# The Potential Role of Management Regulations in Controlling Consumer Exposure to Contaminated Fishery Products

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## INTRODUCTION

The widely publicized mercury poisoning incident in Japan's Minamata Bay, and the resulting health impacts, ignited a public interest in the consumption of mercury contaminated fish. Mercury is a persistent metal that is distributed throughout the environment and originates from both natural sources (e.g. volcanoes) and human activities (e.g. burning coal and mining). Its organic form, methylmercury, accumulates in the tissues of fish and, once ingested, can cause irreversible human health effects (U.S. EPA 2001). Mercury has been found in many fish species throughout world, and dietary intake through fish consumption is the dominant source of mercury exposure for the general population. Fish consumption has been linked to elevated mercury levels in humans (Bjornberg et al. 2003; Schober et al. 2003). The human nervous system is very sensitive to all forms of mercury, and exposure to high levels of methylmercury can permanently damage the brain, kidneys, and developing fetus (ATSDR 1999).

The deleterious health impacts that may result from mercury exposure have led to considerable efforts to reduce the levels that reach the population. These efforts have focused primarily on the issuance of consumption advisories and on long-term pollution reduction. Consumption advisories are recommendations for voluntary action, informing the public that excessive concentrations of chemical contaminants have been found in local fish. These advisories may include recommendations to limit or avoid eating certain fish species or fish caught in specific water bodies. An advisory may be issued for the general population or for sensitive subpopulations such as pregnant women, nursing mothers, and children (U.S. EPA 2005). Consumption advisories are only successful in reducing exposure if consumers are aware of the advisory and respond in the appropriate manner. However, consumer response to advisories is often unpredictable.

While almost all fish contain traces of methylmercury, larger fish that have lived longer have the highest levels due to the persistent and bioaccumulative nature of this contaminant (U.S. EPA 2004b). The 2004 joint federal advisory issued by the U.S. EPA and the Food and Drug Administration (FDA) advises pregnant women, women who may become pregnant, nursing mothers, and young children to avoid consumption of shark, swordfish, tilefish and king mackerel and limit albacore tuna consumption due to high mercury levels. Not coincidentally, these are all large predatory fish. Recent studies have examined the relationship between fish size and mercury concentration in a variety of species from various waterbodies and found a significant positive relationship. Examples include king and spanish Mackerel in the Atlantic and Gulf of Mexico (Adams and McMichael, 2007), swordfish and bluefin tuna from the Mediterranean Sea (Storelli and Marcotrigiano, 2001), tunas from offshore waters of the Florida Atlantic Coast (Adams 2004), swordfish, yellowfin and skipjack tuna, wahoo, and dolphinfish in the Indian Ocean (Kojadinovic et al. 2006), and various commercially important species in Japan, including bluefin tuna (Yamashita, Omura, Okazaki 2005).

The U.S. Environmental Protection Agency (EPA) has made it a priority to reduce risks to human health and the environment from existing and future exposure to priority pollutants, such as mercury (U.S. EPA 2004a). The EPA has taken considerable action to reduce mercury pollution, including issuing stringent regulations for industries that contribute to U.S. mercury emissions. While the aim is to significantly reduce the new deposition of mercury into the environment, its persistence makes it likely that mercury will remain in the nation's fish stocks indefinitely, even as emissions are greatly reduced. Attempts to limit exposure to mercury through normal regulatory emissions controls is confounded by uncertainty concerning the relative importance of anthropogenic versus natural sources and the lack of quantitative estimates of the relationship between mercury deposition and mercury concentrations in fish (U.S. EPA 1997). This latter point is highlighted by the fact that, although U.S. mercury emissions have been greatly reduced since 1990, levels of methylmercury in seafood have not changed substantially over recent decades. Since the available evidence suggests that even deep cuts in domestic mercury emissions are unlikely to bring benefits to public health or ecosystems (Lutter and Irwin 2002), alternative approaches may be needed in order to reduce the public's long-term exposure beyond that achieved through voluntary responses to health advisories. Health advisories themselves are problematic in that an advisory can only be effective if consumers are aware of it and are willing and able to translate that awareness into behavior. For example, Shimshack et al. (2004) examined response to the 2001 FDA methylmercury fish advisory and found that a large group of at-risk consumers (infants, small children, pregnant or nursing mothers, and women who may become pregnant) did not respond to the advisory, particularly in the case of less educated and less informed consumers. Alternative approaches may be needed in order to reduce the public's long-term exposure beyond that achieved through voluntary responses to consumption advisories. One potential alternative that has not yet been considered is to reexamine the way size-based fisheries management is conducted.

As currently implemented, most management plans focus on supporting recruitment to the fish stocks and survival to reproductive age by imposing minimum size limits on captured fish. The bioaccumulative property of mercury often results in a positive relationship between fish size and the levels of mercury concentration, thus paradoxically leading to a situation where management plans designed to protect stocks for ecosystem purposes and for future human use may actually increase the levels of mercury exposure experienced by consumers. At the current time, no pre-harvest methods are used to control the amount of contaminants that reach commercial fish consumers. While a complete ban on the harvesting of a contaminated species is conceptually possible (although unlikely), an alternative might be a more directed, size-based management scheme that explicitly accounts for the economic and public health dynamics of harvesting in the presence of mercury contamination. Intuitively, this approach might require the harvesting of younger, smaller fish with the goal of allowing older, larger fish to serve as both a breeding stock and contaminant sink. The development and analysis of an empirical bioeconomic model for king mackerel (*Scomberomorus cavalla*), a mercury plagued species, is used to investigate these issues, in the process combining the complex sets of population and toxicology information necessary for analyzing the relevant economic tradeoffs.

## THE KING MACKEREL FISHERY

King mackerel is a coastal pelagic that is distributed in the western Atlantic and in the Gulf of Mexico and Caribbean Sea, with substantial commercial and recreational catches occurring in U.S. waters. In the southeast U.S., king mackerel is currently managed under the Coastal Migratory Pelagic Species Fishery Management Plan (FMP). The FMP recognizes two stocks for the purpose of management (Gulf migratory stock and Atlantic migratory stock). Management under the two-group model is complicated due to migrations within the Gulf of Mexico group and the mixing that occurs between the Atlantic and Gulf populations during the winter. The Atlantic migratory stock management area extends from New York to Florida while the Gulf migratory group management area extends from Florida to Texas. For management and assessment purposes, a mixing zone was specified off southeast Florida to assign stock identity to landings captured there (Figure 1). The mixing zone boundaries are defined by the

Volusia\Flagler County border on the east coast of Florida and the Monroe\Collier County border on the southwest coast in Florida. Landings taken in this zone from April 1 to November 31 are attributed to the Atlantic stock, while landings taken in this zone from December 1 to March 31 are attributed to the Gulf stock, despite information suggesting that the Atlantic stock likely contributes a significant percentage of winter landings taken there (DeVries et al. 2002, Fable 1990, Patterson et al. 2004, Sutter et al. 1991).

King mackerel are managed through a total allowable catch (TAC) calculated for each migratory group and allocated to harvesters based on FMP requirements. Commercial fisheries are typically managed through quotas, possession and trip limits, size limits, and seasonal closures, while recreational fisheries are typically managed through possession limits and size limits. Limited entry restrictions are in effect for commercial and charter and headboat fisheries. Modifications to TACs and framework adjustments such as trip limits, size limits, and seasonal closures are addressed and documented through regulatory amendments promulgated by the Councils. The most recent framework adjustment for the Gulf Migratory group of king mackerel, approved in 2003, maintained the status quo TAC of 10.2 million pounds with 3.26 million pounds allocated to the commercial sector. The commercial TAC was allocated by geographic zones and gear types, and restricted by trip limits and seasonal closures specific to each zone and gear. The Gulf group king mackerel fishery opens with a new quota every year on July 1. The most recent framework adjustment for the Atlantic Migratory group of king mackerel was approved in 2000. It increased the TAC to 10.0 million pounds, with 3.71 million pounds allocated to the commercial fishery. Commercial fisheries are restricted by a 3,500 pound trip limit from New York to the Brevard\Volusia County line in Florida, 50 fish from that line south to the Dade\Monroe County line in Florida, and 1,250 pounds in Monroe County.[1] Regulations for both migratory groups currently require a minimum size limit of 24 inches for each fish harvested.

The majority of commercially caught king mackerel are landed off the coast of Florida in the mixing zone. Commercial landings of king mackerel have fallen from their early 1980s levels and the gears used to harvest king mackerel have changed in importance over time. For the Gulf of Mexico, gillnet landings previously accounted for more than half of the commercial harvest,

[1] The current management routine for king mackerel is complex. In addition to the changing regulatory boundaries already discussed, trip limits for some areas are defined in terms of numbers of fish while others are defined in terms of catch weight in ponds.

but in recent years have accounted for only ten to twenty percent of the landings (primarily due to increased restriction on gillnet use because of its nonselective nature) (SEDAR16 2009). Hook and line gear now accounts for the majority of commercially landed king mackerel in U.S. waters.

The choice of king mackerel for this study was prompted by a number of factors. Each of the mackerel fisheries is considered to be biologically distinct with the exception of the mixing interface off of south Florida. Both stocks are currently considered to be recovered from overfishing and, as previously mentioned, are managed through a TAC that divides the harvestable stock between recreational and commercial interests (SEDAR16 2009). Given the current level of management intervention, these fisheries are relatively well documented, both with respect to their biological characteristics and incidence of mercury contamination. Mercury levels in king mackerel harvested off Florida's Atlantic coast and in the Gulf of Mexico ranged from less than 0.5 ppm for individuals with fork lengths of 600 mm to over 3.0 ppm for individuals with fork lengths approaching 1.2 meters (Axelrad et al. 2004). Similarly, Atlantic king mackerel off the coast of Georgia, South and North Carolina were found to contain mercury levels as high as 3.5 ppm (Bender 2003). Given the U.S. Food and Drug Administration's recommended current action exposure level of 1.0 ppm (U.S. FDA 2001), these levels of contamination have prompted the issuance of consumption advisories by most of the states bordering the Atlantic Ocean and Gulf of Mexico. Additionally, the Southeast Data, Assessment, and Review (SEDAR) conducted a stock assessment of the Atlantic and Gulf of Mexico migratory groups of king mackerel in 2008. This current biological data is available for use in constructing a bioeconomic model. In addition, the current active management of the fishery provides real-world relevancy for the project and the opportunity to demonstrate how public health risks can be incorporated into management strategies to minimize mercury exposure.

## THE BIOECONOMIC MODEL

Historically, the main priority in fisheries management has been to maintain fish stocks (Grafton et. al 2006) although protecting the economic position of specific groups in the fishery is sometimes a consideration (Anderson 1977). Fishery economists and policymakers have been concerned with control of total catch in order to avoid excessive harvesting of common property resources (Schott 2001). Common management strategies include size, gear and effort restrictions, quotas, closed areas, shorter seasons, and limited entry.

Bioeconomic models provide an integrated approach to evaluate alternative fishery management strategies (Thunberg, Helser, and Mayo 1998). Fishery bioeconomic models combine models of fish biology, or population dynamics, with an economic model of the fishery. The most commonly used models of fish biology in the economic study of commercial fisheries are the lumped-parameter models of Gordon (1954) and Schaefer (1954) and the Ricker (1958) and Beverton-Holt (1957) age-structured models. The lumped-parameter models, also known as single cohort models, track one age class through time without distinguishing between age classes. A single cohort model, although analytically and empirically more tractable, is unsuited for this study because of the need to explicitly model the variations in contamination and harvestability across age classes. Multiple cohort, or age-structured, models are more applicable for studying many management problems because they track more than one cohort through time and can explicitly distinguish the varying characteristics of each cohort (Schott 2001).

Dynamic age-structured models are the preferred approach to evaluate the impacts of management policies that affect a subset of cohorts, provided that detailed stock information is available (Lee, Larkin and Adams 2000). Recent studies that utilize dynamic age-structured models include Thunberg, Helser, and Mayo (1998), Lee, Larkin and Adams (2000), Bertignac et al. (2000), Pintassilgo and Costa Duarte (2002), Bjørndal, Ussif, and Sumaila (2004), and Kulmala et al. (2008). It is from this literature base that a conceptual multiple cohort model was developed for this study, incorporating not only varying contamination characteristics by age/size class, but also temporal and (to some extent) spatial variability in fishing mortalities.

**Population Dynamics**

An age-structured population dynamics model includes three basic components: recruitment, mortality and individual fish growth (Quinn and Deriso 1999). This section presents the equations for a discrete time biological model of the Atlantic and Gulf of Mexico king mackerel fisheries that reflect the dynamics of the stocks as a result of mortality, reproduction, and growth.

The king mackerel population is distributed in age classes, beginning at age 0, with the time step being one year. The terminal group is age 11, and is calculated as an accumulator age class where all fish age 11 years and older are pooled together.[2] The year-to-year change in the number of fish in a cohort, or age class, depends on instantaneous fishing and natural mortality rates. Natural mortality refers to all deaths that are not a result of fishing, including predation, pollution, and senility, while fishing mortality refers to removals from the stock due to harvesting. The time-dynamics of the cohorts are modeled using the exponential decline function:

$$(1)\qquad N_{s,a,t} = \begin{cases} N_{s,a-1,t-1} e^{-Z_{s,a-1,t-1}} & for\, a = 1,2,...,10 \\ N_{s,10,t-1} e^{-Z_{s,10,t-1}} + N_{s,11,t-1} e^{-Z_{s,11,t-1}} & for\, a = 11 \end{cases}$$

$$(2)\qquad Z_{s,a,t} = M_{s,a} + F_{s,a,t}$$

where $N_{s,a,t}$ is the number of fish of age *a* at the beginning of year *t* in stock *s* (s=Atlantic, Gulf), $Z_{s,a,t}$ is the total instantaneous mortality rate of fish of age *a* during year *t* for stock *s*, $M_{s,a}$ is the instantaneous rate of natural mortality on fish of age *a* for stock *s*, and, $F_{s,a,t}$ is the total instantaneous fishing mortality rate of fish of age *a* during year *t* for stock *s*. The number of fish in each cohort in the initial year, denoted $N_{s,a,0}$, are assumed known at the beginning of a simulation.

In addition to accounting for losses due to natural and fishing mortality, it also necessary to account for recruitment of new fish to the stock. Recruitment is often assumed to be a function of the spawning stock, or the fish in a stock that are old enough to reproduce. In particular, the commonly used Beverton and Holt (1957) stock recruitment function relates the number of recruits in a year to the previous year's spawning stock fecundity:

$$(3)\qquad N_{s,0,t} = \frac{\alpha_s SSF_{s,t-1}}{(\beta_s + SSF_{s,t-1})}$$

$$(4)\qquad SSF_{s,t} = \sum_{a=1}^{11} Mat_{s,a} N_{s,a,t} Fec_{s,a} Fem_{s,a,t}$$

where $N_{s,0,t}$ is the number of recruits (age-0 fish) in year *t* for stock *s*, $SSF_{s,t-1}$ is the spawning stock fecundity in year *t-1* for stock *s*, $Mat_{s,a}$ is the proportion of age *a* fish in stock *s* that are mature enough to spawn, $N_{s,a,t}$ is the number of fish of age a at the beginning of year *t* in stock *s*, and $Fec_{s,a}$ is the fecundity or number of eggs produced by a fish of age *a* in stock *s*, and $Fem_{s,a,t}$

[2] The use of an accumulator age class, often called a plus group, is common in fisheries models. Scientists define a plus group based on the ability to predict age from length, which becomes more difficult in older fish that may not exhibit much change in length as they age, or based on the age above which very few individuals appear in the data set (Cooper 2006).

is the proportion of age *a* fish in year *t* from stock *s* that are female. $\alpha_s$ and $\beta_s$ are positive recruitment function parameters for the stock *s*.[3]

The model also tracks the biomass, or total weight of the stock. Biomass is important in fisheries models because it is often used to determine the status of a stock. It is calculated by taking the number of fish in each age class, multiplying by the weight at age, and then summing across ages as follows:

$$B_{s,t} = \sum_{a=0}^{11} N_{s,a,t} \cdot W_{s,a,t} \tag{5}$$

where $B_{s,t}$ is the biomass of stock *s* in year *t*, $N_{s,a,t}$ is the number of fish of age a at the beginning of year *t* in stock *s*, and $W_{s,a,t}$ is the average weight of an individual fish of age *a* in year *t* for stock *s*.

Total removals from the stock are accounted for in equation 1, but it is also necessary to separate the removals due only to fishing. Catch is modeled as a function of fishing mortality, total mortality, and numbers of fish:

$$CN_{s,a,t} = \frac{F_{s,a,t} \cdot N_{s,a,t}}{Z_{s,a,t}} \left(1 - e^{-Z_{s,a,t}}\right) \tag{6}$$

where $CN_{s,a,t}$ is the number of age *a* fish caught in year *t* from stock *s*, $F_{s,a,t}$ is the total instantaneous fishing mortality rate of fish of age *a* during year *t* for stock *s*, $N_{s,a,t}$ is the number of fish of age *a* at the beginning of year *t* in stock *s*, and $Z_{s,a,t}$ is the total instantaneous mortality rate of fish of age *a* during year *t* for stock *s*. It is also useful to have a measure of the total weight of the fish caught. This is modeled as:

$$C_{s,t} = \sum_{a=0}^{11} CN_{s,a,t} \cdot W_{s,a,t} \tag{7}$$

where $C_{s,t}$ is the total weight of all fish caught in year *t* from stock *s*, $CN_{s,a,t}$ is the number of age *a* fish caught in year *t* from stock *s*, and $W_{s,a,t}$ is the weight of an age a fish in year *t* from stock *s*. Equations 6 and 7 account for all removals of the stock due to fishing. This includes both commercial and recreational king mackerel fishing as well as dead recreational discards and

[3] The Beverton-Holt recruitment function is often reparameterized for estimation and interpretation purposes as illustrated in Haddon (2001). In the form of equation 3, the parameter $\alpha$ is the maximum number of recruits produced and $\beta$ is the spawning stock needed to produce an average recruitment equal to half of the maximum, although their interpretation is not vital to this research.

bycatch from the shrimp (and other) fishing industry. While this measure of fishing mortality is vital for tracking the overall dynamics of the stock, it is also necessary to explicitly model the commercial catch. To accomplish this, total fishing mortality $F$ is partitioned into commercial fishing mortality and the remaining fishing mortality due to recreational fishing and bycatch:

(8) $$F_{s,a,t} = FComm_{s,a,t} + FRem_{s,a,t}$$

where $F_{s,a,t}$ is the total instantaneous fishing mortality rate of fish of age $a$ during year $t$ for stock $s$, $FComm_{s,a,t}$ is the instantaneous fishing mortality rate of fish of age $a$ resulting from commercial king mackerel fishing activity during year $t$ for stock $s$, and $FRem_{s,a,t}$ is the remaining instantaneous fishing mortality rate of fish of age $a$ during year $t$ for stock $s$. $FRem_{s,a,t}$ accounts for aggregate stock removal resulting from the recreational king mackerel fleet, including dead discards, and bycatch of king mackerel occurring in fishing activities targeting other species.

The partitioned fishing mortality can be used to model commercial catch. Substituting equation 8 into equation 6 into yields:

(9) $$CN_{s,a,t} = \frac{(FComm_{s,a,t} + FRem_{s,a,t}) \cdot N_{s,a,t}}{Z_{s,a,t}} \left(1 - e^{-Z_{s,a,t}}\right)$$

Rearranging equation 9 allows the partition of total catch into that of commercial catch plus the remaining catch from recreational catch and bycatch:

(10) $$CN_{s,a,t} = \frac{FComm_{s,a,t} \cdot N_{s,a,t}}{Z_{s,a,t}} \left(1 - e^{-Z_{s,a,t}}\right) + \frac{FRem_{s,a,t} \cdot N_{s,a,t}}{Z_{s,a,t}} \left(1 - e^{-Z_{s,a,t}}\right)$$

Equations 11 and 12 then give the commercial catch in numbers and weight, respectively:

(11) $$CommCN_{s,a,t} = \frac{FComm_{s,a,t} \cdot N_{s,a,t}}{Z_{s,a,t}} \left(1 - e^{-Z_{s,a,t}}\right)$$

(12) $$CommCW_{s,t} = \sum_{a=0}^{A} CommCN_{s,a,t} \cdot W_{s,a,t}$$

where $CommCN_{s,a,t}$ is the number of age $a$ fish commercially caught in year $t$ from stock $s$ and $CommCW_{s,a,t}$ is the total weight of the commercial catch in year $t$ from stock $s$.

The population dynamics parameters were obtained from the latest king mackerel stock assessment as outlined in the SEDAR 16 Stock Assessment Report (SEDAR16 2009). The stock assessment makes use of Virtual Population Analysis (VPA) to estimate the yearly numbers of fish in each age class ($N_{s,a,t}$ ) and the annual fishing mortality at age ($F_{s,a,t}$). VPA is a commonly used modeling technique that reconstructs historical fish numbers at age through backward projections. VPA assumes that catch at age is known with certainty for all years covered by the stock assessment and requires "tuning" through the incorporation of relative indices of abundance during the estimation process (Butterworth and Rademeyer 2008) [4]. While classical VPA is not a statistical analysis, it serves as a basis for the adaptive framework VPA (ADAPT) that is used in the king mackerel stock assessment (Lassen and Medley 2001). ADAPT, introduced by Gavaris (1988), is one of the most popular tuning models and involves the minimization of the sum-of-squares over any number of indices of abundance to find best-fit parameters (Lassen and Medley 2001). The VPA base model parameters were used for the Atlantic stock, while the VPA final model results were used for the Gulf stock.[5]

It should be noted that because of management definitions, the stock assessment used fishing year rather than calendar year. The fishing year in the Gulf runs from July 1 to June 30 of the following year while in the Atlantic it runs from April 1 to March 31 of the following year. For notational purposes in this study, the fishing year 1981 refers to the fishing season from April 1, 1981 to March 31, 1982 for the Atlantic stock and the season from July 1, 1981 through June 30, 1982. In addition, it must be noted that the stock assessment (upon which this study is based) was carried out under the assumption that fifty percent of the catch in the mixing zone during the winter months (November 1-March 31) belonged to the Gulf stock and fifty percent to the Atlantic stock. The catch-at-age information used as an input into the ADAPT model was constructed under this assumption, and the resulting output therefore accounts for this assumption. Given that the mixing is mostly limited to southern Florida, it was not possible to explicitly model the migrations without assuming that the mixing could occur anywhere throughout the Gulf and Atlantic regions (SEDAR16 2009).

The remaining population dynamics parameters needed for the model (natural mortality at age for each stock $M_{s,a}$, the Beverton-Holt stock recruitment parameters $\alpha_s$ and $\beta_s$, and weights-at-age, $W_{s,a,t}$) were used as inputs in the VPA analysis and were taken from the Final Stock Assessment Report (SEDAR16 2009). Given the lack of availability of more detailed information, it was assumed that 50% of the fish in each age class during each year are female

[4] Tuning a model involves adjusting parameter estimates to minimize differences between predicted population catches and observations from indices of population abundance (NRC 1998).

[5] This is only because a final model was not presented for the Atlantic stock in the latest stock assessment report. It is worth noting that the differences in output from the Gulf base and final models are small.

for both stocks.

While most of the required population dynamics parameters were easily obtained from the 2009 stock assessment report, annual commercial fishing mortality at age for each stock ($FComm_{s,a,t}$) was not readily available. The fishing mortality for a particular fleet can be separated into an age effect (selectivity of the fishery) and a year effect (intensity of the fishing mortality) (Fournier and Archibald 1982; Deriso et al. 1985; Myers and Quinn 2002). Ideally, determining fishing mortality at age for the commercial king mackerel fleet requires information on selectivity at age and annual fishing mortality at maximum selectivity. While this information is available in stock assessments for some species, it is not for king mackerel. Consequently, an alternative method for determining commercial fishing mortality had to be devised.

The 2009 stock assessment report did not provide any information about the overall catch-at-age breakdown for the commercial king mackerel fishery, but partial catches at age were given for several of the tuning indices. For the commercial fisheries, partial catches at age were given for the Gulf of Mexico logbook index and the North Carolina Trip Ticket index[6]. Assuming that catches from the logbooks and trip tickets are accurate representations of the fishing activity throughout the Gulf and Atlantic, then that data can be used to determine the commercial catch proportion by age for each stock. Given that the total commercial catch for each stock is known, this information can be combined with weights at age for each stock to generate an estimate of the total number of king mackerel commercially caught from each stock:

$$(13) \qquad CommCN_{s,t} = \frac{CommCW_t}{\sum_{a=0}^{11} \rho_{s,a,t} W_{s,a,t}}$$

where $CommCN_{s,t}$ is the total number of commercially caught fish in year $t$ from stock $s$ and $CommCW_{s,t}$ is the total weight of the commercial catch in year $t$ from stock $s$, $\rho_{s,a,t}$ is the proportion of age $a$ fish commercially caught from stock $s$ during year $t$, and $W_{s,a,t}$ is the weight of an age $a$ fish in year $t$ from stock $s$. Commercial fishing mortality at age can then be calculated as:

$$(14) \quad FComm_{s,a,t} = \frac{Z_{s,a,t} \rho_{s,a,t} CommCN_{s,t}}{N_{s,a,t}\left(1 - e^{-Z_{s,a,t}}\right)}$$

[6] The North Carolina Trip Ticket index was chosen over the Atlantic logbook index for the Atlantic VPA model by the SEDAR assessment workshop.

where $FComm_{s,a,t}$ is the instantaneous fishing mortality rate of age *a* fish resulting from commercial fishing activity during year *t* for stock *s*, $Z_{s,a,t}$ is the total instantaneous mortality rate of age *a* fish during year *t* for stock *s*, $\rho_{s,a,t}$ is the proportion of age *a* fish commercially caught from stock *s* during year *t*, $CommCN_{s,t}$ is the total number of commercially caught fish in year *t* from stock *s*, and $N_{s,a,t}$ is the number of age *a* fish at the beginning of year *t* in stock *s*. Although this may not completely reflect the true catch at age distribution of the stock, it should be reasonably close.[7]

**Economic Model**

The economic submodel accounts for the revenues and costs of harvesting king mackerel and is defined in terms of commercial catch. A standard revenue function for the commercial fishery can be represented as:

(15) $$\mathrm{Re}v_{s,t} = P \cdot CommCW_{s,t}$$

where $\mathrm{Re}v_{s,t}$ is the revenue generated in year *t* by catches from stock *s*, $P$ is the average unit ex-vessel price for king mackerel, and $CommCW_{s,a,t}$ is the total weight of the commercial catch in year *t* from stock *s*.[8] The National Marine Fisheries Service (NMFS) maintains the Accumulated Landings System (ALS) database of monthly landing and the value of these landings for a variety of species. The ALS database[9] was used to calculate an average ex-vessel price of $1.49 per pound for king mackerel over the years 1999 to 2006. A single price was used for both stocks because of the difficulty brought about by the mixing zone and the way the biological model was defined and parameterized.[10] While some authors have included price-quantity relationships in their bioeconomic models (e.g., Thunberg, Helser, and Mayo 1998; Kennedy 1999), many studies assume constant prices, either because the fishery studied is a small fraction of the overall market (Bjorndal, Ussif and Sumaila 2004; Yew and Heaps 1996; Amundsen, Bjorndal, and Conrad 1995) or due to the lack of adequate data (Pintassilgo and

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[7] Given that there is no way to know with certainty the true catch distribution, this process at a minimum allows a baseline (if not the true baseline) to be determined against which alternative harvesting patterns can be compared.
[8] This formulation of the revenue function implicitly assumes that prices are not a function of the distribution of size or quality of the fish caught. There was no available data for king mackerel that distinguishes price by size class.
[9] Source: http://www.st.nmfs.noaa.gov/st1/commercial/
[10] Recall that the population dynamics model makes use of parameters generated under the assumption that 50% of the winter mixing zone catches are from the Atlantic and not under the FMP assumption that attributes them all to the Gulf stock. Therefore, a fish caught in the mixing zone in the winter could be from either stock and trying to assign prices based on stocks is impossible given the lack of catch-specificity in the data.

Duarte 2002; Kulmala, Laukkanen, and Michielsens 2008). An unpublished analysis of the demand for king mackerel (Vondruska 1999) suggests that the constant price assumption is reasonable in this case, as demand was found to be highly elastic with respect to price.[11] Additionally, an examination of the relationship between king mackerel price and quantity landed from 1977-2007 revealed no significant relationship.[12]

The link between the population dynamics and economic model is a Cobb Douglas harvest function relating catch to fishing effort and biomass. Fishing effort is simply a measure of the amount of fishing and is expressed in a variety of terms in the fishery economics literature. Commonly used measures include fishing days, gear days, days at sea, or number of trips. The harvest function for this study is given by

(16) $$CommCW_{s,t} = q_s E_{s,t}^{\phi_s} B_{s,t}^{\gamma_s}$$

where $CommCW_{s,t}$ is the total weight of all fish caught in year *t* from stock *s*, $q_s$ is the catchability coefficient for stock *s*, $E_{s,t}$ is the fishing effort exerted on stock *s* in year *t*, $B_{s,t}$ is the biomass of stock *s* in year *t*, $\phi_s$ is the catch-effort elasticity for stock *s*, and $\gamma_s$ is the catch-stock elasticity for stock *s*. Harvest functions of this type are often used for schooling species like mackerel (Kennedy 1992; Bjorndal 1988; Pintassilgo and Duarte 2002). Additionally, this form of the harvest function relates commercial catch to a measure of effort that can be evaluated in economic terms (Pintassilgo and Duarte 2002). Thus, given an estimate of the commercial catch weight, equation 16 allows for the calculation of an estimate of fishing effort that can ultimately be used in a cost equation.

Data used to estimate the harvest function was obtained through the Coastal Logbook database maintained by NMFS. The database includes a unique trip identifier, landing date, fishing gear deployed, areas fished, number of days at sea, number of crew, species caught, whole weight of the landings, and gear specific fishing effort. In the case of hook and line fisheries, these effort measures include number of lines fished, number of hooks per line and

[11] The referenced study estimated that if landings of king mackerel were reduced by 1 million pounds, ex-vessel price would only increase by 2 cents per pound. It should be noted that Vondruska acknowledged uncorrected problems of serially correlated residuals in his models. His findings, however, were consistent with those in an earlier unpublished work by Easley et al. (1993) who used an autoregressive procedure to address the problem.
[12] An early study of the king mackerel pricing system by Prochaska (1979) found that a change in landings of 1 million pounds resulted in a 7 cent change in price. However, this study was conducted when the industry was much larger than it is today, and the results are not directly meaningful to this research. Additionally, the scenarios presented in this research sought to minimize overall changes in commercial catch.

estimated total fishing time. Collection of effort data on the logbook form began in 1998 for king mackerel and, for the purposes of this study, extended through the year 2006. Biomass estimates were calculated from the numbers-at-age and weights-at-age for each migratory group given in the SEDAR 16 Final Stock Assessment Report (2009). The data available for estimation therefore consisted of 9 years of observations (1998-2006).

Only trips that reported one area and one gear fished were included in the analysis.[13] Additionally, data were limited to catch and effort measures reported from vessels that had king mackerel as its primary harvested species (i.e. king mackerel accounted for the greatest percentage of catch on that trip) and that utilized hook and line gear. Clear outliers in the data were also excluded from the analyses, including trips reporting more than seven lines fished, 20 hooks per line fished, more than 10 days at sea, or more than 3,120 pounds of king mackerel landed.[14] Because the logbook only contains information from fishing trips taken by fishermen holding a federal fishing permit, it therefore does not contain all the king mackerel landings reported in the ALS data. For the purposes of this study, however, it was assumed that the information found in the logbook data could be extended to adequately represent non-federal permit holders who commercially fished for king mackerel.

The presence of a stock mixing zone off of the south coast of Florida presented additional problems for analyzing the commercial catch of king mackerel, as catches reported in the mixing zone during winter could belong to either the Atlantic or Gulf stock. Thus, the approach used in this study was to separate the logbook catch and effort data into three regions: the Atlantic, Gulf, and Mixing (defined in SEDAR16 2009). The mixing zone was further broken down into summer catches attributed entirely to the Atlantic stock, and winter catches that (for management purposes) are counted as Gulf catches. The data were then aggregated by year for each region. The ALS catch data for the same years was then broken down using the same process. The proportion of total catch accounted for by the logbook data was calculated for each group during each year, and used to scale effort to correspond with the ALS catch. In other words, if the 1999 logbook catches attributed to the Gulf represented 81% of the Gulf catch reported in the ALS, the corresponding logbook effort was divided by that proportion to obtain a scaled version of

[13] A single fishing trip may report multiple gears and multiple areas fished. In that case, it is difficult to assign catch and effort to specific gears or locations. Eliminating trips with more than one area or gear fished accounted for the removal of less than one percent of the available observations.

[14] These outlier values were used by McCarty (2008) in constructing a king mackerel tuning index using the coastal logbook data and were adopted here to allow for consistency with previous studies.

effort to use in the estimation.[15] The data were then aggregated by year for the Gulf and Atlantic stocks using the 50% winter mixing zone assumption employed by SEDAR 16. Gulf catch was calculated by summing Gulf catches and half the winter mixing zone catches from the ALS data set, while the Atlantic catch was determined by summing Atlantic catches, summer mixing zone catches, and half of the winter mixing zone catches for a given year. A similar approach was employed for the rescaled effort measures.

Given that the available data was limited, it was not feasible to estimate a separate harvest function for each migratory group (stock). Under the assumption that the catchability coefficient, catch-stock elasticity, and catch-effort elasticity were the same for both stocks, a single production function was estimated from the constructed data (2 stocks for each of 9 years, or 18 total observations). This approach was considered reasonable given that hook and line was the primary gear used throughout the king mackerel fishery for the years examined, thereby avoiding the specification problems that may have occurred with changing gears by stocks.

Hours fished was chosen as the measure of effort for the production (harvest) estimation after some experimentation with various effort metrics. Estimation then proceeded using the Gulf catch and effort data described above with the calculated Gulf biomass, and the Atlantic catch and effort data with the Atlantic biomass. Equation 16 was linearized by taking the natural log of both sides, and then estimated using OLS regression. While the overall model fit is rather low (implying the potential for better specifications, especially in terms of explanatory variables, if the data were available), the parameter estimates appear reasonable given previously reported values in the literature.

The catch-stock elasticity estimate of 0.2948 is in line with prior applied studies of schooling species that used constant elasticity production functions, most of which found very low catch-stock elasticities (Amunsden, Bjorndal, and Conrad 1995; Bjorndal 1988). Although Pintassilgo and Duarte (2002) note that catch-effort elasticities for schooling species are generally very close to one (Pintassilgo and Duarte 2002), the estimated result of 0.5256 does not seem unreasonable given that king mackerel are primarily harvested with hook and line gear and tend to strongly school only during migration. Under these conditions, an increase in effort, holding stock size constant, would be expected to lead to a less than proportional increase in

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[15] This rescaling was necessary because of the catch-effort elasticity parameter on effort in equation 16. In order to accurately estimate this relationship, it is important to have a measure of all of the effort.

catch. In the final analysis, the catch-effort and catch-stock relationships for any given species are empirical questions. Despite the limited data and low degree of fit, it was felt that the estimated parameters were preferred to the alternative used by Pintassilgo and Duarte (2002), where the catch-effort elasticity was assumed one, the catch-stock elasticity was assumed to be either 0.20 or 0.80 depending on the gear utilized, and then the catchability coefficient was calculated for the base year and assumed to hold for all remaining years.

Given the assumptions and estimates above, fishing costs can be modeled as a function of fishing effort, where the cost of fishing for king mackerel is represented as:

(17) $$Cost_{s,t} = cE_{s,t}$$

where $Cost_{s,t}$ is the variable cost of fishing from stock s in year t, *c* is the constant cost per unit of effort, and $E_{s,t}$ is the fishing effort exerted on stock *s* in year *t*. Fixed costs were not considered because modeling was not done at the vessel level and because most fleets pursue other species in addition to king mackerel, thus making the assignment of fixed cost to mackerel fishing problematic (Pintasilgo and Duarte 2002; Thunberg, Helser, and Mayo 1998). The assumption of constant cost per unit of effort is commonly used in the fishery economics literature (Kulmala, Laukken, and Michielsens 2008; Garza-Gil and Varela-Lafuente 2007; Bjorndal and Brasao 2006; Garza-Gil, Varela-Lafuente, and Suris-Regueiro 2003; Pintassilgo and Duarte 2002; Thunberg; Helser, and Mayo 1998)

Cost information was obtained from NMFS through the coastal logbook database. The logbook form was modified in 2002 to collect data on the variable expenditures associated with each fishing trip. Available data for years 2002 through 2007 included the amount and cost of fuel, ice, bait and groceries, along with the wages or shares for the crew and captain. As before, this study focused on catch and effort measures reported from vessels that had king mackerel as its primary harvested species and that utilized hook and line gear. Clear outliers in the data were again excluded from the analyses. Trip cost was calculated by summing labor cost, fuel cost, ice cost, bait cost, and groceries. This was divided by hours fished to obtain a cost per hour fished for each trip. The average cost per hour fished over the time period 2002-2007 was then calculated for the model ($25.60). As in the case of prices, the same cost is used for both migratory groups, a reasonable assumption given that most catches occur in the mixing zone and the gear used to target king mackerel is primarily hook and line for both stocks.

With the revenue and cost functions defined, the profit function can be described as:

(18) $$\pi_{s,t} = \mathrm{Re}v_{s,t} - Cost_{s,t}$$

where $\pi_{s,t}$ is the profit from commercial king mackerel fishing in stock *s* during year *t*. For all forward-looking simulations of the system, the profit was discounted over a study period of 25 years to obtain the net present value:

(19) $$NPV_s = \sum_{t=1}^{T} \left( \frac{1}{1+r} \right)^t \pi_{s,t}$$

where $NPV_s$ is the net present value of the fishery for stock *s*, $\pi_{s,t}$ is the profit from commercial king mackerel fishing in stock *s* during year *t*, and *r* is the discount rate. The discount rate chosen for this study was 5 percent, a value that is similar to those recently used by Bjorndal and Lindroos (2004), Bjorndal et al. (2004) , and Kulmala, Laukken, and Michielsens (2008).[16]

**Mercury Concentration Model**

One of the unique contributions of this research is the linking of species-specific mercury concentration information with a bioeconomic model of the commercial mackerel fishery. In order to accomplish this linkage, functional relationships need to be identified between biological stages of the fish and the degree to which mercury (in this case) has bioaccumulated over time. One approach for developing these linkages is to relate fish size with mercury concentration information. To do this, growth curves are presented for king mackerel that relate fish length to age, thus providing the backward linkage into the population dynamics model. Next the equations relating fish size to mercury concentration are presented, and then the relationship is extended to show mercury concentration by age class. Finally, the average mercury concentration for commercially caught king mackerel is determined.

King mackerel are assumed to grow according to a standard Von Bertalannfy growth function (as in SEDAR 16 Final Report 2009) such that

(20) $$FL_{s,a} = L_{\infty,s}[1 - e^{-K_s(a-a_{0,s})}]$$

[16] Given that this study focuses on how NPV might change given various regulatory changes, the exact discount rate used is not critical as long as the time dynamics of the regulatory impacts are similar across scenarios. To the extent that they are not, however, sensitivity analysis could be used to determine the impact of changing discount rates on implications of model results.

where $FL_{s,a}$ is the fork length (measured in centimeters) of an age *a* king mackerel from stock *s*, $L_{\infty,s}$ is the asymptotic length for stock *s*, $K_s$ is a positive parameter for stock s , and $a_{0,s}$ is the arbitrary origin of the growth curve for stock *s* (Beverton and Holt 1957). The estimation of the parameters in this model is discussed in Ortiz and Palmer (2008), and their parameter estimates for the Gulf and Atlantic groups are available in SEDAR 16 (2009). There are slight differences in the growth patterns between the two king mackerel stocks, with the Gulf group growing slightly larger. This is illustrated in Figure 2, along with the observation that king mackerel are fast growing fish, reaching the current minimum legal size limit of 24 inches at approximately 2 years of age.

Given the prevalence of mercury bioaccumulation in aquatic species, larger king mackerel would be expected to have greater concentrations of mercury. This has led many states to issue king mackerel consumption advisories to recreational fisherman based on the fork length of the fish caught.[17] In a recent study, Adams and McMichael (2007) examined mercury levels for king mackerel off the Gulf and Atlantic coasts of Florida and found a significant positive relationship between fish size and mercury concentration for king mackerel. They sampled 143 fish from the near and offshore waters of Florida's Atlantic coast and 136 from near and offshore waters of the Gulf coast of Florida. The Gulf king mackerel were found to contain significantly higher amounts of mercury than those in the Atlantic, with mean mercury levels in the sample of 0.94 parts per million (ppm) for the Atlantic waters and 1.51 ppm for the Gulf waters. All but a few of the fish sampled were above the minimum legal size limit. Linear and non-linear regressions were used to describe the relationships between king mackerel size and total mercury concentration. The estimations from that study, which will be used to quantify the relationship between king mackerel size and mercury concentration, are given below:[18]

(21) $$Hg_s = \begin{cases} 1.11 \cdot 10^{-7} FL_s^{3.51} & for s = Atlantic \\ e^{-3.09+.032 FL_s} & for s = Gulf \end{cases}$$

where $Hg_s$ is the mercury concentration in ppm for a fish from stock *s* and $FL_s$ is the fork length in centimeters for a fish from stock *s*. While it would have been preferable to obtain size/mercury

[17] See http://www.epa.gov/waterscience/fish/states.htm for detailed information on each state.

[18] The equations given in 21 have been converted to use fork length in centimeters. Adams and McMichael (2007) use fork length in millimeters for their estimations. Additionally, the Gulf equation was presented and estimated in logged form in the original work.

samples from throughout the Gulf and Atlantic waters to estimate the relationship, it is not unreasonable to use the Adams and McMichael (2007) estimations given that most king mackerel are caught off the Florida coast (and, in particular, in the mixing zone). It should be noted that mercury data were available for states bordering the Northern Gulf of Mexico through a database developed for the Gulf of Mexico Mercury Project (Ache, Boyle, and Morse 2000). This information, however, was simply a compilation of state monitoring databases that were inconsistent in their sampling procedures and reporting, with the bulk of the observations from Texas where little king mackerel is commercially caught. Thus, for the purposes of this study, it was assumed that the Adams and McMichael information was more directly applicable.

Given that the king mackerel population dynamics model was constructed using age classes, it is useful to convert the size-mercury relationship reported in Adams and McMichael into age-mercury relationship by using equation 20 to calculate the average length of a fish for each age class. Subsequently, equation 21 can be used to determine average mercury concentration at age by substituting the average length for each age class into the equation as follows:

$$(22) \qquad Hg_{s,a} = \begin{cases} 1.11 \cdot 10^{-7} FL_{s,a}^{3.51} \;\; for s = Atlantic \\ \\ e^{-3.09+.032 FL_{s,a}} \;\; for s = Gulf \end{cases}$$

where $Hg_{s,a}$ is the mercury concentration in ppm for a fish of age *a* from stock *s* and $FL_{s,a}$ is the average fork length in centimeters for a fish of age *a* from stock *s*. The resulting relationship is presented graphically in Figure 3 with the current FDA limit of 1 ppm highlighted.[19] For both stocks, the average king mackerel is at or exceeds the FDA limit by the time it reaches 6 years of age.

With a relationship between age and mercury concentration established, it would be ideal to use surveyed population consumption information to link this back through the bioeconomic model and ultimately to human exposure. Unfortunately, there is little information available regarding the consumption of king mackerel in the United States. It is known that king mackerel

[19] While the graph includes up through age 15, recall that the terminal age class in the population dynamics model is the age 11+ group which contains all fish age 11 or older. For determining the appropriate parameters to use for the 11+ age class, the preferred method is to construct a weighted average of the parameter values over the remaining ages that make up the plus group. There was no information available about the age breakdown within the plus group. Rather than equally weight the mean mercury concentration over an arbitrary number of age classes, this study uses the age 11 values for the age 11+ group.

are not widely consumed in the U.S., with a recent mercury assessment study estimating the market share to be around .05% based on 2001 reported landings (Carrington, Montwill, and Bolger 2004). Further compounding the issue is the fact that king mackerel are often lumped together in consumption surveys with other mackerel species such as Spanish or Atlantic mackerels. In the absence of specific consumption information for king mackerel, this study calculated the average mercury concentration for all commercially caught king mackerel. This is done by linking the relationship between age and mercury concentration with the output of the bioeconomic model as follows:

$$\overline{Hg}_{s,t} = \frac{\sum_{a=0}^{11} Hg_{s,a} \cdot CommCN_{s,a,t}}{CommCN_{s,t}} \tag{23}$$

where $\overline{Hg}_{s,t}$ is the mean mercury concentration for all commercially caught king mackerel from stock s in year t, $Hg_{s,a}$ is the mercury concentration in ppm for a fish of age *a* from stock *s*, $CommCN_{s,a,t}$ is the number of age *a* fish commercially caught in year *t* from stock *s*, and $CommCN_{s,t}$ is the total number of commercially caught fish from stock *s* in year *t*. This metric will be used as a benchmark to measure the impacts of simulated changes in how king mackerel are harvested or targeted. If the total annual amount of mercury in all commercially caught fish cannot be reduced, it seems unlikely that any health benefits would come from any alternative harvesting scenarios.

## SIMULATION RESULTS

The integrated population dynamics, economic, and contamination model was designed to investigate the impact of alternative fisheries management schemes on the movement of mercury from its environmental stock to the human population. Specifically, the study sought to discover if alternative harvesting patterns could reduce the amount of mercury reaching king mackerel consumers without severely affecting the economic viability of the harvesting industry or damaging the biological viability of the king mackerel stocks. Given that mercury contamination of fish is primarily an age/size phenomenon, it was anticipated that the primary policy objective would be to alter the age (and therefore size) composition of the commercial catch. From a modeling perspective, this can be accomplished by changing commercial fishing mortality at age and comparing the results across scenarios. For the purposes of the discussion below, these scenarios were developed to compare the results of shifting fishing pressure to progressively smaller and younger (and thus, less contaminated) fish.[20] Specifically, the simulated scenarios examine the (1) status quo, (2) elimination from the catch of fish age 6 and older; (3) the establishment of a less than 33" fork length maximum size limit (with no increased catch of smaller fish), (4) scenario 3 with an increase in catch of smaller fish, (5) a reduction in the catch of age 4 fish accompanied by an increased catch of younger fish, and (6) scenario 5 with consideration for incidental catch. The model was implemented in Matlab.

The results from the selected scenarios are presented next, with the accompanying discussions focusing on the following key variables; annual mean mercury concentration in the harvest, annual commercial catch in pounds, annual stock biomass, annual profits in the fishing industry, and NPV of the fishery. Figure 4 graphically depicts simulated mercury concentration, catch, biomass, and profit for all Gulf scenarios, thereby allowing for easy comparison among the potential management actions. Figure 5 present the same for the Atlantic scenarios. Table 1 presents the NPV for each Gulf scenario along with minimum, maximum, and mean mercury concentrations over the 25 year simulation time frame, while Table 2 presents the same for the Atlantic scenarios.

**Gulf Scenario (1): Status Quo**

The status quo scenario establishes a baseline model that describes the biological, economic, and contamination status of the Gulf king mackerel stock for use in evaluating the effect of the other alternatives. The time horizon of the simulation is 25 years, spanning 1999-2023. This time span was chosen because it allows the complete tracking of a number of cohorts through time and, thus, allows the full implications of any new management regime to be examined. The economic parameters outlined above are used throughout the simulation time span. In terms of the population dynamics model, all time invariant parameters previously described are used. Initial numbers at age for 1999 are taken from SEDAR16, as are weights at

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[20] The bioeconomic literature typically approaches these types of investigation in two distinct ways; direct and indirect optimization. Direct optimization is generally relegated to those models that are analytically tractable, which is not the case in this study. Indirect optimization involves a wide range of approaches that usually incorporate some form of a grid search (either formal or informal) over the potential solution space. This study takes the informal approach, examining potential solutions via a set of pre-specified scenarios. Although these scenarios will not result in the identification of an optimal solution, it does provide an opportunity to determine if a solution might exist within the defined space and helps to narrow the space for use in potential future multi-objective optimization studies.

age for 1999-2006. The commercial fishing mortality and remaining fishing mortality are derived for the years 1999-2006 and used in the simulation, but assumptions concerning these parameters must be used for the latter part of the simulation time horizon. One approach would be to use the mean values from 1999-2006 (or a subset of those years) for all remaining years in the simulation horizon (2007-2023), as done with recruitment values in Bjorndal, Ussif, and Sumaila (2004). Using this approach, simulated biomass and catches (along with the corresponding profit and average mercury concentration) quickly level off as the system reaches a steady state. It is unrealistic, however, to think that catches will remain the same from year to year. Even when regulations remain largely unchanged, there is always some variability in the year-to-year catches due to both economic and environmental conditions. Thus, for the purposes of this research, it was decided to simply repeat the 1999-2006 time series of fishing mortality values throughout the simulation time span. Assuming that regulations remain the same, this approach captures the inherent variability in the catches while projecting the current system characteristics into the future.[21]

Results for the status quo scenario indicate that under the current catch composition, the average mercury concentration of commercially caught king mackerel ranges from a low of 0.64 ppm to a high of 0.88 ppm with a mean of 0.76 ppm over the simulation time span. Stock biomass increases throughout the simulation years, albeit at a decreasing rate over the later years. This is not surprising given that commercial catches follow a similar pattern and the fishery is currently managed under a TAC that was designed to rebuild the stock from an overfished level. Annual profits to the fishery average $2.5 million over the simulation period.

One aspect of the status quo scenario that warrants more discussion is the mean mercury concentration of 0.76 ppm over the simulation time frame. Given the U.S. FDA's action limit of 1 ppm, it is tempting to conclude that, since the simulated mean is lower, no action is warranted. The U.S. FDA (2001), however, reported a mean mercury value of 0.73 for all king mackerel, a value that was high enough to prompt consumption advisories and a study to reevaluate the original 1.0 ppm limit. The U.S. EPA already has put in place a more stringent threshold regarding exposure to mercury. Defined as a reference dose (RfD), or the estimated daily amount of a substance that can be consumed safely over a lifetime, this new threshold calls for a

[21] An alternative would be to develop the model using stochastic functions for the parameters, but given the limited data, it was not obvious that the additional complexity of this approach would yield any improvements in the model's ability to represent future outcomes.

maximum mercury exposure of 0.1 micrograms per kilogram of body weight. Unlike the U.S. FDA's limit, the U.S. EPA RfD depends not just on the concentration of mercury in the fish consumed, but also on the amount of consumption, the frequency of consumption, and the bodyweight of the consumer. Based on the mean mercury level of 0.76 found in the status quo simulation, even a consumer weighing 250 pounds would greatly exceed the weekly RfD if they ate even one 6 ounce meal each week[22]. Keeping this result in mind, the remainder of the simulations will be discussed.

**Gulf Scenario (2): Eliminate Harvesting of Fish Age 6 and Older**

The next scenario investigated the effects on the fishery if management regulations prohibited catching king mackerel over age 6, or the age when the average king mackerel from the Gulf stock exceeds the U.S. EPA limit of 1 ppm.[23] Commercial fishing mortalities were set to zero for ages 6-11, while commercial fishing mortalities for ages 0-5 were left at their baseline levels. As is the case in all scenarios investigated, the remaining fishing mortality is assumed unchanged from the baseline scenario.[24] Simulation results for this scenario indicate that average mercury concentration of the commercially caught fish would be reduced to 0.57 ppm, but at a substantial cost to the harvesting industry. While biomass increases in this scenario relative to the status quo (as would be expected given that fishing mortality – and thus targeted effort – is assumed unchanged for the allowable age classes), commercial catches and profits dropped dramatically compared to the baseline model, with the NPV of the fishery decreasing by 29%.

**Gulf Scenario (3): Establish a Less than 33" FL Maximum Size Limit**

Given the reduction of mercury found in Scenario 2 from eliminating the catches of age 6 and older fish, scenario 3 investigated an even more restrictive model. Many states that issue consumption advice for king mackerel consider those with a fork length of 33 inches or less safe for unrestricted consumption. A fork length of 33 inches corresponds to age 4 in the Gulf stock, so this scenario eliminated all catches of age 5 and older fish. Commercial fishing mortalities were set to zero for ages 5-11, while commercial fishing mortalities for ages 0-4 were left at their baseline levels. As in scenario 2, average mercury levels were significantly reduced from the

[22] For more information see PBS Now. Science and Health: The Mercury Story. January 21, 2005. See http://www.pbs.org/now/science/mercuryinfish.html for more details.
[23] Of course, in practice this age restriction would be implemented using a fork-length size restriction.
[24] This research is concerned only with the commercial fishery, and does not aim to change the behavior of the recreational fisherman. Given that many recreational fisherman fish for fun or pleasure rather than food, it does not make sense to limit the size of their catch.

baseline – in this case to an average of 0.52 ppm – but at the cost of a 44% reduction in the NPV of the fishing industry. Similarly to what occurred in scenario 2, biomass increases in this scenario relative to the status quo. Again this was expected given that fishing mortality –is assumed unchanged for the allowable age classes even as the number of harvestable age classes declines.

**Gulf Scenario (4): Scenario 3 With an Increase in the Catch of Younger Fish**

Scenario 4 builds on scenario 3 by adding some realism to the allocation of harvest (and, implicitly, the allocation of effort) across the age classes. While eliminating the catch of older fish can significantly decrease the average mercury level that will reach consumers, it is unrealistic to think that fishing effort will not be reallocated (in the absence of restrictive TACs) from larger to smaller fish. Scenario 4 assumes that commercial fishing mortality on ages 0 and 1 are unchanged (given the continuation of the current 24" minimum size limit) and that for ages 5-11 commercial fishing mortalities are again set to zero. For ages 2 and 3, it is assumed that commercial fishing mortalities will double from their baseline levels and age 4 commercial fishing mortalities remain at their baseline levels. This assumption about increasing fishing mortality for ages 2 and 3 was made in order to examine the effect of increased fishing on the younger age classes, with the specific magnitude of the change being arbitrary but large enough to expect some response from the system simulation. Age 4 was left at baseline in an attempt to further alter the age composition of the catch and reduce average mercury concentration. Under these simulation assumptions, average mercury levels were reduced from the baseline levels to 0.50 ppm, or just slightly lower than what occurred without effort reallocation. Commercial catches and profits fell from baseline levels, but increased from scenarios 2 and 3. King mackerel stocks remained higher than baseline levels over time, suggesting that a switch to harvesting smaller fish does not necessarily have a negative impact on the stock health when larger, highly fecund fish are allowed to remain in the reproducing population and when catches remain below the baseline levels. Overall, fishing industry NPV was 25% lower compared to the baseline scenario 1.

**Gulf Scenario (5): Reduction in Age 4 Catch Plus Increased Catch of Younger Fish**

Given that the increased fishing pressure on younger fish in Scenario 4 does not negatively impact stock health, scenario 5 increases the fishing effort to an even larger degree. As in the previous scenario, scenario 5 assumes that commercial fishing mortality on ages 0 and

1 are unchanged and that for ages 5-11 commercial fishing mortalities are zero. For ages 2 and 3, it is assumed that commercial fishing mortalities will quadruple from their baseline levels. Age 4 commercial fishing mortalities are assumed to be half of their baseline levels in an attempt to reduce average mercury concentration even further. While these changes are to an extent arbitrary, they were chosen to keep the average commercial catch and effort levels relatively close to the average commercial catch from the baseline scenario. Average mercury concentration of the harvest under this scenario was reduced to 0.48 ppm, while the NPV of the fishing industry only fell 7% from the baseline scenario. Stock biomass is slightly below baseline in this scenario, but still exhibiting a pattern of increases over time.

**Gulf Scenario (6): Scenario 5 Plus Incidental Catch**

The final scenario explored is an extension of scenario 5. Given that fishing pressure on ages 2 and 3 are already quadrupled from baseline levels and it is most likely impossible to increase it without bound, it does not seem realistic to simulate the effects of further increases. However, it also seems unrealistic to simply eliminate all catches of age 6 and older king mackerel. While a maximum size limit can be implemented, thus rendering the sale of oversized fish illegal, the regulation will not actually stop these catches altogether – it merely prevents (for the most part) the marketing of the catch. Bycatch, or non-targeted or incidental catch of non-target age classes, is going to occur. To capture this phenomenon, this scenario builds on scenario 5 by including the bycatch of the larger age classes.

The inclusion of bycatch in the simulations is important for two reasons. First, if enough larger fish are caught incidentally this could negatively impact biomass, depending on release mortality. Second, even though a fisherman may not be able to legally sell oversized fish, they certainly incur a cost in terms of effort from landing the incidental catch. Unfortunately, under current management regimes larger fish are targeted (in king mackerel and most other species) and there is little or no information concerning potential bycatch of the larger age classes if they were made illegal. Given that it is in the fishermen's best interest to limit bycatch from an effort/cost perspective, this scenario assumed that commercial fishing mortalities for ages 5-11 fell to only 10% of their baseline values and not to zero as would occur under perfect adherence to size limits. All of the resulting catches from those age classes were then considered incidental and incurred a cost (both monetary and biological) even though they did not contribute to revenue**.** Further, it was assumed that the release mortality of the incidental catch was 100%, or that all fish caught and released later die. This is a somewhat extreme assumption, as the actual release mortality may be relatively low for hook and line fisheries in general and for king mackerel in particular (SEDAR16 RD09 2009). This assumption was made because it can be viewed as a worst case scenario for the stock. The remaining fishing mortalities by age class are unchanged from scenario 5.

Scenario 6 simulated commercial catches and average mercury concentrations remained identical to scenario 5 because it was assumed that the incidental catch was not marketed. The difference with scenario 6 results lies in biomass and profits. With an additional cost incurred in harvesting unmarketable fish, average profits were predictably lower. These catches also resulted in a lower average biomass compared to scenario 5 and the baseline scenario 1, although the stock health still appears to be high. The NPV of the fishery was 14% less than baseline, with the average mercury reduction remaining at 0.48 ppm, a 37% change from baseline.

**Atlantic Scenario (1): Status Quo**

The status quo scenario for the Atlantic stock was constructed in the same manner as described for the Gulf status quo. Results for the status quo scenario indicate that under the current catch composition, the yearly average mercury concentration of all commercially caught king mackerel ranges from a low of 0.56 ppm to a high of 0.86 ppm with a mean of 0.67 ppm over the simulation time span. Stock biomass decreases throughout the early simulations years before mostly leveling off over the latter simulation years. Commercial catches over the simulation period averaged 2.5 million pounds, while annual profits to the fishery averaged $1.9 million over the simulation period.

**Atlantic Scenario (2): Eliminate Harvesting of Fish Age 6 and Older**

The next scenario investigated the effects on the fishery if management regulations prohibited catching king mackerel over age 6, or the age when the average king mackerel from the Atlantic stock exceeds the U.S. EPA limit of 1 ppm. Commercial fishing mortalities were set to zero for ages 6-11, while commercial fishing mortalities for ages 0-5 were left at their baseline levels. As is the case in all scenarios investigated, the remaining fishing mortality is assumed unchanged from the baseline scenario. Simulation results for this scenario indicate that average mercury concentration would be reduced to 0.51 ppm, but at a cost of a 15% decrease in the NPV of the fishery. As expected (given the decreased harvesting of highly fecund older fish), stock biomass increases in this scenario relative to the status quo, while commercial catches and profits dropped dramatically compared to the baseline model.

**Atlantic Scenario (3): Establish a Less than 33" FL Maximum Size Limit**

Given the reduction of mercury found in Scenario 2 from eliminating the catches of age 6 and older fish, scenario 3 investigated an even more restrictive model for the Atlantic stock. A fork length of 33 inches corresponds to age 4 in the Atlantic stock, so this scenario eliminated all catches of age 5 and older fish. Commercial fishing mortalities were set to zero for ages 5-11, while commercial fishing mortalities for ages 0-4 were left at their baseline levels. As in scenario 2, average mercury levels were significantly reduced from the baseline – in this case to an average of 0.44 ppm – but at the cost of a 27% reduction in the NPV of the fishing industry. Biomass is again significantly higher than baseline, an expected result given the assumptions.

**Atlantic Scenario (4): Scenario 3 With an Increase in the Catch of Younger Fish**

Scenario 4 builds on scenario 3 by adding some realism to the allocation of harvest across the age classes. While eliminating the catch of older fish can significantly decrease the average mercury level that will reach consumers, it is unrealistic to think that fishing effort will not be reallocated to target smaller fish. Scenario 4 assumes that commercial fishing mortality on ages 0 and 1 are unchanged and that for ages 5-11 commercial fishing mortalities are again set to zero. For ages 2 and 3, it is assumed that commercial fishing mortalities will double from their baseline levels and age 4 commercial fishing mortalities remain at their baseline levels. Under these simulation assumptions, average mercury levels were reduced from the baseline levels to 0.41 ppm, or just slightly lower than what occurred without effort reallocation. On average, commercial catches and profits fell from baseline levels, but increased from scenarios 2 and 3. King mackerel stocks remained slightly higher than baseline levels over time, once again highlighting that a switch to harvesting smaller fish does not necessarily have a negative impact on the stock health when larger, highly fecund fish are allowed to remain in the reproducing population and when catches remain below the baseline levels. Overall, fishing industry NPV was more than 10% lower when compared to the baseline scenario.

**Atlantic Scenario (5): Reduction in Age 4 Catch plus Increased Catch of Younger Fish**

Given that the increased fishing pressure on younger fish in Scenario 4 does not negatively impact stock health, scenario 5 increases the fishing effort to an even larger degree. As in the previous scenario, scenario 5 assumes that commercial fishing mortality on ages 0 and

1 are unchanged and that for ages 5-11 commercial fishing mortalities are zero. For ages 2 and 3, it is assumed that commercial fishing mortalities will triple from their baseline levels. Age 4 commercial fishing mortalities are assumed to be half of their baseline levels in an attempt to reduce average mercury concentration even further. As in the case of the Gulf, these changes were chosen to keep the average commercial catch and effort levels relatively close to the average commercial catch and effort levels from the baseline scenario. Average mercury concentration of the harvest under this scenario was again reduced to 0.38 ppm, while the NPV of the fishing industry decreased only 8% from the baseline scenario. Commercial catches were lower than baseline on average, as were profits. Biomass values were higher than baseline for this scenario, an expected result given the decreased catch.

**Atlantic Scenario (6): Scenario 5 Plus Incidental Catch**

As in the case of the Gulf stock, the final scenario explored is an extension of scenario 5 that includes incidental catch of the larger age classes. This scenario assumed that commercial fishing mortalities for ages 5-11 fell to only 10% of their baseline values and not to zero as modeled in the other scenarios. All of the resulting catches from those age classes were then considered incidental and incurred a cost (both monetary and biological) even though they did not contribute to revenue. Further, it was assumed that the release mortality of the incidental catch was 100%, or that all oversized fish caught and released later die. The remaining fishing mortalities by age class are unchanged from scenario 5. Scenario 6 simulated commercial catches and average mercury concentrations remained identical to scenario 5 because it was assumed that the incidental catch was not marketed. The difference with scenario 6 results lies in biomass and profits. With an additional cost incurred in harvesting unmarketable fish, average profits were lower than in Scenario 5. These catches also resulted in a slightly lower average biomass compared to scenario 5 and the baseline scenario 1. After the initial decline, the biomass levels are generally fairly stable (suggesting good stock health), but possibly exhibit a slight downward trend over the last few years of the simulation horizon. The NPV of the fishery was 19% less than baseline, while the average mercury is reduced by 44%.

## DISCUSSION AND CONCLUSIONS

Although there are infinitely many scenarios that could have been examined, the chosen simulations demonstrate the possibility for reducing the amount of mercury that reaches consumers by altering the age composition of the commercially marketed catch. The Gulf and Atlantic simulations illustrate that it is even possible for this to occur without seriously impacting either commercial catch or the long-run stability of the biomass stock. Both the Atlantic and Gulf stock reductions in mercury came at the price of reduced fishery profits and losses in NPV, highlighting that some tradeoffs are necessary. While mercury levels under Scenario 6 in the Gulf were reduced by over 36%, to under half of the U.S. FDA limit (based on Table 4.3), those levels would still put virtually all consumers over the U.S. EPA RfD. Average mercury concentrations from Atlantic harvesting were reduced substantially from baseline levels under Scenario 6, down to a level of 0.38 ppm. This level of exposure would allow consumers over 210 lbs to safely eat one 6 ounce meal of king mackerel per week without exceeding the U.S. EPA's RfD. However, it should be noted that the U.S. EPA RfD is one of the most stringent recommendations concerning mercury. In 2003, the World Health Organization revised its recommendation for safe intake levels to 1.6 micrograms per kg bodyweight per week, or approximately .23 micrograms per day (WHO 2003). The U.S. Agency for Toxic Substances and Disease Registry maintains that daily intake of methylmercury at a level of 0.3 micrograms per kilogram of body weight per day for a lifetime presents no risk of adverse health outcomes in even the most sensitive human populations (such as pregnant women, developing fetuses, and young children) -- ATSDR 1999). Under these guidelines, the simulated reductions can be viewed as substantial improvements.

Another issue worthy of exploration is how to transfer the model findings into real world management rules and regulations (Thunberg, Helser, and Mayo 1998). In the simulation scenarios, commercial fishing mortalities were changed, but the drivers behind those changes were not defined. Recall from the population dynamics model that the commercial fishing mortality can be separated into an age effect representing the selectivity of the fishery and a year effect representing intensity of the fishing mortality. Altering either of these effects will change fishing mortality at age. The intensity of fishing mortality can be altered through changes in TACs or by incorporating effort limitations. This will not generally reduce mercury exposure, however, because simply changing the overall fishing mortality without changing the age composition of the catch will not lead to an overall reduction in the contamination level of the marketed fish. Any policy or regulation must alter the selectivity patterns by age class of the fishery. This could be achieved in a number of ways, ranging from gear modifications to restrictions on times and areas fished (Thunberg, Helser, and Mayo 1998). Of course, area and seasonal restrictions will only be effective if the stock exhibits a distinct spatial or temporal distribution (Anderson 1977). Although king mackerel are known to form schools of similar sized individuals, further research will be needed to examine the spatial and seasonal distribution of smaller-sized king mackerel to determine if area or seasonal restrictions can be used to shift fishing pressure towards younger age classes.

As illustrated by Scenario 6 for both the Atlantic and Gulf stocks, it seems that a harvesting slot limit, where all fish below the current minimum size limit and all fish above a maximum size limit are off-limits, could effectively reduce the mercury concentration that reaches consumers. When implemented to preserve stocks, however, size limits will only be effective if fish can be returned to the water unharmed or if size can be determined before capture (Anderson 1977). In this case, the slot limits would be implemented to reduce the amount of mercury reaching consumers, but would still require some ability to minimize incidental catch of larger fish in order to prevent depletion of the stock. The simulated scenarios show that slot limits are effective in reducing the average mercury in marketed fish, and when catches remain around historical levels, can also preserve the stock if bycatch is low. If bycatch of oversized fish was high enough, there could be a negative impact on biomass, jeopardizing the status and stability of the stock. Scenarios 5 and 6 show that minimizing bycatch is also necessary to limit losses to the commercial fisherman. For both stocks, losses in NPV were smallest under Scenario 5 which assumed perfect adherence to the slot limit with no incidental catch. Losses were considerably greater in Scenario 6 highlighting the importance of minimizing bycatch of larger fish and the cost associated with it.

It is also important to understand some of the limitations of this study and directions for future research. While the assumption of constant price does not seem unreasonable when looking at overall price levels for the catch, it would be preferable to incorporate price by age class to account for any differences in quality by size. Unfortunately, no data is available distinguishing king mackerel price by size or age class. More research is needed to determine if there are substantial price differences by age class. Additionally, if there are no current differences in price by age class, it is reasonable to think that in the future there could be based on the reduced mercury from the harvesting patterns proposed in this research. More work is needed to determine the amount (if any) of a price premium for lower mercury levels in king mackerel. If the price premium for smaller, less contaminated fish were substantial enough, the losses to the commercial fisherman's profit and the NPV of the fishery could be offset (to some degree) by the increase in revenue. This raises the possibility of a win-win situation and certainly warrants further investigation.

In addition to the assumption of constant price, this study also made use of a constant cost per unit of effort, in this case hours fished. The incorporation of cost into bioeconomic models of fisheries is usually problematic due to inadequate data. The cost data for this study came from self-reported logbook observations and accounted only for variable costs, including labor, fuel, bait, ice and miscellaneous costs. While most fisheries operate under a share system, the logbook data do not provide strong evidence of any relationship between reported labor costs and revenue. Many boats were also owner operated, with the captain as the sole crew member on board, making it difficult to discern whether the fishery operated under a share system or a some sort of wage rate. This research also relied on the assumption that the cost structure of the fishery would not change as effort is reapportioned to younger age classes. This may not be realistic depending on how much effort is shifted. Future work is needed to develop a more comprehensive cost analysis of the king mackerel fishery, possibly involving personal interviews with fisherman in order to get a stronger understanding of the cost structures of their harvesting activities. Finally, if any gear or technology improvements are needed for the fleet to harvest smaller fish, those costs are not accounted for in the model. If those costs are large enough, the results of this study may be misleading, as the impact on the fishery in Scenario 6 would be greater than presented.

Future research will involve dynamically optimizing and analyzing the model under various objectives (i.e., pure profit maximization, minimization of average mercury, profit maximization constrained by mercury limits and biomass limits). A comparison of the different optimization scenarios could then be used to generate policy relevant management suggestions under varying management objectives. It also may be interesting to apply a similar model to a mercury contaminated fishery that is both more widely consumed and for which there is more extensive demand data available, such as one of the tuna species. Given the depleted nature of many of the tuna stocks, it would be enlightening to examine what economic and biological tradeoffs would be necessary to reduce the average mercury reaching consumers.

The bioaccumulative nature of mercury, and its multiple anthropogenic and natural sources, ensures that it will be present in our fish stocks for many years to come. Mercury exposure through food supplies will continue to remain a public health concern among consumers and potential consumers of seafood products. Currently, the amount of mercury reaching consumers is not considered in the harvesting decision, even when it is known that larger fish contain significantly higher amounts of mercury than smaller fish. This research demonstrated what might happen if attempts were made to reduce the mercury that reaches consumers through the harvest of smaller fish, and it can be used as a base for further research that seeks to examine contaminant concentration and health concerns associated with fishery harvesting decisions.

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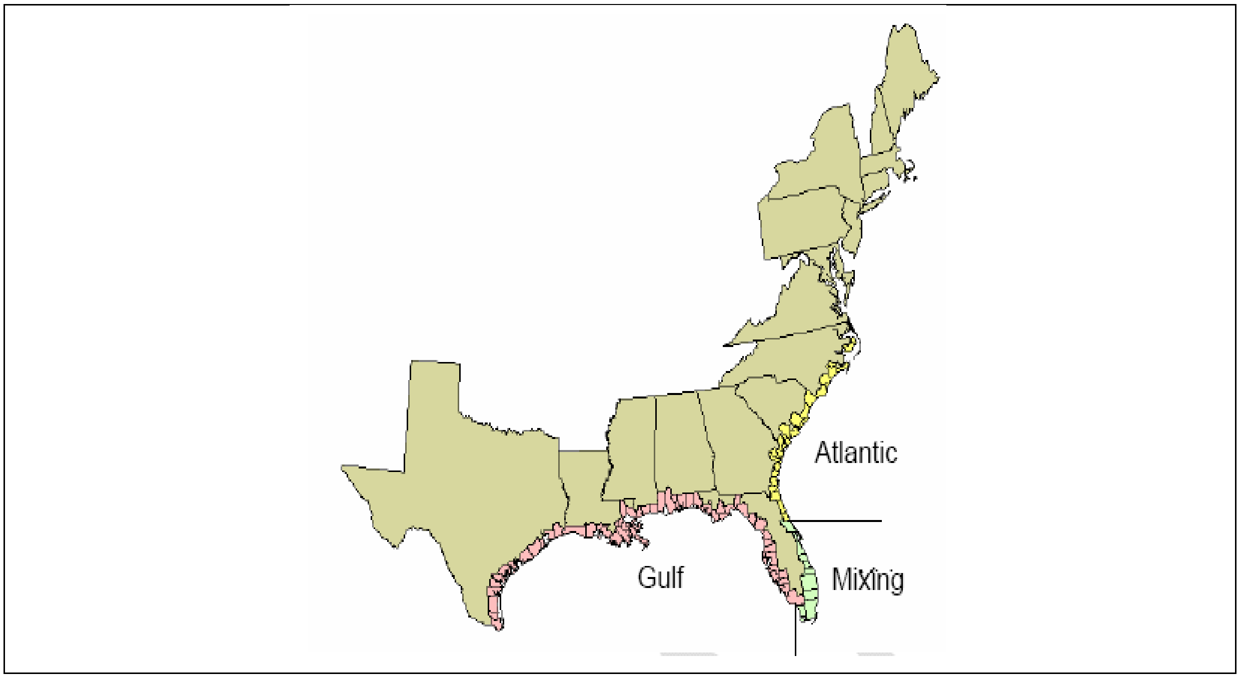



Figure 1: Map indicating the Atlantic, Gulf, and Mixing zones for U.S. king mackerel
Source: SEDAR 16 2009.

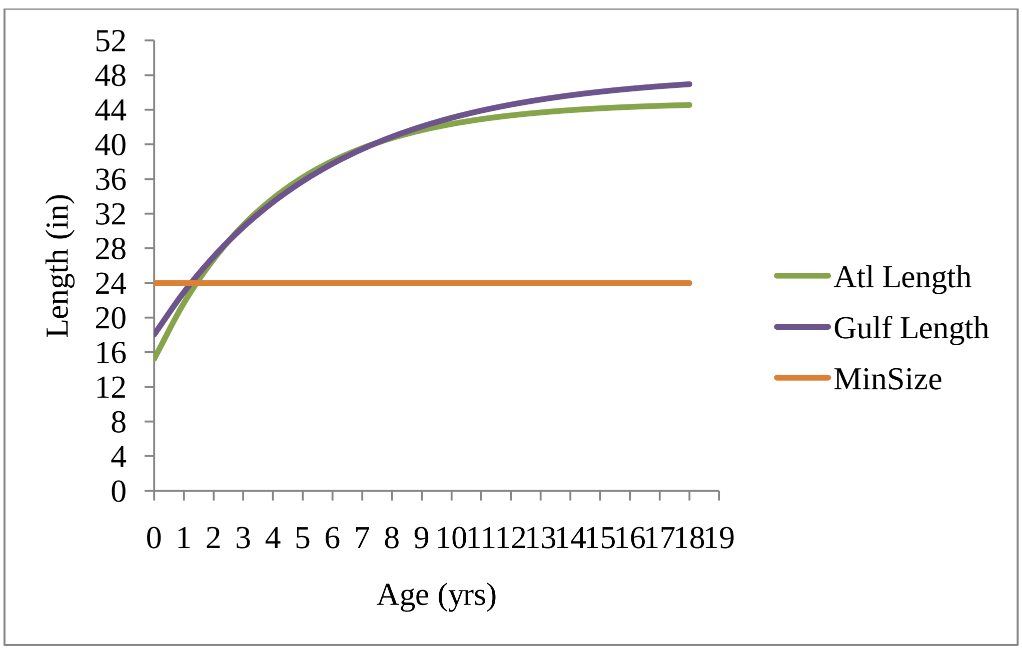



Figure 2: Von Bertalannfy growth curves and the minimum size limit for the Atlantic and Gulf of Mexico king mackerel migratory groups[25]

[25] While the growth relationships define length in terms of centimeters, they are graphed here in terms of inches for clarity with respect to the 24 inch catch size limit.

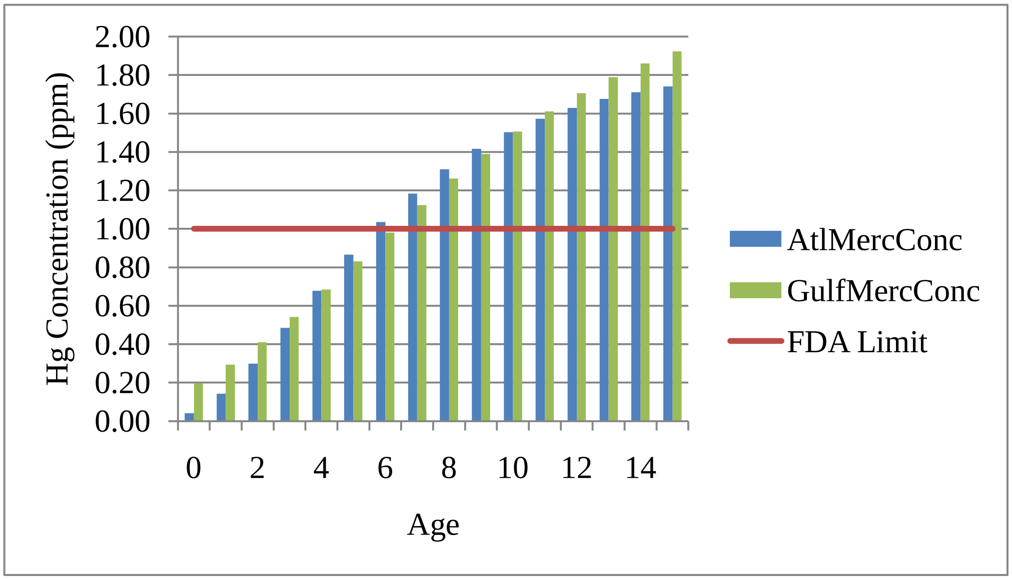
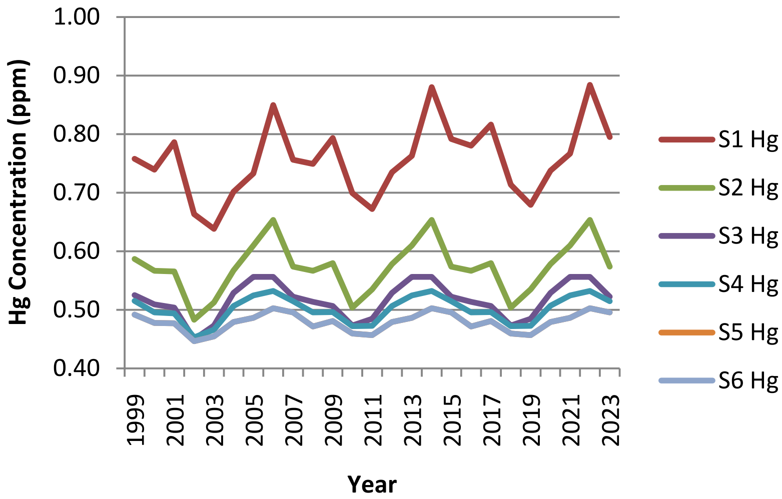
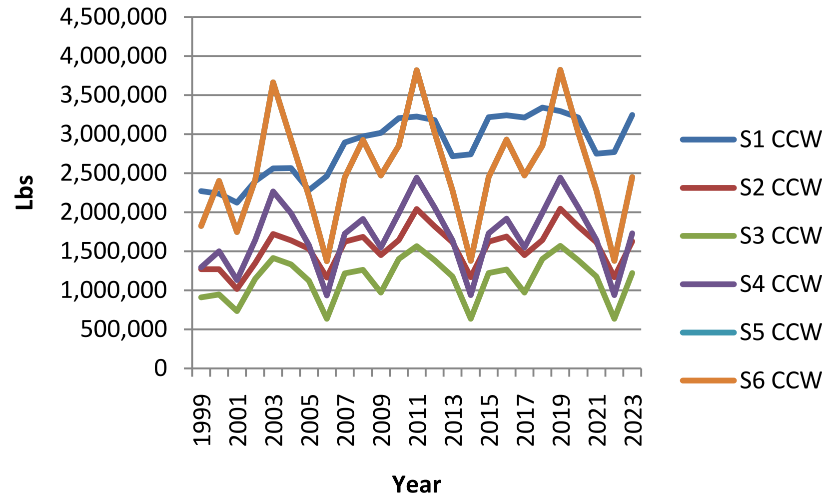


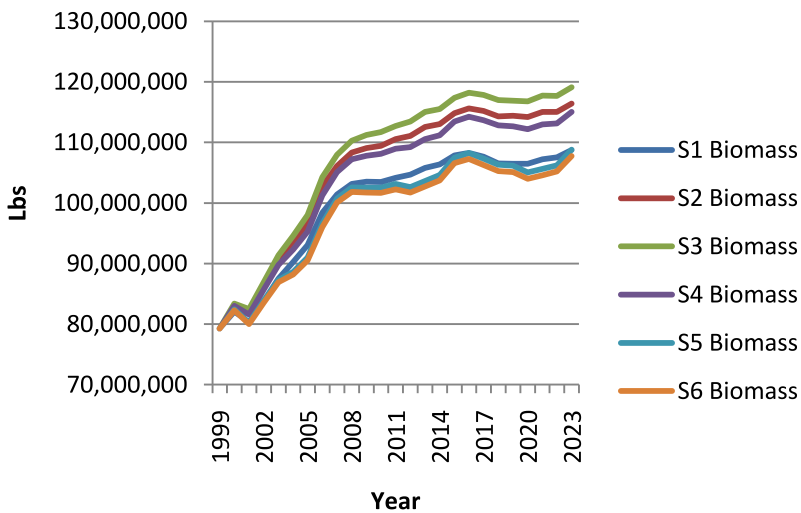

Figure 3: Average mercury concentration by age for the Gulf and Atlantic king mackerel stocks



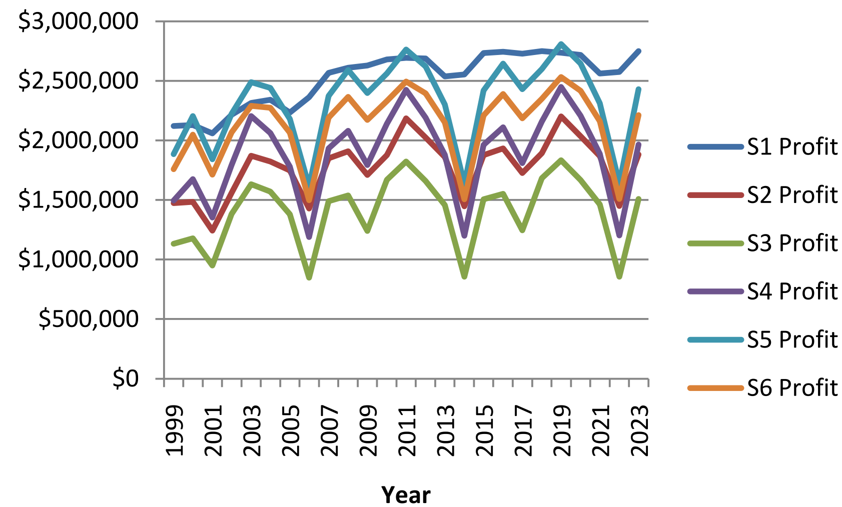

Simulated mercury concentrations (Hg) for given scenarios




Simulated commercial catch in lbs for given scenarios

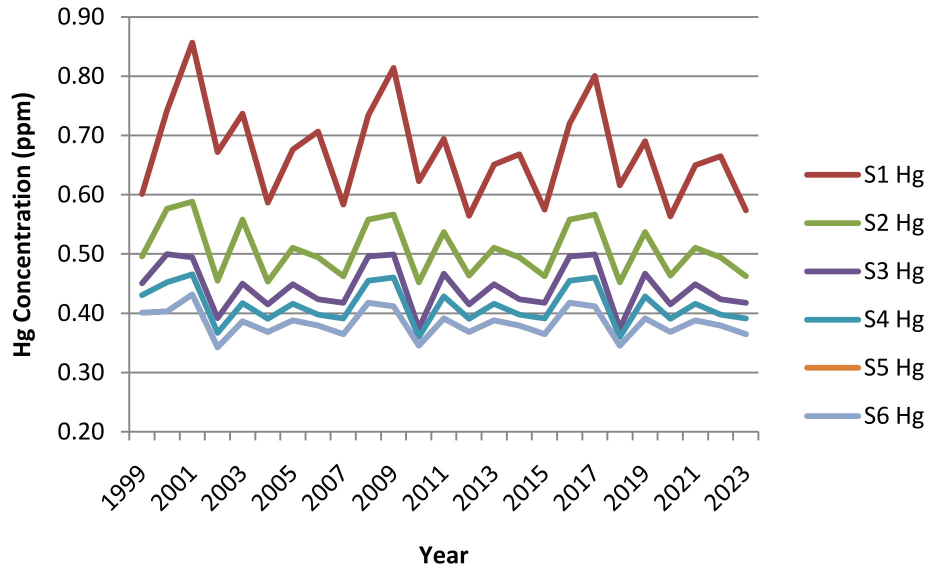



Simulated biomass for given scenarios

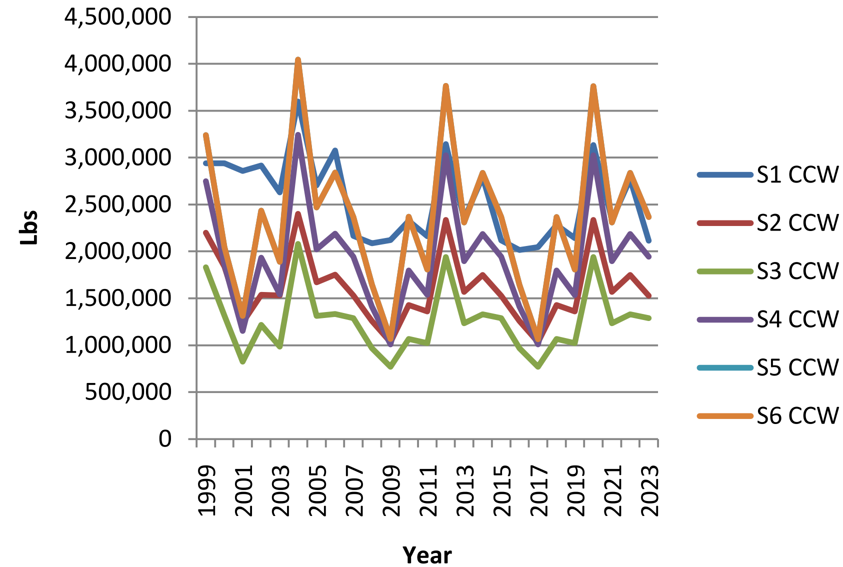



Simulated profit for given scenarios

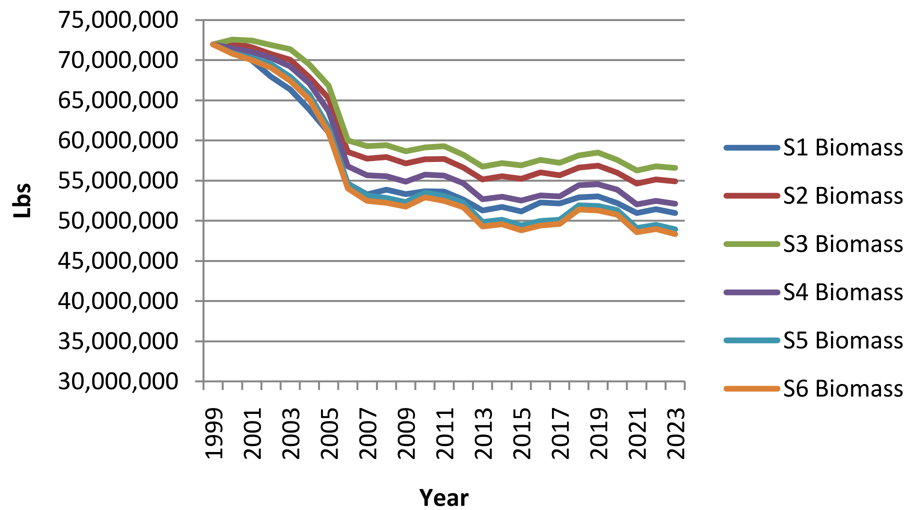
Figure 4: Gulf Simulation Results



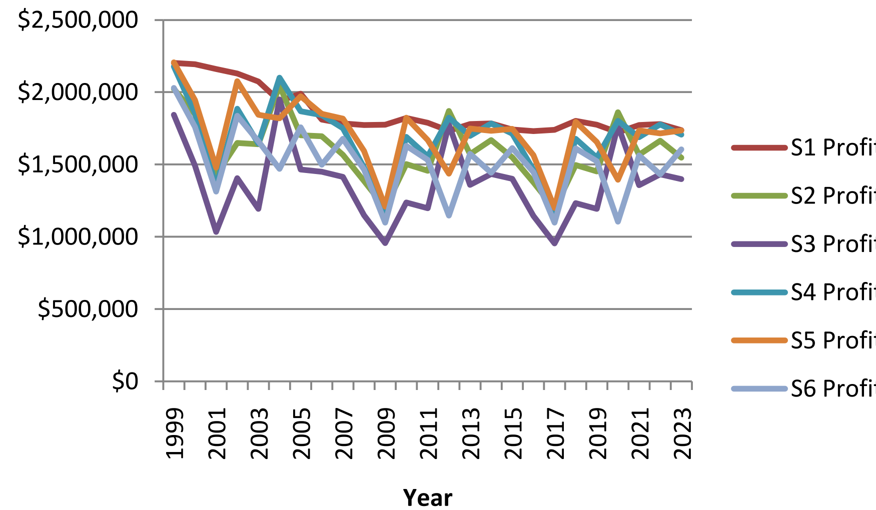

Simulated mercury concentrations (Hg) for given scenarios




Simulated commercial catch in lbs for given scenarios




Simulated biomass for given scenarios




Simulated profit for given scenarios

Figure 5: Atlantic Simulation Results

Table 1: Comparison of simulated NPV, percentage change from status quo, and mercury concentrations (Hg) for given scenarios, Gulf stock

| Scenario | NPV | % Change | Min Hg | Max Hg | Mean Hg |
|---|---|---|---|---|---|
| 1 | $34,561,343 | - | 0.64 | 0.88 | 0.76 |
| 2 | $24,403,130 | -29.39% | 0.48 | 0.65 | 0.57 |
| 3 | $19,406,615 | -43.85% | 0.45 | 0.56 | 0.52 |
| 4 | $25,985,333 | -24.81% | 0.45 | 0.53 | 0.50 |
| 5 | $32,192,745 | -6.85% | 0.45 | 0.50 | 0.48 |
| 6 | $29,635,679 | -14.25% | 0.45 | 0.50 | 0.48 |

Table 2: Comparison of simulated NPV, percentage change from status quo, and mercury concentrations (Hg) for given scenarios, Atlantic stock

| Scenario | NPV | % Change | Min Hg | Max Hg | Mean Hg |
|---|---|---|---|---|---|
| 1 | $26,920,041 | - | 0.56 | 0.86 | 0.67 |
| 2 | $22,923,928 | -14.84% | 0.45 | 0.59 | 0.51 |
| 3 | $19,540,856 | -27.41% | 0.37 | 0.50 | 0.44 |
| 4 | $24,170,976 | -10.21% | 0.36 | 0.47 | 0.41 |
| 5 | $24,669,159 | -8.36% | 0.34 | 0.43 | 0.38 |
| 6 | $21,873,321 | -18.75% | 0.34 | 0.43 | 0.38 |