23%</td>
<td>1.32%</td>
<td>-0.66%</td>
<td>-1.55%</td>
<td>-2.16%</td>
<td>-2.65%</td>
<td>-3.06%</td>
</tr>
</tbody>
</table>

Table 7: Steady state maturation rates for myopic and dynamic fisheries at the steady states (price per kilogram increasing). The number in each cell indicates the fraction of the population that is mature at a given age. $\delta$ refers to the discount rate of the dynamic fishery manager.

<table>
<thead>
<tr>
<th>Age</th>
<th>$\delta = 0.00$</th>
<th>$\delta = 0.01$</th>
<th>$\delta = 0.02$</th>
<th>$\delta = 0.03$</th>
<th>$\delta = 0.04$</th>
<th>$\delta = 0.05$</th>
<th>$\delta = 0.06$</th>
<th>$\delta = 0.07$</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>0.00</td>
<td>0.00</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>4</td>
<td>0.26</td>
<td>0.58</td>
<td>0.89</td>
<td>0.91</td>
<td>0.92</td>
<td>0.92</td>
<td>0.93</td>
<td>0.90</td>
</tr>
<tr>
<td>5</td>
<td>0.98</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>6</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
</tr>
</tbody>
</table>
Table 8: Steady state biomass by age for myopic and dynamic fisheries at the steady states (price per kilogram increasing). The number in each cell indicates the biomass (in million metric tons) of a given age group. δ refers to the discount rate of the dynamic fishery manager.

<table>
<thead>
<tr>
<th>Age</th>
<th>δ =0.00</th>
<th>δ =0.01</th>
<th>δ =0.02</th>
<th>δ =0.03</th>
<th>δ =0.04</th>
<th>δ =0.05</th>
<th>δ =0.06</th>
<th>δ =0.07</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>0.10</td>
<td>0.09</td>
<td>0.09</td>
<td>0.09</td>
<td>0.09</td>
<td>0.09</td>
<td>0.09</td>
<td>0.09</td>
</tr>
<tr>
<td>4</td>
<td>0.65</td>
<td>0.64</td>
<td>0.64</td>
<td>0.64</td>
<td>0.64</td>
<td>0.64</td>
<td>0.64</td>
<td>0.64</td>
</tr>
<tr>
<td>5</td>
<td>1.46</td>
<td>1.22</td>
<td>0.97</td>
<td>0.95</td>
<td>0.94</td>
<td>0.93</td>
<td>0.92</td>
<td>0.92</td>
</tr>
<tr>
<td>6</td>
<td>2.25</td>
<td>1.85</td>
<td>1.63</td>
<td>1.57</td>
<td>1.52</td>
<td>1.47</td>
<td>1.43</td>
<td>1.39</td>
</tr>
</tbody>
</table>

Table 9: Steady state yield by age for of dynamic fisheries at the steady state, relative to the myopic fishery’s steady state (price per kilogram increasing). The number in each cell indicates the percent difference in dynamic steady state yield for a given age, relative to the myopic steady state yield for that age. δ refers to the discount rate of the dynamic fishery manager.

<table>
<thead>
<tr>
<th>Age</th>
<th>δ =0.00</th>
<th>δ =0.01</th>
<th>δ =0.02</th>
<th>δ =0.03</th>
<th>δ =0.04</th>
<th>δ =0.05</th>
<th>δ =0.06</th>
<th>δ =0.07</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>4.64%</td>
<td>0.36%</td>
<td>7.15%</td>
<td>11.02%</td>
<td>14.74%</td>
<td>18.44%</td>
<td>22.13%</td>
<td>25.83%</td>
</tr>
<tr>
<td>4</td>
<td>21.17%</td>
<td>2.34%</td>
<td>11.29%</td>
<td>16.96%</td>
<td>22.62%</td>
<td>28.34%</td>
<td>34.13%</td>
<td>40.00%</td>
</tr>
<tr>
<td>5</td>
<td>76.94%</td>
<td>49.55%</td>
<td>7.77%</td>
<td>6.98%</td>
<td>8.11%</td>
<td>9.70%</td>
<td>11.47%</td>
<td>13.31%</td>
</tr>
<tr>
<td>6</td>
<td>20.63%</td>
<td>9.77%</td>
<td>-1.66%</td>
<td>-3.41%</td>
<td>-4.76%</td>
<td>-6.01%</td>
<td>-7.22%</td>
<td>-8.41%</td>
</tr>
<tr>
<td>net</td>
<td>36.56%</td>
<td>20.62%</td>
<td>1.66%</td>
<td>0.56%</td>
<td>0.27%</td>
<td>0.18%</td>
<td>0.16%</td>
<td>0.19%</td>
</tr>
</tbody>
</table>

3 Discussion

As a result of intense fishing pressure, which is believed to outstrip natural selection by up to 400% (Jørgensen et al. 2007, Swain et al. 2007), fisheries induced evolution is occurring at a rapid rate. Often the result of fisheries induced evolution is appreciable within only a few generations, or even in a matter of years (Devine et al. 2012, Stockwell et al. 2003, Haugen and Vøllestad 2001, Conover and Munch 2002). The short timeframe within which fisheries induced evolution can be appreciated stresses the relevance of the results of this paper. The results show that if the dynamic fishery manager has a low discount rate (less than 4%) there are significant steady state profit gains to including fisheries induced evolution in the fishery management decision framework (up to 29%; table 2). This result persists when large fish sell for more per kilogram on the market than small fish, but the range of discount rates is narrower (less than 2%) while the steady state profit gained is potentially larger (up to 34%) since the value of large fish, and thus the gains to mitigating fisheries induced evolution, is increased (table 6). These results suggest that the benefit of accounting for fisheries induced evolution to the net present value of the fishery will be highest when the discount rate is low, and that fisheries induced evolution is likely an important fishery externality to consider.

At higher discount rates, the effect of valuing the future less (and thus leaving less stock for the steady state) on steady state profit outstrips the effect of ignoring evolution, since the myopic fishery essentially has a 0% discount rate. This results in a net decrease in steady state profit when the dynamic fishery manager’s steady state is compared to the myopic steady state. It is important to keep in mind that the net present value of the fishery is necessarily higher when the fishery is dynamically optimized, so long as the fishery manager is using the appropriate discount rate in their calculations. The fact the steady state results depend so much on the discount rate highlights the importance of modeling this fishery in a fully dynamic model in order to ascertain the magnitude of the benefit to including fisheries induced evolution in the management framework.
When we consider other measures of fishery health and productivity (such as maturation rate, biomass, and yield), the results are generally similar to what is found in the profit comparison. If the dynamic fishery manager has a low discount rate the dynamic steady state maturation rate is slower than the myopic steady state maturation rate (tables 3 and 7) and net biomass is larger than at the myopic steady state (tables 4 and 8). The difference between the dynamic and myopic steady state maturation rates implies that, if the discount rate is low enough, it might be best to mitigate the amount of evolution that occurs in a fishery. This is important to consider since fisheries induced evolution is extremely slow to reverse, and so failing to mitigate the evolution of earlier maturation rates would result in a virtually irreversible loss to fishery profitability (Law and Grey 1989, Enberg et al. 2009). Additionally, all else equal, less evolution is likely better as fisheries induced evolution drives the population away from the natural optimum, which may have a negative impact on the population that would be difficult to model or predict.

While both maturation rate and biomass are only ‘better’ (slower and larger, respectively) when the discount rate is sufficiently low, the annual yield of the dynamic fishery is greater than that of the myopic fishery for all of the discount rates considered (tables 5 and 9). This is a particularly surprising result when discount rates are high since, under those conditions, the biomass of the dynamic fishery is lower than the myopic. The increased yield, along with the differences in steady state effort and mesh size (tables 2 and 6) suggests a rather surprising result: that mitigating evolution and maximizing yield can be complementary objectives. As the discount rate increases, steady state fishing pressure increases since the future is valued less and so the fishery manager will leave less stock for the future. Since a decrease in mesh size decreases the amount of evolution that occurs for a given amount of effort (figure 4), the decrease in mesh size that occurs as a result of increasing discount rate not only increases harvest rate but also decreases the amount of evolution towards early maturation rate that occurs in the fishery.

Unfortunately, while the results in this paper do suggest that fishery induced evolution is an important factor to include in fishery management, they are not easily translated into management advice. Whether effort should be decreased or increased depends on the discount rate of the fishery manager, and at what discount rate at which that switch occurs depends on the economic and population characteristics of the fishery.

It is tempting to conclude that mesh size should be smaller, since the dynamic fishery manager always chooses a smaller mesh size than the myopic. This is perhaps the closest thing to a ‘rule of thumb’ that can be taken from the results, however not without caveats. The way I modeled the myopic fishery manager was a rather conservative ‘status quo’, which was done in order to be able to attribute the differences between the steady states to accounting for evolution in the management framework. In reality, many fisheries have less efficient or less obvious management goals: many fisheries aim to harvest the maximum sustainable yield, for example, and most include cultural considerations when deciding policy. In the NEA Cod fishery, which this model is based on and for most purposes is very well managed, the minimum mesh size of 130mm (ICES 2014). This is smaller than the dynamic or myopic steady state mesh size for any of the discount rates and price structure combinations considered which ranged from 142mm to 149mm. More importantly, it would be unwise to base a ‘rule of thumb’ for either effort or mesh size based on the optimum steady state, since the optimum trajectory which leads to the steady state is unknown.

Future research includes modeling this problem as a fully dynamic optimization, in order to be able to give the best advice to fishery managers. Work that accounts for environmental stochasticity, climate change, and natural selection, will be important in understanding how, and whether, fisheries induced evolution should be considered by the fishery manager. Such processes could add additional costs (or benefits) to the evolution of earlier maturation rates (such as creating fish that are ill-suited for the
References


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