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MANAGEMENT BRIEF

Contrasting Maturation and Growth of Northern Rock Sole in the Eastern Bering Sea and Gulf of Alaska for the Purpose of Stock Management

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Abstract
The primary purpose of this study was to provide commercial fishery managers with the age- and length-at-maturity information about northern rock sole *Lepidopsetta polyxystra* needed for them to set a sustainable overfishing limit and evaluate the precision of the two predictors of maturity. The estimated length at which 50% of eastern Bering Sea female northern rock sole matured (L_{50}) was 309 mm, which was significantly smaller than that for Gulf of Alaska females. We determined that the differences in L_{50} between populations were probably the result of differences in the rate of female growth. Growth was significantly faster in the Gulf of Alaska than in the eastern Bering Sea during 1996 and 1999. However, by 2007 the growth rates were similar between these areas. The variability in growth was correlated with seawater temperature. There were also differences in the age at which 50% of the females matured (A_{50}) between the populations in the eastern Bering Sea (9 years) and the Gulf of Alaska (7 years). In contrast, within the eastern Bering Sea, females maintained a similar A_{50} over several years, which indicates that age is the most reliable predictor of maturity for northern rock sole.

The northern rock sole *Lepidopsetta polyxystra* is the third most numerous groundfish species in the eastern Bering Sea, the current population and biomass being over 10×10^9 individuals and over 2×10^6 metric tons (mt; Acuna and Lauth 2008). Northern rock sole distribution overlaps widely with its congener, rock sole *L. bilineata*, in the eastern Aleutian Islands and southern portion of the eastern Bering Sea, the Gulf of Alaska, and down the west coast of North America to Puget Sound (Stark and Somerton 2002). Northern rock sole is predominant in the southern Bering Sea and Aleutian Islands, and rock sole predominates in the Gulf of Alaska. Northern rock sole also overlaps with the ricecake sole (also known as the dusky sole) *L. mochigarei* in the western extent of its distribution off the Kuril Islands of the western North Pacific. Northern rock soles are most abundant in the southeastern Bering Sea (Fadeev 1965) where it is widely distributed in depths to 200 m but concentrated off the Pribilof Islands and in Bristol Bay (Acuna and Lauth 2008). In contrast, 80% of all the Gulf of Alaska northern rock soles is found in depths less than 100 m in the western and central areas (von Szalay et al. 2010).

Northern rock sole has high commercial value, primarily from the roe and fillet products (Wilderbuer and Nichol 2007). Sustainable management of northern rock sole is dependent upon having realistic estimates of the female reproductive potential for each stock. Typically the most reliable correlates of female maturity are age and body length. Previously, management of eastern Bering Sea northern rock soles relied on age at maturity estimates that were based on macroscopic anatomical maturity classifications collected by fishery observers during the 1993 and 1994 eastern Bering Sea rock sole roe fishery. To improve the precision of the maturity estimates, this study was initiated as part of the Bering Sea northern rock sole stock assessment conducted by the National Marine Fisheries Service's Alaska Fisheries Science Center (AFSC) Resource Assessment and Conservation Engineering Division. The maturity estimates are used with the AFSC survey estimates of population recruitment to estimate the spawning biomass and spawner–recruit relationship, which are used to calculate the population's maximum sustainable yield (MSY), the fishery mortality rate that would give MSY (F_{MSY}), and the overfishing limit (Wilderbuer and Nichol 2007). This study employed histological maturity classification methods to determine female maturity, which are known to be less biased than the anatomical maturity classification methods (Hunter et al. 1992) previously

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used for eastern Bering Sea northern rock soles. Histological maturity assessments were previously used by Stark and Somerton (2002) to define the maturity of the Gulf of Alaska northern rock sole population and its congener the rock sole.

METHODS

Sample collection.—Observers of the AFSC Fisheries Monitoring and Analysis Division collected 209 northern rock soles taken in the eastern Bering Sea and delivered by commercial bottom trawl vessels to seafood processing plants in Dutch Harbor, Alaska, during February and March 2006. The observers were specifically trained in the taxonomic identification of rock soles. The species were differentiated using blind side coloration and gill raker and supraorbital pore counts (Orr and Matarese 2000). All specimens were measured for total length (cm) and selected using length-stratified samples of three to seven females from each centimeter category. The specimen measurement scale was designed so that each 10 cm unit of measure spans the range from −5 to +5 mm total body length (L; note L was measured in centimeters and converted to millimeters for purposes of analysis).

Ovary tissue was excised from each specimen, placed in a labeled histology cassette, which was submerged in a bottle containing a solution of 10% formalin. The maturity collection included specimens as small as 21 cm. This length range was considered fully representative, based on a 1999 Gulf of Alaska northern rock sole maturity collection (Stark and Somerton 2002), which included specimens as small as 19 cm but found no mature females smaller than 30 cm in length.

Northern rock sole growth determinations were made from unpublished AFSC bottom trawl survey age data, stratified by length and area, taken from the eastern Bering Sea and Gulf of Alaska bottoms trawl surveys of 1996, 1999, and 2007. These survey collections were designed to provide the most representative growth data available and allow for valid comparisons between years and areas. The AFSC surveys used standardized fishing methods, including standardized station patterns to assess the condition of groundfish stocks across the eastern Bering Sea. The full bottom depth distribution of northern rock soles was trawl-sampled, and for each North Pacific Fishery Management Council statistical area, specimens were selected using random stratified sampling of two to six specimens from each 1-cm category of total body length distributed. These collections included northern rock sole specimens with body lengths as small as 5 cm, as effected by a standard 0.89-cm-mesh cod end liner in the survey trawl.

Maturity assessment.—In the laboratory the cassette of ovary tissues were then removed from the 10% formalin preservative, dehydrated through graded ethanol, cleared, and embedded in Paraplast blocks. The embedded ovaries were cut into sections 0.003–0.005 mm thick, mounted on a glass slide with a cover slip, stained with hemotoxin, and counterstained with eosin. The cover slip was then sealed onto the slide. The stains were used to unambiguously delineate important structures within the oocytes and ovary. Eosin was used to give a bright pink coloration to all yolk residing within all oocytes contained within the ovary tissue. The eosin also stained fully developed outer cell membranes (chorion) found in all oocytes; maturity stages ranged from cortical alveioi to hydrated. The hemotoxin stain gave a distinct violet coloration to noneosinophylic structures of the cell to make them clearly discernable. All specimens were assessed according to a five-stage scale of ovary maturity based on cell structure criteria (Table 1). Females were classified according to the most advanced stage of histological development that occurred in the ovary. Mature females included those individuals that had any of the yolk-filled oocyte development stages (i.e., vitellogenesis, advanced yolk, and hydrated). Mature females also included those with postovulatory follicles. All the mature females were those expected to spawn that year. Spawning females were those with maturity stage classifications of either hydrated or postovulatory follicle.

Statistical methods.—All analysis utilized S-Plus software (version 2000 Professional release3, MathSoft Inc., Cambridge, Massachusetts). Maturity was estimated as a function of L by fitting a logistic function to the binary maturity data with generalized linear modeling (Venables 1997). The between-month and between-area differences were tested by fitting the model of maturity as a function of L, with and without terms distinguishing month and area, and then judging the significance of the terms via analysis of deviance (Venables 1997). Length at 50% maturity (L_{50}) was estimated for each month and area by evaluating the fitted model of maturity at 50% maturity and

TABLE 1. Ovary development stages and maturity categories assigned to individual northern rock sole females based on histological assessment of the most advanced cellular structures in the ovary.

Development stage	Maturity category	Cellular structures
Perinucleus	Immature	Oocyte with multiple nucleoli bordering the nucleus; chorion absent.
Cortical alveoli	Immature	Oocyte with cortical alveoli adjacent to developing chorion.
Vitellogenesis	Mature	Oocyte predominantly contains yolk spheres.
Advanced yolk	Mature	Oocyte filled with fused yolk; no individual yolk spheres.
Hydrated	Mature and spawning	Oocyte expanded by hydration, located in lumen of ovary.
Postovulatory follicles	Mature and spawning	Postovulatory follicles present.

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algebraically solving for length. The variance of L_{50} was estimated using bootstrapping (Efron and Tibshirani 1993) based on 1,000 resamplings, with replacement, of the maturity and length data. Differences in the L_{50} by month and area were tested with a Z-test (Sokal 1969). The same procedures were used to compare maturity as a function of age and to compare length results from this study with northern data from a Gulf of Alaska study by Stark and Somerton (2002). Based on their study, February was assumed to be the most representative period for sampling because all females that were expected to spawn that year would unambiguously appear to be mature and few would have completed spawning. The March collection provided the means to test whether smaller and younger females matured later in the year than larger females.

Length at age was described by the von Bertalanffy growth function, fitted using nonlinear least squares (Venables 1997). To evaluate differences in northern rock sole growth between areas and years the von Bertalanffy model of growth was fitted to the length-at-age data with terms distinguishing area and year and retested for the combined areas and years. The goodness of fit to the data was tested comparing the separate-category and combined-category models via the likelihood ratio test (Kimura 1980). Otoliths were aged by personnel of the AFSC Age and Growth Program with standard validated methods (Fargo and Chilton 1987; Kimura and Anderl 2005; Kimura et al. 2007), which includes sectioning transversely through the otolith nucleus and heating the otolith to increase the contrast between the growth (transparent) and opaque layers. The growth layers are considered to be the annuli, which are enumerated via a dissecting microscope.

RESULTS

Age and Length at Maturity

The collection included females ranging in length from 210 mm to 490 mm; ages ranged from 4 to 23 years. We found no differences between the February and March collections for maturity at age ($P = 0.89$) and length ($P = 0.73$); consequently the data were pooled to increase sample size to 162 for age and 209 for length. Fifty percent of female northern rock soles in the eastern Bering Sea reached maturity at the age (A_{50}) of approximately 9 years (Figure 1; Table 2), which was significantly ($P < 0.001$) older than for Gulf of Alaska females ($A_{50} = 7$ years; Stark and Somerton 2002). The youngest mature eastern Bering Sea female collected was also the smallest mature female, at 240 mm and age 6. Half the eastern Bering Sea females matured (L_{50}) at 309 mm in the eastern Bering Sea (Figure 2; Table 3), which was significantly ($P = 0.003$) smaller than Gulf of Alaska females (328 mm; Stark and Somerton 2002). The proportion of mature eastern Bering Sea female northern rock soles was similar during February and March 2006, although the rate of spawning increased from less than 5% in February to approximately 30% in March (Figure 3). This result suggests that the spawning season of eastern Bering Sea northern rock soles began just before the February collection period and peaked during the spring.

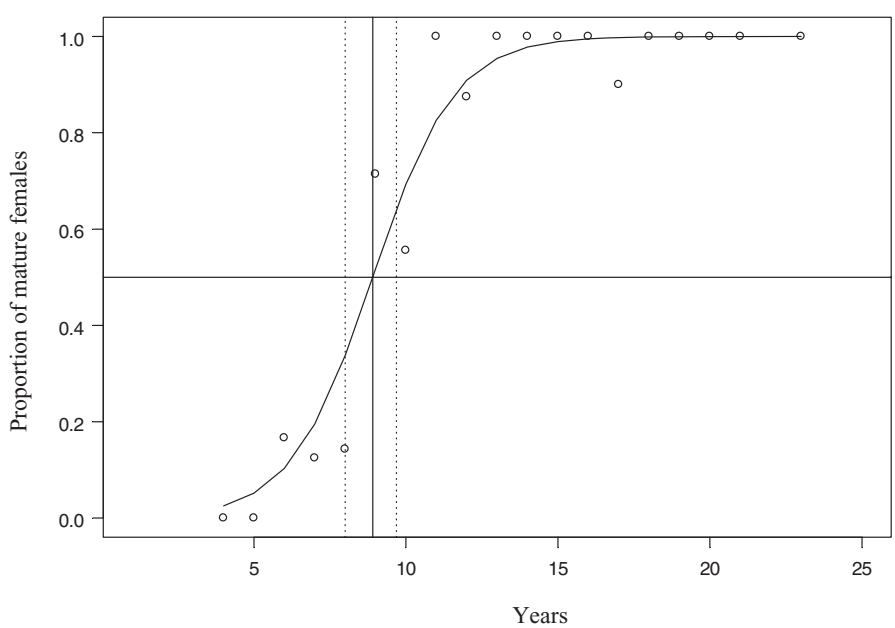

FIGURE 1. Maturity estimated as a function of age for female northern rock soles collected in February and March 2006 ($n = 162$) in the eastern Bering Sea, as depicted by fitting a logistic function to the maturity data. The mean age at 50% maturity (8.9 years) is indicated by solid vertical line; the 95% confidence interval is represented by the dotted lines.

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TABLE 2. Female northern rock sole age-at-maturity results based on ovary histology samples collected from the eastern Bering Sea by the Alaska Fisheries Science Center during February and March 2006. The parameters of the logistic equation fit to the data are n (sample size), B (slope of the line) and its variance, A (y intercept) and its variance, the covariance of A and B (the product of the SDs of B and A and the coefficient of correlation between them), and A_{50} (the age at which 50% of females were expected to reach sexual maturity) and its variance.

Sampling variable	Sampling statistic
n	162
B	0.74466
A	−6.63200
Variance of B	0.00107
Variance of A	5.48510
Covariance of B, A	−0.00385
A_{50} (years)	8.90603
Variance of A_{50}	0.19481

Growth

The precision of rock sole age determinations was tested by AFSC Age and Growth Program personnel (Kimura and Anderl 2005). The average reader and tester agreement for these years averaged 70% (CV = 3). To determine if area differences in length at maturity were consistent with growth, I made the first growth comparison between regions for northern rock sole (Figure 4; Table 4). The results indicate that female growth rates were significantly ($P < 0.001$) faster in the Gulf of Alaska than in the eastern Bering Seas during 1996 and 1999. However, by 2007 the rate of female growth had increased in the eastern Bering Sea to a rate similar to that of the Gulf of Alaska population ($P = 0.69$).

TABLE 3. Female northern rock sole length-at-maturity results based on ovary histology samples collected from eastern Bering Sea trawl samples (1996, 1999, 2007) by the Alaska Fisheries Science Center by date of collection. See Table 2 for additional details.

Sampling variable	Sampling statistic
n	209
B	0.08130
A	−25.09109
Variance of B	6.17796
Variance of A	100.89386
Covariance of B, A	0.00020
L_{50} (mm)	308.62537
Variance of L_{50}	33.12513

DISCUSSION

Length at Maturity and Growth

My study is the first to determine both the age and length at maturity of female northern rock soles in eastern Bering Sea, and the histological maturity classification methods used improved accuracy of the estimates. The results from the February collection were corroborated by the results from the March collection and suggested that by February all females that would mature for the annual maturation cycle had matured.

I estimated that female northern rock soles of the eastern Bering Sea reached L_{50} at 309 mm, which was significantly smaller than the Gulf of Alaska L_{50} estimate of 328 mm. The smallest mature females found in the eastern Bering Sea were 240 mm, compared with 300 mm for the Gulf of Alaska collection. The smaller female L_{50} in the eastern Bering Sea was

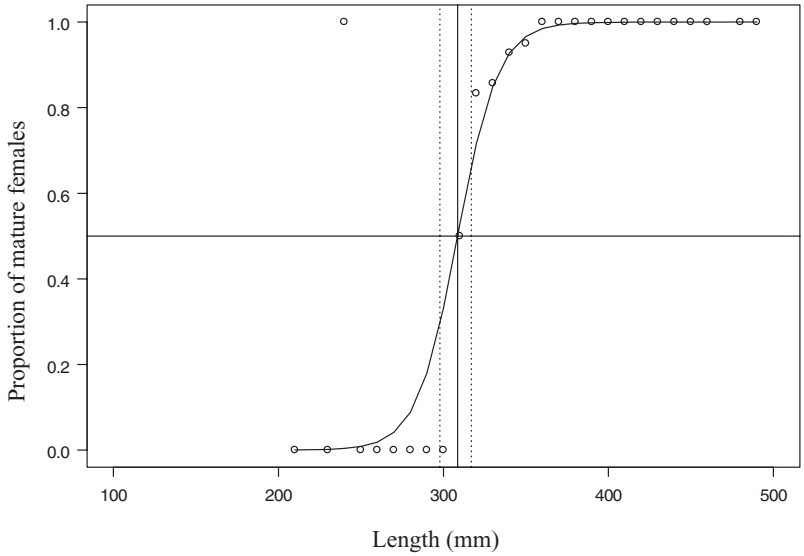

FIGURE 2. Maturity estimated as a function of total length for female northern rock soles collected in February and March 2006 ($n = 209$) in the eastern Bering Sea, as depicted by fitting a logistic function to the maturity data. The mean length at 50% maturity (309 mm) is indicated by solid vertical lines; the 95% confidence interval represented by dotted lines.

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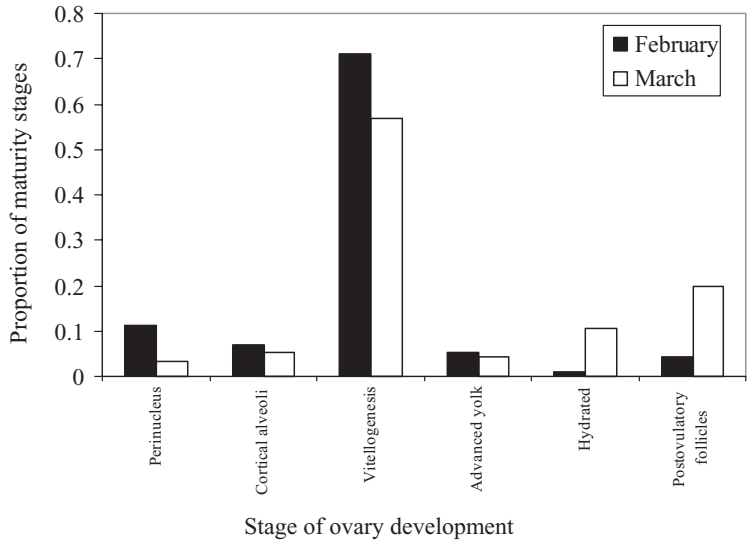

FIGURE 3. Proportion of eastern Bering Sea female northern rock soles classified within each ovarian maturity category from collections made during February ($n = 114$) and March ($n = 95$) of 2006. All females that had reached the 240-mm minimum length at maturity were included to investigate the progression of ovarian maturity.

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probably due to significant differences in the rate of growth between the two populations. The female northern rock sole population in the Gulf of Alaska had approximately twice the rate of growth as the Bering Sea population, during 1996 and 1999. However, by 2007 the rate of growth of the eastern Bering Sea female population had become similar to the growth rate of the Gulf of Alaska population. In contrast, the Gulf of Alaska female population maintained a similar rate of growth during 1996, 1999, and 2007. Growth rates of eastern Bering Sea northern rock sole, and two other flatfish species were directly affected by summer seawater temperatures on the shelf (Matta et al. 2010). Summer is the feeding and growing season for these species, and they have the same feeding grounds every year. The otolith annuli growth correlated chronologically with summertime bottom temperatures for northern rock sole ($R^2 = 0.34$), yellowfin sole *Limanda aspera* ($R^2 = 0.81$), and Alaska plaice *Pleuronectes quadrituburculatus* ($R^2 = 0.61$), based on fish aged as old as 23 years.

Extreme average summer sea bottom temperatures occurred in 1999 (0.83°C) and 2003 (3.87°C), which produced narrow growth annuli within the otoliths of all three flatfish species. In contrast, broad annuli growth occurred during years that had average bottom temperatures of 2.3°C. Colder bottom temperatures correlated with slower growth in northern rock sole, and this was confirmed for northern rock sole reared under laboratory conditions (Hurst and Abookire 2006). The summer

TABLE 4. Female northern rock sole length at age as described by the von Bertalanffy growth equation for females in the Bering Sea and Gulf of Alaska during 1996, 1999, and 2007, based on summer Alaska Fisheries Science Center groundfish surveys. Components include n (the sample size) and equation parameters L_∞ (length at maximum age), k (the estimated growth increment), and t_0 (the theoretical age when fish length is 0).

	Bering Sea			Gulf of Alaska		
Sampling variable	1996	1999	2007	1996	1999	2007
n	280	298	263	142	227	261
L_∞ (mm)	488.807	571.613	418.235	429.3187	434.9223	472.1492
var(L_∞)	193.4323	1022.7257	45.9070	195.5226	430.6108	221.6947
k	0.1096	0.0710	0.1581	0.2360	0.1596	0.1668
var(k)	0.0001	0.0001	0.0001	0.0014	0.0011	0.0004
t_0	0.2563	0.0982	0.9135	0.3869	−0.9860	−0.0352
var(t_0)	0.0329	0.0873	0.0295	0.1944	0.5160	0.1188
cov(L_∞, k)	−0.1039	−0.2548	−0.0558	−0.4391	−0.6405	−0.2609
cov(L_∞, t_0)	−1.8848	−7.9425	−0.7017	−3.6262	−12.1423	−3.4234
cov(k, t_0)	0.0012	0.0022	0.0014	0.0147	0.0223	0.0059

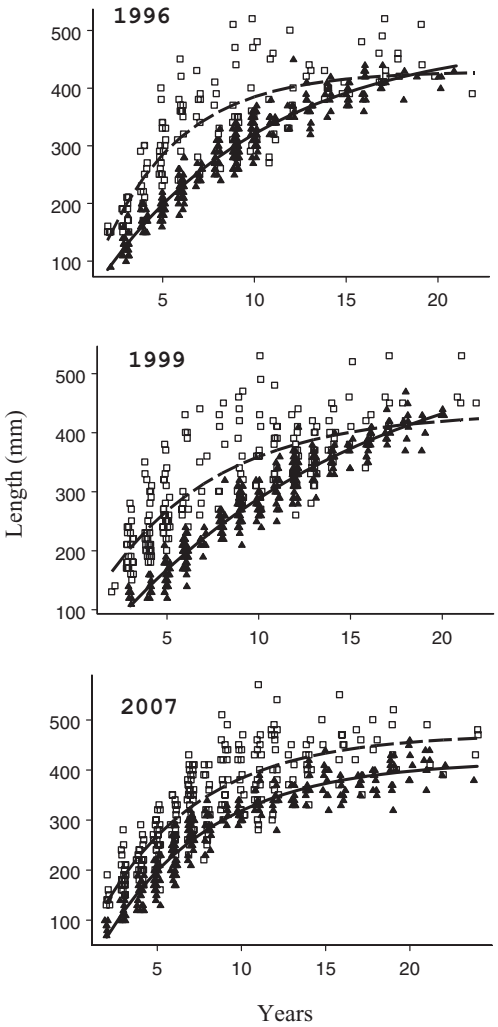

FIGURE 4. Total length at age of female northern rock soled from collections made in the eastern Bering Sea (solid triangles, solid line) and Gulf of Alaska (open squares, dashed line) during areawide groundfish assessment surveys conducted by the Alaska Fisheries Science Center. Sample sizes by year—1996, 1999, and 2007, respectively—were 281, 298, and 263 for the Bering Sea and 142, 227, and 261 for the Gulf of Alaska.

growing period bottom temperatures and spring plankton bloom directly correlate with the extent of the annual winter sea ice sheet formation and the timing and extent of the sea ice melts on the Bering Sea shelf (Stabeno et al. 2001). Sea ice that extends into the shelf during March or April indicates stratification of the water column, which produces an early and intense plankton bloom at the ice edge. This type of plankton bloom can produce up to 65% of the annual primary productivity over the shelf (Niebauer et al. 1990). In years that have strong mixing of the seawater column during March and April, there is no ice formation, and the plankton bloom is delayed until May or June and is attenuated. Water temperatures are expected to undergo more frequent fluctuations and rise an average of 2°C by the year 2050 in the eastern Bering Sea (Hollowed et al. 2009). The change would further affect northern rock sole growth through changes in food supply and body metabolism and, consequently, the size at which females mature in the future. In contrast, females of the Gulf of Alaska northern rock sole population may continue to have a lower interannual variability in growth and mean length at maturity than the eastern Bering Sea population because of a more moderate temperature regime. Compared with the Bering Sea, the Gulf of Alaska is more insulated from arctic temperatures because of its lower latitude and greater circulation of seawater (Stabeno et al. 2001). Consequently, the Gulf of Alaska is not subject to an annual accumulation of sea ice, which can alter the timing and abundance of primary and secondary production and, thereby, northern rock sole metabolism and growth.

Age at Maturity

Although female northern rock soles in the eastern Bering Sea had very different growth rates over years, the age at which females matured was similar between years. Based on my study, the eastern Bering Sea population reached A_{50} at an estimated age of 9 years. The A_{50} estimate was comparable to the previous age estimate of 9–10 years used by eastern Bering Sea stock managers (Wilderbuer and Nichol 2007), that was based on a 1994 collection. Similarities in the estimated female age at maturity in the eastern Bering Sea between 1994 and 2006 suggests that age is a reliable predictor of maturity for northern rock soles, at least for the eastern Bering Sea population. As a consequence of maturing at a significantly older age (2 years older) than Gulf of Alaska females, the eastern Bering Sea population was more dependent upon older females to sustain the population. Females of both populations have the same potential life span (Figure 4). Compared with the younger maturing Gulf of Alaska females, delayed maturation in the eastern Bering Sea means that these females would probably have fewer years available for spawning, potentially decreasing the individual reproductive production from each female.

The results suggest the spawning season begins before February and peaks during the spring for the eastern Bering Sea population, which is consistent with observations by Shubnikov and Lisovenko (1964) in the southeastern Bering Sea and in the Gulf of Alaska (Stark and Somerton 2002). The depth and location of spawning is not well known for the eastern Bering Sea population. In the western Bering Sea northern rock sole spawned in depths less than 200 m (Pertseva-Ostroumova 1961), and in the Gulf of Alaska spawning occurred in depths less than 65 m (Stark and Somerton 2002). The spawning grounds were located within bays, near shore, and on the inner portions of banks in areas that had gravel and a hard sandy bottom. This type of substrate is essential for the attachment of the rock sole's demersal adhesive eggs.

Results of my study provide fishery managers with the necessary maturity estimates that allow them to refine the overfishing and allowable catch limits of northern rock sole in the eastern

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Bering Sea. I determined that age-based maturity estimates would be much more reliable than length-based estimates and provides managers with a much more accurate estimate of the age at which females mature. Consequently managers can now produce more precise estimates of the spawning biomass and spawner–recruit relationship. As a result, managers will have more precise estimates of the maximum sustainable yield, fishery mortality rate, and overfishing limit than was previously possible using other methods.

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