Age- and length-at-maturity of female arrowtooth flounder (*Atheresthes stomias*) in the Gulf of Alaska

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Arrowtooth flounder (*Atheresthes stomias*) has had the highest abundance of any groundfish species in the Gulf of Alaska since the 1970s (Matarese et al., 2003; Turnock et al., 2005; Blood et al., 2007); however, commercial catches have been restricted because Pacific halibut (*Hippoglossus stenolepis*) are caught as bycatch in the fishery. Arrowtooth flounder plays a key role in the ecosystem because it is a dominant organism within the food web, both as an apex predator of fish and invertebrates, as well as an important prey for walleye pollock (*Theragra chalcogramma*; Aydin et al., 2002). Walleye pollock is the dominant groundfish in the Bering Sea, a principal groundfish in the Gulf of Alaska, and the primary prey for marine mammals. The distribution of arrowtooth flounder extends from Cape Navarin and the eastern Sea of Okhotsk in Russia, across the Bering Sea, Aleutian Islands, Gulf of Alaska, and south to the coast of central California (Shuntov, 1964; Britt and Martin, 2001; Chetvergov, 2001; Weinberg et al., 2002; Zenger, 2004). Because of the importance of arrowtooth flounder in the marine ecosystem of Alaska, a maturity study of this species was undertaken to determine age-at-maturity, which is essential for age-based stock management models. Before these results, management has had to rely upon a length-at-maturity-based estimate (Zimmermann, 1997) to manage stocks in the Gulf of Alaska (GOA), Bering Sea, and Aleutian Islands. The central GOA was selected as the location for this maturity study because it contains approximately 70% of the total Gulf of Alaska arrowtooth flounder biomass (1.9×10^6 t, age 3 and older)— the highest percentage in the world (Shuntov, 1964; Britt and Martin, 2001; Weinberg et al., 2002; Wilderbuer and Nichol, 2006).

Materials and methods

All female arrowtooth flounder used in this study were collected with bottom trawls. The central GOA was initially sampled during February 2002 (Fig. 1) from the National Oceanic and Atmospheric Administration (NOAA) ship *Miller Freeman* during an Alaska Fisheries Science Center (AFSC) Recruitment Processes Program cruise (Blood et al., 2007). The area selected for trawling was sampled the prior year by the AFSC and had produced a high abundance of arrowtooth flounder eggs and larvae.

A second collection was made in July 2003 during the AFSC biennial GOA groundfish assessment survey. In both years, whole ovaries and otoliths were collected. All specimens were selected by using length-stratified sampling method so that three to seven females were collected for each cm interval of total body length larger than 18 cm.. The sampling protocol, histological methods, ovary maturity classifications, and aging methods followed those described in Stark (2007). Mature females were those specimens classified with ovary stages ranging from cortical alveoli to postovulatory follicles, which were the same criteria used by Zimmermann (1997) for a September 1993 GOA arrowtooth flounder maturity assessment. To investigate the consistency of oocyte maturation within the ovary, two additional sections were taken from the anterior and medial regions of both ovaries from 10 specimens collected during February 2002 and 10 specimens from July 2003. These sections were compared with the standard sample section taken from the posterior area of one ovary. For all the following procedures, S-Plus software was used (vers. 2000 Professional release 3, MathSoft Inc., Cambridge, MA). Maturity was estimated as a function of length and age by fitting a logistic function to the maturity data with generalized linear modeling (Venables, 1997). The significance of temporal differences was tested by fitting the model of maturity as a function of total body length (L) and age (A), including the date of sampling, and by recalculating without the date term. Significance of the date term was determined by using analysis of deviance (Venables, 1997). The variance of age (A_{50}) and total body length (L_{50}) at 50% maturity were estimated for February 2002 and July 2003 by using bootstrapping (Efron and Tibshirani, 1993) based on 200 resamplings with replacement of the maturity, age, and length data. February 2002 and July 2003 differences in the A_{50} and L_{50}were tested with a Z-test (Sokal, 1969). The February 2002 L_{50} result was also tested against the September 1993-based estimate by Zimmermann (1997) with a Z-test. To assess the temporal progression of ovary maturity between February 2002 and July 2003, ovary maturity classifications were summarized for females that had reached A_{50} as determined by this study.

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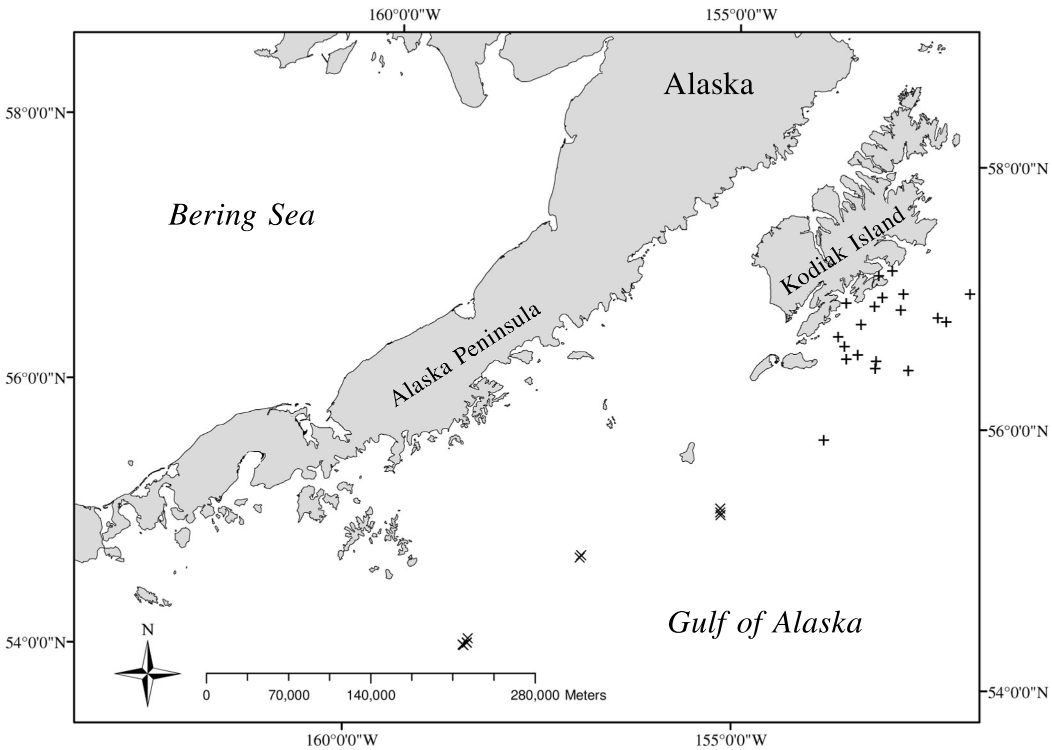

Figure 1

Locations where arrowtooth flounder (*Atheresthes stomias*) were collected by bottom trawl during National Oceanic and Atmospheric Administration Alaska Fisheries Science Center cruises during February 2002 (×) and July 2003 (+) in the Gulf of Alaska.

To determine if ovary growth occurred between February and July, the gonadosomatic index (somatic body weight/ovary weight, *I*G) of females $\geq A_{50}$ was determined by methods described by Stark (2007). The comparison did not include females with hydrated oocytes or postovulatory follicles.

Results

In the February 2002 collection, approximately 50% of the females were classified as spawning and 10% were nearing spawning condition (advanced yolk). By July, spawning activity was <5% but continuing, and 20% of the females were at the advanced yolk stage of maturity based on the 2003 collection.

Mature female arrowtooth flounder were found in every location where sample collections were made, namely on the outer continental shelf at 101–200 m depths and upper slope at 301–700 m depths, during February 2002. During July 2003, the locations and depths sampled ranged from the intertidal zone at 1–100 m down to the continental banks, gullies, and outer shelf at 101–200 m. Mature female specimens were as young as 3 years of age and 260 mm *L*.

This study was the first to determine that age was a significant predictor ($P<0.001$) of maturity for female arrowtooth flounder. The estimated age at 50% maturity (A_{50}) was 7.0 years, based on the February 2002 collection (Fig. 2, Table 1). The February 2002 result did not differ significantly ($P=0.38$) from the July 2003 result (6.6 years). Of the two results, the February 2002 A_{50} estimate had a much lower variance (Table 2) and consequently was the most reliable. The estimated length at which 50% of the females were mature (L_{50}) was 460 mm for the February 2002 collection (Fig. 3, Table 2) and did not differ ($P= 0.68$) for the July 2003 collection (464 mm). However, the variance of the L_{50} estimate was much lower for the February 2002 collection, and thus February represented the more optimal month for assessing arrowtooth flounder maturity. Oocyte development was consistent within the ovaries and between each ovary pair for every compared specimen. No significant growth occurred between February and July, based on the *I*G results, which declined from a mean of 3.6 *I*G in February 2002 (n=167) to 1.8 *I*G in July 2003 (n=115).

Discussion

This study was the first to establish arrowtooth flounder age-at-maturity. The estimated age at 50% maturity (A_{50}=7 years) in the GOA was based on the February

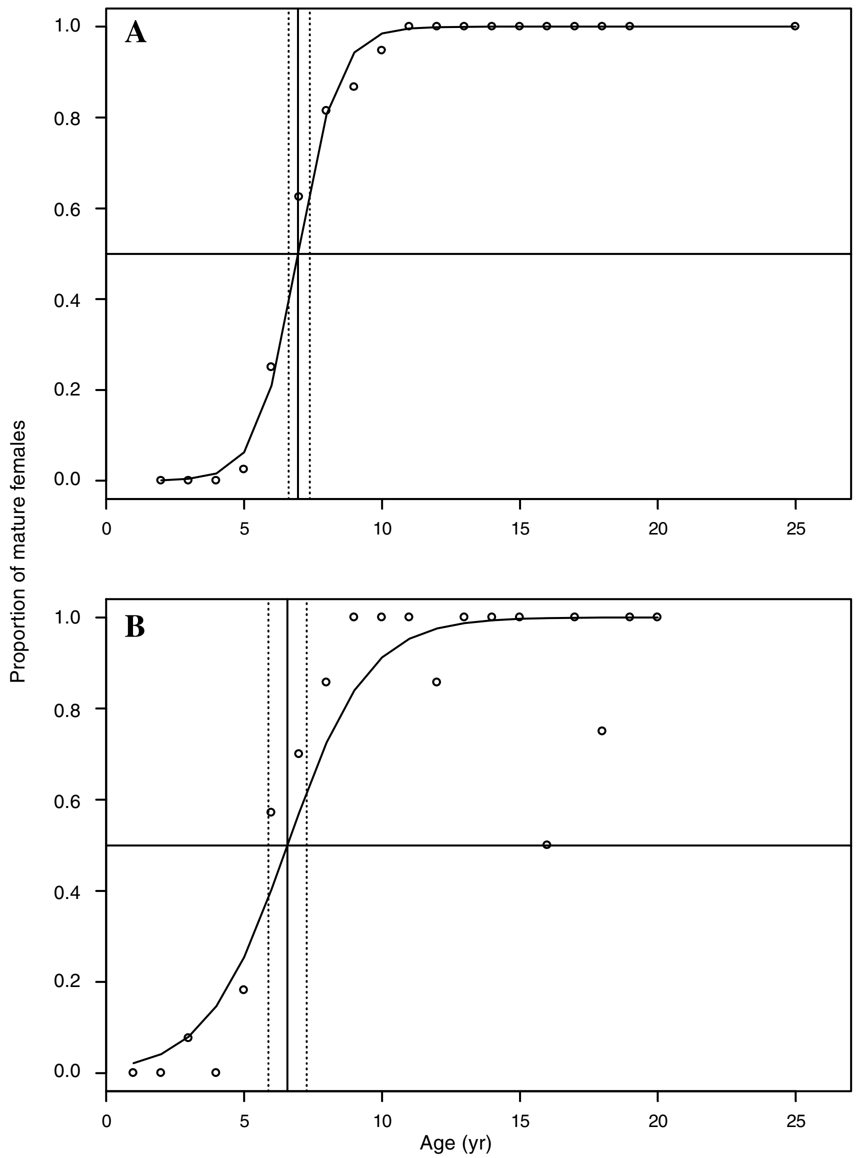

Figure 2

Maturity estimated as a function of age for female arrowtooth flounder (*Atheresthes stomias*) in the Gulf of Alaska by fitting a logistic function to the maturity data based on (**A**) the February 2002 (n=301) collection, and (**B**) the July 2003 (n=226) collection. Mean age at 50% maturity, indicated by the solid vertical lines, was 7.0 years (A) and 6.6 years (B) and 95% confidence intervals are represented by dotted lines.

2002 maturity collection results that were supported by the July 2003 results. Age-based estimates of maturity should be less variable, and less affected by changes in environmental conditions, population abundance, and spawning biomass levels than length-based estimates. Those changes can affect arrowtooth flounder growth rates. Growth was significantly faster for Pacific cod (*Gadus macrocephalus*) in the Bering Sea than in the Gulf of Alaska (Stark, 2007). Together with growth, cod L_{50} differed significantly (P<0.001) between areas; in contrast, cod A_{50} differed only slightly (P=0.02). Therefore, age-based maturity estimates should generally be considered the more reliable.

Although not as reliable, the estimated length-at-maturity of female arrowtooth flounder has remained stable in the GOA, based on the results of this study

Table 1

Female arrowtooth flounder (*Atheresthes stomias*) age-at-maturity results based on ovary histological samples (n) collected between the spawning and late spawning periods in the Gulf of Alaska by date of collection. The parameters of the logistic equation that were used to fit the data were the following: B (slope of the line) and A (y intercept), variance (the square of the standard deviation of B and A), covariance (the product of the standard deviations of B and A and the coefficient of correlation between them), age (years) at which 50% of females were expected to reach sexual maturity (A_{50}), and variance of A_{50}.

	Date of collection	
	February 2002	July 2003
n	301	226
B	1.3817	0.6835
A	–9.6183	–4.4945
Variance (B)	0.0077	0.0016
Variance (A)	1.7381	1.3528
Covariance (B, A)	0.0070	0.0007
A_{50}	6.9614	6.5754
Variance (A_{50})	0.0326	0.1448

Table 2

Female arrowtooth flounder (*Atheresthes stomias*) length-at-maturity results based on ovary histology samples (n) collected between the spawning and late spawning periods in the Gulf of Alaska by date of collection. The parameters of the logistic equation that were used to fit the data were the following: B (slope of the line) and A (y intercept), variance (the square of the standard deviation of B and A), covariance (the product of the standard deviations of B and A and the coefficient of correlation between them), length (mm) at which 50% of females were expected to reach sexual maturity (L_{50}), and variance of L_{50}.

	Date of collection	
	February 2002	July 2003
n	303	251
B	0.0455	0.0215
A	–20.9220	–9.9786
Variance (B)	1.1171	2.9534
Variance (A)	6.9072	6.3385
Covariance (B, A)	0.0002	–0.0002
$L_{50\ (mm)}$	459.6917	464.1629
Variance (L_{50})	27.5705	75.9320

and the 1993 maturity study results by Zimmermann (1997). For this present study, the estimated female L_{50} was 460 mm, which did not differ significantly (P=0.08) from the September 1993 L_{50} estimate of 469 mm. Currently, that length-at-maturity estimate is used to manage the arrowtooth flounder stocks of both the GOA and Bering Sea, because the A_{50} has not been known. Consequently, with the use of the age-at-maturity estimates determined in the present study, the estimates of arrowtooth flounder abundance would be expected to improve significantly within the stock management model.

Stock management would also benefit from a determination of the arrowtooth flounder annual spawning period. The arrowtooth flounder spawning period probably begins in December, based on results from the AFSC ichthyoplankton surveys in the Gulf of Alaska, during which developing embryos and larvae were found at the end of January (Blood et al., 2007). The rate of spawning declined from February 2002 (50%) to July 2003 (<5%), according to this study. Spawning may conclude at the end of summer because Zimmermann (1997) found no spawning females during September. Therefore, the overall spawning period of arrowtooth flounder appears to extend for over 8 months or more in the GOA. This is a longer spawning period than has been found for other principal groundfish species in Alaska, which have spawning periods of 6 months or less (Matarese et al., 2003; Stark, 2004, 2007). A protracted spawning period could promote stock recruitment by increasing the dispersion of progeny and thereby increasing the probability of placing progeny in a favorable rearing environment. Turnock et al. (2005) estimated that the spawning biomass of female arrowtooth flounder has increased annually since 1961 (1.98×10^5 t) and remains above 1.24×10^6 t in the GOA. Similarly, the spawning biomass was estimated to be at its highest level ever recorded in the Bering Sea and Aleutian Islands, at more than 8.24×10^5 t (Wilderbuer and Nichol, 2006). However, the size of the spawning biomass may be overestimated for the Bering Sea and Aleutian Islands because of the reliance on the Gulf of Alaska L_{50} estimate for the Bering Sea and Aleutian Islands management model. This overestimate could occur if the rate of female arrowtooth flounder growth was significantly higher for the Bering Sea and Aleutian Islands population than it was for the Gulf of Alaska population. A significantly higher rate of growth could result in a significantly larger L_{50}, which could lower the spawning biomass estimate by excluding smaller females that may have been mature. Therefore, the estimates of the arrowtooth flounder spawning biomass that are determined by stock managers should be more reliable after the current length-based maturity models are replaced with age-based maturity models using the A_{50} estimate from this study.

Conclusions

Arrowtooth flounder has consistently been the most abundant groundfish species in the Gulf of Alaska because of its high levels of recruitment and low fishing-induced mortality. Age was found to be a significant

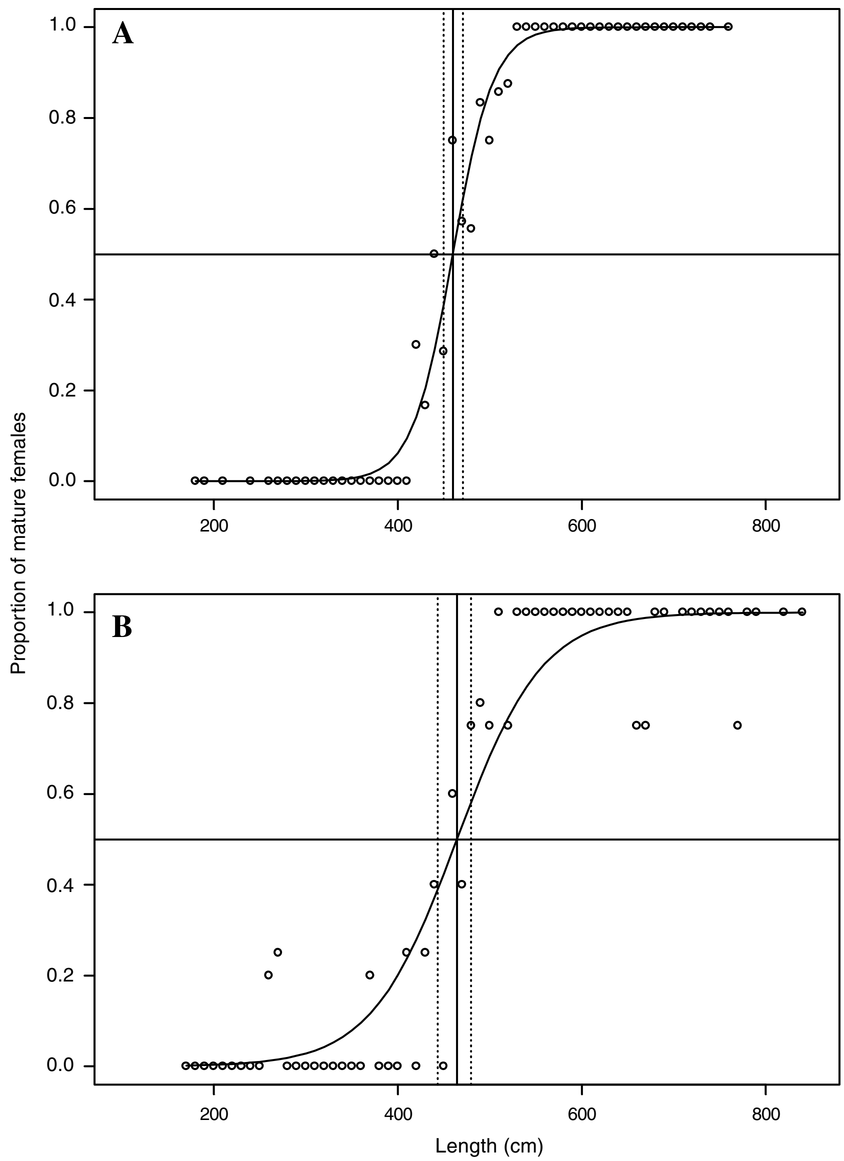

Figure 3

Maturity estimated as a function of total length (L) for female arrowtooth flounder (*Atheresthes stomias*) in the Gulf of Alaska by fitting a logistic function to the maturity data based on the (**A**) February 2002 collection (n=303), and (**B**) July 2003 collection (n=251). Mean length at 50% maturity, indicated by solid vertical lines, was 460 mm (A) and 464 mm (B) and 95% confidence intervals are represented by dotted lines.

predictor of female maturity in this study and a mean age-at-maturity (A_{50}, 7 years) was established for female arrowtooth flounder that will allow for the development of an improved stock management model. The model should provide more reliable estimates of arrowtooth flounder abundance in the Gulf of Alaska as well as the Bering Sea. This study also documented the total body length (L 460 mm) at which 50% of the females are mature in the Gulf of Alaska—an estimate that did not differ significantly from a 1993-based estimate.

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