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Potential Natural Mortality Rates of North Pacific Swordfish, *Xiphias gladius*

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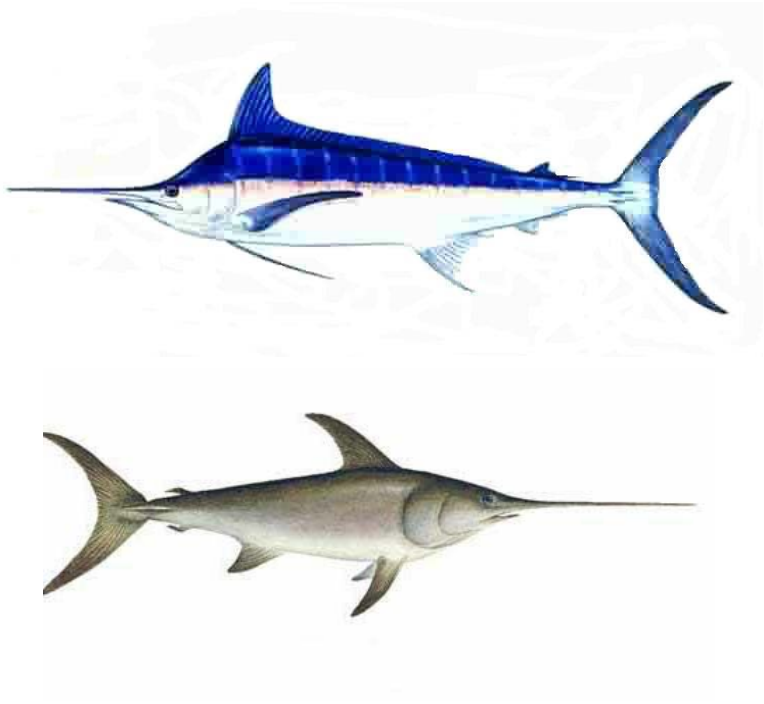

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Abstract

Natural mortality rates are key parameters for stock assessments that are generally not well determined (Vetter 1988). In this working paper, potential natural mortality rates for assessing North Pacific swordfish were investigated. Natural mortality rates (M) were estimated using several empirical and theoretical approaches that depend on estimates of life history parameters. Sex-specific estimates of M were developed to account for sexual dimorphism in swordfish growth. Age-dependent estimates of M were also evaluated to account for changes in survival rates as fish age.

Materials and Methods

Empirical and theoretical models have been constructed to estimate the instantaneous natural mortality rate of marine fish and invertebrate stocks. Empirical approaches to estimating M due to Alverson and Carney (1975), Pauly (1980), Hoenig (1983), Lorenzen (1996), and Hewitt and Hoenig (2005) were applied to North Pacific swordfish. Theoretical approaches developed by Peterson and Wroblewski (1984), Jensen (1996), and Chen and Watanabe (1989) were also considered. In what follows, a brief description of each approach is provided along with the required life history data for the primary analysis using the Central North Pacific data and the sensitivity analysis using the Eastern North Pacific data.

Alverson and Carney (1975) considered the relationship between the critical age (T*) at which the biomass of an individual cohort was maximized and the natural mortality rate where growth followed an isometric von Bertalanffy curve with Brody growth coefficient K

$$T^* = \frac{1}{K}\log\left(\frac{M+3K}{M}\right) \tag{0.1}$$

This can be solved to give an expression for M as a function of T* and K

$$M = \frac{3K}{\exp(K \cdot T^*) - 1} \tag{0.2}$$

Alverson and Carney (1975) estimated that $T^* \approx 0.38 T_{MAX}$ where T_{MAX} is the maximum observed age in the fish stock based on an empirical regression with 66 fish stocks. This approximation was used to estimate T* for equation (0.2). Required inputs for the Alverson and Carney method were K and T_{MAX}. These values were available in length units of eye-fork length for both Central and Eastern North Pacific swordfish populations (Table 1, Figure 1).

Pauly (1980) developed a predictive regression model from data on 175 fish stocks to estimate annual natural mortality rate (units are y^{-1}) as a function of Brody growth coefficient K (units are y^{-1}), asymptotic length (L_{INF}, units are cm), and mean water temperature (T, units are ˚C). The predictive relationship, converted to natural logarithmic units from the original paper (Quinn and Deriso 1999) was

(0.3) $$\log(M) = -0.0152 - 0.279\log(L_{INF}) + 0.6543\log(K) + 0.4634\log(T)$$

Input life history parameters were available for swordfish collected in the Central and Eastern North Pacific and the mean water temperature was approximated as T=20˚C using the average of the temperature range of swordfish reported by Nakamura (1985).

Hoenig (1983) developed another set of predictive models for the natural mortality rate. Based on the estimated relationship between M (y^{-1}) and maximum observed age in 84 fish stocks, M was predicted to be

(0.4) $$\log(M) = 1.46 - 1.01 \cdot \log(T_{MAX}) \quad or \quad M \approx \frac{4.31}{(T_{MAX})^{1.01}}$$

Estimates of maximum observed age for predicting M were available for both Central and Eastern North Pacific swordfish populations (Table 1).

Lorenzen (1996) developed a set of empirical relationships for natural mortality as a function of body weight (W) in different aquatic ecosystems. The general relationship between annual natural mortality and weight (g) was

(0.5) $$M(W) = M_U \cdot W^b$$

where M_U was natural mortality at unit weight and "b" was an allometric scaling exponent. Lorenzen's estimates of M_U and b for ocean ecosystems (M_U=3.69 and b= -0.305), tropical systems (M_U=3.08 and b= -0.210), and temperate systems (M_U=3.13 and b= -0.309) were applied to predicted weight at age of swordfish in the Central and Eastern North Pacific. In this case, the von Bertalanffy curves for the Central and Eastern North Pacific were used to predict mean length at age and length-weight relationships ($W=aL^b$) were applied to predict mean weight at age for input to eqn 0.5 (Table 1, Figure 2).

Hewitt and Hoenig (2005) compared two approaches for estimating natural mortality rates: Hoenig (1983) and the 5% rule of thumb. They found that the regression approach of Hoenig was recommended because it had an empirical basis and did not depend on an arbitrary constant. Regardless, the 5% rule of thumb was applied to predict swordfish natural mortality using the observed maximum ages. In this case, the chance of observing the maximum swordfish age was assumed to be 5%, on average. This implies that M is a function of the assumed 5% value and T_{MAX} where

(0.6) $$0.05 = \exp(-M \cdot T_{MAX}) \quad or \quad M = \frac{3.00}{T_{MAX}}$$

This expression was applied to the observed values of T_{MAX} for the Central and Eastern North Pacific (Table 1).

Peterson and Wroblewski (1984) developed a theoretical relationship between natural mortality rate and the body mass in the pelagic ecosystem. Their approach depends on a general equation for describing the size distribution of organisms in the pelagic food chain assuming that mortality is primarily due to predation and that there is constant influx of biomass at the base of the food chain. Their expected relationship between body weight (units are g) and natural mortality rate (units are y^{-1}) was

(0.7) $$M(W) = 1.92 \cdot W^{-0.25}$$

As in the Lorenzen estimator, the von Bertalanffy curves for the Central and Eastern North Pacific were used to predict mean length at age and length-weight relationships ($W=aL^b$) were applied to predict mean weight at age for input to eqn 0.7 (Table 1).

Jensen (1996) investigated the so-called Beverton-Holt life history invariants and their relationship to tradeoffs between the energetic costs of reproduction and survival. Maximizing fecundity as a function of age of reproduction (T_{MAT}) assuming von Bertalanffy growth leads to

(0.8) $$T_{MAT} = \frac{1}{K} \cdot \log\left(\frac{3K + M}{M}\right)$$

Assuming that the age of maturity corresponds to the inflection point of the isometric weight at age relationship, the value of $T_{MAT} = \log(3)/K$. This leads to the first Beverton-Holt invariant relating natural mortality and age at maturity as

(0.9) $$M = \frac{1.65}{T_{MAT}}$$

The second Beverton-Holt invariant is derived from the first invariant and the inflection point assumption to give

(0.10) $$M = 1.5 \cdot K$$

To apply the first invariant, estimates of a logistic model for swordfish length at maturity for the Central Pacific (Table 1) were collected from DeMartini et al. (2000). Age at maturity was assumed to occur at the age associated with the length at 95% probability of being mature (Figure 3). No values of swordfish length or age at maturity were available from the Eastern Pacific. In this case, age at maturity values from the Central Pacific were imputed. This second invariant was applied to the observed values of K for the Central and Eastern North Pacific (Table 1).

Chen and Watanabe (1989) developed an age-specific estimator of natural mortality for fish species with a von Bertalanffy growth pattern assuming that natural mortality was inversely related to a measure of growth at age, e.g., $M(t) \propto \frac{1}{G(t)}$

This relationship provided an approximation of the theoretical expectation of a bathtub-shaped natural mortality curve which includes an initial high juvenile death rate, a lower stable adult death rate, and a higher senescent death rate. The natural mortality at age function had a change point at the age corresponding to the end of the reproductive span of the fish (T_S). Their estimator of natural mortality at age t was

$$M(t) = \frac{K}{1-\exp\left(-K\left(t-T_0\right)\right)} \quad if \quad t \le T_S \quad or$$

(0.11)

$$M(t) = \frac{K}{a_0 + a_1\left(t-T_S\right) + a_2\left(t-T_S\right)^2} \quad if \quad t > T_S$$

where the constants a_0, a_1, and a_2 depended on the von Bertalanffy parameters and T_S as

$$a_0 = 1-\exp\left(-K\left(T_S-T_0\right)\right)$$

(0.12)

$$a_1 = K\cdot\exp\left(-K\left(T_S-T_0\right)\right)$$

$$a_2 = \frac{-1}{2}K^2\cdot\exp\left(-K\left(T_S-T_0\right)\right)$$

Values of von Bertalanffy parameters were available for the Central and Eastern North Pacific (Table 1). No data were available to estimate the reproductive life span and it was assumed that $T_S = T_{SMAX} - 2$.

Results

Estimates of annual female swordfish mortality in the Central North Pacific exhibited a wide range of age-specific values (Table 2.1). For the constant natural mortality rate estimators, estimates of M ranged from M=0.25 to M=0.38 with five out of six values between M=0.35 to M=0.38. In this case, the outlier was the 5% rule of thumb estimator. The age-specific natural mortality estimates ranged from low values of M≈0.20 at age-1 to higher values of M≈0.50 at age-1. The Lorenzen tropical system and Chen and Watanabe estimators were more consistent with the constant natural mortality estimates for female swordfish than the other age-specific estimators.

Estimates of annual male swordfish natural mortality in the Central Pacific exhibited a similar pattern to that of females (Table 2.2). The age-specific estimates varied considerably among approaches. Four out of six of the constant M estimators range from M=0.38 to M=0.41 with the 5% rule of thumb producing a much lower value (M=0.27) and the Beverton-Holt invariant 1 producing a much larger value (M=0.83). In this case, the male estimate of age of maturity (T_{MAT}=2 y) had a strong influence on the estimated M value. Overall, the Lorenzen tropical system and Chen and Watanabe estimators were most consistent with the constant natural mortality estimates for male swordfish.

Estimates of unfished female swordfish probability of survival to age in the Central North Pacific could be grouped into two general patterns (Table 2.3, Figure 4.1). The first pattern had estimates of survival probability to the maximum observed age that were on the order of 1% to 5% which is consistent with expectations. The second pattern had an anomalously high probability of survival to age-12 (>25%) and mean generation times in excess of 9 years (Table 2.3). Overall, the calculated survival probabilities showed that some of the age-specific estimators (Peterson and Wroblewski, Lorenzen ocean and temperate system) did not appear to be consistent with the maximum observed female age.

Estimates of unfished male swordfish probability of survival to age in the Central North Pacific were similar to those of females (Table 2.4). Eight out of eleven estimators had

probabilities of survival to age on the order of 1% to 5% that were consistent with the maximum observed age of male swordfish. The remaining three age-specific estimators (Peterson and Wroblewski, Lorenzen ocean and temperate system) did not appear to be consistent with the maximum observed male age.

Alternative estimates of female and male swordfish natural mortality at age based on Eastern North Pacific life history parameters exhibited greater variation than those based on the Central North Pacific data (Tables 3.1 and 3.2). The associated probabilities of survival to age suggested that several estimators were not consistent with the expectation of 1% to 5% survival to maximum observed age (Tables 3.3 and 3.4); these included Peterson and Wroblewski, Alverson and Carney, Pauly, Beverton and Holt Invariant 2, Lorenzen Ocean and Temperate Systems.

Overall, the Hoenig (1983), Alverson and Carney (1975), Pauly (1980), and Beverton-Holt invariant 2 (Jensen 1996) provided consistent estimates of constant natural mortality of female and male swordfish in the Central North Pacific with M ranging from roughly M=0.35 to M=0.41 y^{-1}. Of the variable M estimators, the Lorenzen (1996) tropical system estimator appeared to provide the most plausible results that were consistent with the central tendency of the constant M estimators.

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Table 1. North Pacific swordfish life history parameters used to estimate potential natural mortality rates.

Life History Parameter	Female Value	Male Value	Source
Central North Pacific Von Bertalanffy growth parameters (cm of eye-fork length)	K=0.246 ± 0.019 L_{INF}=230.5 ± 3.94 T_0= -1.24 ± 0.167	K=0.271 ± 0.034 L_{INF}=208.9 ± 5.60 T_0= -1.37 ± 0.259	Uchiyama and Humphreys (2007), DeMartini et al (2007)
Central North Pacific maximum observed age T_{MAX} (y)	T_{MAX}=12	T_{MAX} =11	Uchiyama and Humphreys (2007), DeMartini et al (2007)
Central North Pacific length-weight relationship pooled sexes (cm of eye fork length, kg)	$W=aL^b$ a=0.000012988 b=3.0738		Uchiyama and Humphreys (2007)
Eastern North Pacific Von Bertalanffy growth coefficient K (cm of eye-fork length)	K=0.1162 L_{INF}=263.7 T_0= 4.05	K=0.077 L_{INF}=273.2 T_0= -3.20	Uchiyama and Humphreys (2007), Castro-Longoria (1995)
Central North Pacific maturity probability (p(L) at length (cm of eye fork length)	$p(L) = \left(1+\exp\left(\frac{-(L-L_{50})}{\sigma}\right)\right)^{-1}$ L_{50}=143.6 σ =9.67	L_{50}=102.0 σ =7.08	
Eastern North Pacific maximum observed age T_{MAX} (y)	T_{MAX}=9+	T_{MAX}=7+	Uchiyama and Humphreys (2007), Castro-Longoria (1995)
Eastern North Pacific length-weight relationship pooled sexes (cm of eye fork length, kg)	$W=aL^b$ a=0.0000137 b=3.04	$W=aL^b$ a=0.00000662 b=3.19	Uchiyama and Humphreys (2007)

Table 2.1. Estimates of female swordfish natural mortality at age (y^{-1}) in half-year increments in the Central North Pacific.

Estimates of Central North Pacific Female Swordfish Natural Mortality at Age

Age (yr)	Female Length (cm)	Female Weight (kg)	Female Fraction Mature	Peterson & Wroblewski Female Natural Mortality	Hoenig Fish 1983 Female Natural Mortality	Hewitt and Hoenig Percent Rule Female Natural Mortality	Alverson and Carney Female Natural Mortality	Pauly Female Natural Mortality	Jensen BH Invariant 1 Female Natural Mortality	Jensen BH Invariant 2 Female Natural Mortality	Lorenzen Ocean Ecosystem Female Natural Mortality	Lorenzen Tropical Ecosystem Female Natural Mortality	Lorenzen Temperate Ecosystem Female Natural Mortality	Chen and Watanabe Female Natural Mortality
0.5	80	9.3	0.00	0.20	0.35	0.25	0.36	0.35	0.38	0.37	0.23	0.45	0.19	0.71
1	98	17.0	0.01	0.17	0.35	0.25	0.36	0.35	0.38	0.37	0.19	0.40	0.15	0.58
1.5	113	26.6	0.04	0.15	0.35	0.25	0.36	0.35	0.38	0.37	0.17	0.36	0.13	0.50
2	127	37.7	0.15	0.14	0.35	0.25	0.36	0.35	0.38	0.37	0.15	0.34	0.12	0.45
2.5	139	49.8	0.37	0.13	0.35	0.25	0.36	0.35	0.38	0.37	0.14	0.32	0.11	0.41
3	149	62.5	0.64	0.12	0.35	0.25	0.36	0.35	0.38	0.37	0.13	0.30	0.10	0.38
3.5	159	75.4	0.83	0.12	0.35	0.25	0.36	0.35	0.38	0.37	0.12	0.29	0.10	0.36
4	167	88.2	0.92	0.11	0.35	0.25	0.36	0.35	0.38	0.37	0.11	0.28	0.09	0.34
4.5	174	100.7	0.96	0.11	0.35	0.25	0.36	0.35	0.38	0.37	0.11	0.27	0.09	0.33
5	181	112.7	0.98	0.10	0.35	0.25	0.36	0.35	0.38	0.37	0.11	0.27	0.09	0.31
5.5	187	124.1	0.99	0.10	0.35	0.25	0.36	0.35	0.38	0.37	0.10	0.26	0.08	0.30
6	192	134.8	0.99	0.10	0.35	0.25	0.36	0.35	0.38	0.37	0.10	0.26	0.08	0.30
6.5	196	144.7	1.00	0.10	0.35	0.25	0.36	0.35	0.38	0.37	0.10	0.25	0.08	0.29
7	200	153.9	1.00	0.10	0.35	0.25	0.36	0.35	0.38	0.37	0.10	0.25	0.08	0.28
7.5	204	162.4	1.00	0.10	0.35	0.25	0.36	0.35	0.38	0.37	0.10	0.25	0.08	0.28
8	207	170.1	1.00	0.09	0.35	0.25	0.36	0.35	0.38	0.37	0.09	0.25	0.08	0.27
8.5	210	177.2	1.00	0.09	0.35	0.25	0.36	0.35	0.38	0.37	0.09	0.24	0.07	0.27
9	212	183.6	1.00	0.09	0.35	0.25	0.36	0.35	0.38	0.37	0.09	0.24	0.07	0.27
9.5	214	189.4	1.00	0.09	0.35	0.25	0.36	0.35	0.38	0.37	0.09	0.24	0.07	0.26
10	216	194.6	1.00	0.09	0.35	0.25	0.36	0.35	0.38	0.37	0.09	0.24	0.07	0.26
10.5	218	199.3	1.00	0.09	0.35	0.25	0.36	0.35	0.38	0.37	0.09	0.24	0.07	0.26
11	219	203.5	1.00	0.09	0.35	0.25	0.36	0.35	0.38	0.37	0.09	0.24	0.07	0.26
11.5	220	207.2	1.00	0.09	0.35	0.25	0.36	0.35	0.38	0.37	0.09	0.24	0.07	0.26
12	222	210.6	1.00	0.09	0.35	0.25	0.36	0.35	0.38	0.37	0.09	0.23	0.07	0.26
12.5	223	213.6	1.00	0.09	0.35	0.25	0.36	0.35	0.38	0.37	0.09	0.23	0.07	0.26

Table 2.2. Estimates of male swordfish natural mortality at age (y^{-1}) in half-year increments in the Central North Pacific.

Estimates of Central North Pacific Male Swordfish Natural Mortality at Age

Age (yr)	Male Length (cm)	Male Weight (kg)	Male Fraction Mature	Peterson & Wroblewski Male Natural Mortality	Hoenig Fish 1983 Male Natural Mortality	Hewitt and Hoenig Percent Rule Male Natural Mortality	Alverson and Carney Male Natural Mortality	Pauly Male Natural Mortality	Jensen BH Invariant 1 Male Natural Mortality	Jensen BH Invariant 2 Male Natural Mortality	Lorenzen Ocean Ecosystem Male Natural Mortality	Lorenzen Tropical Ecosystem Male Natural Mortality	Lorenzen Temperate Ecosystem Male Natural Mortality	Chen and Watanabe Male Natural Mortality
0.5	83	10.3	0.06	0.19	0.38	0.27	0.39	0.38	0.83	0.41	0.22	0.44	0.09	0.68
1	99	17.7	0.40	0.17	0.38	0.27	0.39	0.38	0.83	0.41	0.19	0.39	0.09	0.57
1.5	113	26.5	0.82	0.15	0.38	0.27	0.39	0.38	0.83	0.41	0.17	0.36	0.09	0.50
2	125	36.3	0.96	0.14	0.38	0.27	0.39	0.38	0.83	0.41	0.15	0.34	0.08	0.45
2.5	136	46.6	0.99	0.13	0.38	0.27	0.39	0.38	0.83	0.41	0.14	0.32	0.08	0.42
3	145	57.1	1.00	0.12	0.38	0.27	0.39	0.38	0.83	0.41	0.13	0.31	0.08	0.39
3.5	153	67.5	1.00	0.12	0.38	0.27	0.39	0.38	0.83	0.41	0.12	0.30	0.08	0.37
4	160	77.6	1.00	0.12	0.38	0.27	0.39	0.38	0.83	0.41	0.12	0.29	0.08	0.35
4.5	166	87.2	1.00	0.11	0.38	0.27	0.39	0.38	0.83	0.41	0.11	0.28	0.08	0.34
5	172	96.2	1.00	0.11	0.38	0.27	0.39	0.38	0.83	0.41	0.11	0.28	0.08	0.33
5.5	176	104.5	1.00	0.11	0.38	0.27	0.39	0.38	0.83	0.41	0.11	0.27	0.07	0.32
6	181	112.2	1.00	0.10	0.38	0.27	0.39	0.38	0.83	0.41	0.11	0.27	0.07	0.31
6.5	184	119.2	1.00	0.10	0.38	0.27	0.39	0.38	0.83	0.41	0.10	0.26	0.07	0.31
7	187	125.5	1.00	0.10	0.38	0.27	0.39	0.38	0.83	0.41	0.10	0.26	0.07	0.30
7.5	190	131.3	1.00	0.10	0.38	0.27	0.39	0.38	0.83	0.41	0.10	0.26	0.07	0.30
8	192	136.4	1.00	0.10	0.38	0.27	0.39	0.38	0.83	0.41	0.10	0.26	0.07	0.29
8.5	195	141.0	1.00	0.10	0.38	0.27	0.39	0.38	0.83	0.41	0.10	0.26	0.07	0.29
9	196	145.1	1.00	0.10	0.38	0.27	0.39	0.38	0.83	0.41	0.10	0.25	0.07	0.29
9.5	198	148.8	1.00	0.10	0.38	0.27	0.39	0.38	0.83	0.41	0.10	0.25	0.07	0.29
10	199	152.0	1.00	0.10	0.38	0.27	0.39	0.38	0.83	0.41	0.10	0.25	0.07	0.28
10.5	201	154.9	1.00	0.10	0.38	0.27	0.39	0.38	0.83	0.41	0.10	0.25	0.07	0.28
11	202	157.4	1.00	0.10	0.38	0.27	0.39	0.38	0.83	0.41	0.10	0.25	0.07	0.28
11.5	203	159.6	1.00	0.10	0.38	0.27	0.39	0.38	0.83	0.41	0.10	0.25	0.07	0.28

Table 2.3. Estimates of female swordfish unfished survival probabilities at age in the Central North Pacific.

Estimates of Central North Pacific Female Swordfish Unfished Survival Probability at Age

Age Class (yr)	Female Length (cm)	Female Weight (kg)	Female Fraction Mature	Peterson & Wroblewski Female Natural Mortality	Hoenig Fish 1983 Female Natural Mortality	Hewitt and Hoenig Percent Rule Female Natural Mortality	Alverson and Carney Female Natural Mortality	Pauly Female Natural Mortality	Jensen BH Invariant 1 Female Natural Mortality	Jensen BH Invariant 2 Female Natural Mortality	Lorenzen Ocean Ecosystem Female Natural Mortality	Lorenzen Tropical Ecosystem Female Natural Mortality	Lorenzen Temperate Ecosystem Female Natural Mortality	Chen and Watanabe Female Natural Mortality
0.5	80	9.3	0.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
1	98	17.0	0.01	0.91	0.84	0.88	0.84	0.84	0.83	0.83	0.90	0.81	0.92	0.72
1.5	113	26.6	0.04	0.84	0.70	0.78	0.70	0.71	0.69	0.69	0.82	0.67	0.85	0.55
2	127	37.7	0.15	0.78	0.59	0.69	0.59	0.60	0.57	0.57	0.76	0.56	0.80	0.43
2.5	139	49.8	0.37	0.73	0.50	0.61	0.49	0.50	0.47	0.48	0.71	0.47	0.75	0.35
3	149	62.5	0.64	0.69	0.42	0.54	0.41	0.42	0.39	0.40	0.66	0.40	0.71	0.28
3.5	159	75.4	0.83	0.65	0.35	0.47	0.34	0.35	0.32	0.33	0.62	0.35	0.68	0.24
4	167	88.2	0.92	0.61	0.29	0.42	0.29	0.30	0.27	0.27	0.59	0.30	0.65	0.20
4.5	174	100.7	0.96	0.58	0.25	0.37	0.24	0.25	0.22	0.23	0.55	0.26	0.62	0.17
5	181	112.7	0.98	0.55	0.21	0.33	0.20	0.21	0.18	0.19	0.52	0.23	0.59	0.14
5.5	187	124.1	0.99	0.52	0.17	0.29	0.17	0.18	0.15	0.16	0.50	0.20	0.57	0.12
6	192	134.8	0.99	0.50	0.15	0.25	0.14	0.15	0.13	0.13	0.47	0.18	0.54	0.11
6.5	196	144.7	1.00	0.47	0.12	0.22	0.12	0.13	0.10	0.11	0.45	0.16	0.52	0.09
7	200	153.9	1.00	0.45	0.10	0.20	0.10	0.11	0.09	0.09	0.43	0.14	0.50	0.08
7.5	204	162.4	1.00	0.43	0.09	0.17	0.08	0.09	0.07	0.08	0.41	0.12	0.48	0.07
8	207	170.1	1.00	0.41	0.07	0.15	0.07	0.07	0.06	0.06	0.39	0.11	0.47	0.06
8.5	210	177.2	1.00	0.39	0.06	0.14	0.06	0.06	0.05	0.05	0.37	0.09	0.45	0.05
9	212	183.6	1.00	0.37	0.05	0.12	0.05	0.05	0.04	0.04	0.36	0.08	0.43	0.05
9.5	214	189.4	1.00	0.35	0.04	0.11	0.04	0.04	0.03	0.04	0.34	0.07	0.42	0.04
10	216	194.6	1.00	0.34	0.04	0.09	0.03	0.04	0.03	0.03	0.32	0.07	0.40	0.03
10.5	218	199.3	1.00	0.32	0.03	0.08	0.03	0.03	0.02	0.02	0.31	0.06	0.39	0.03
11	219	203.5	1.00	0.31	0.03	0.07	0.02	0.03	0.02	0.02	0.30	0.05	0.37	0.03
11.5	220	207.2	1.00	0.30	0.02	0.06	0.02	0.02	0.02	0.02	0.28	0.05	0.36	0.02
12	222	210.6	1.00	0.28	0.02	0.06	0.02	0.02	0.01	0.01	0.27	0.04	0.35	0.02
12.5	223	213.6	1.00	0.27	0.01	0.05	0.01	0.02	0.01	0.01	0.26	0.04	0.34	0.02

Table 2.4. Estimates of male swordfish unfished survival probabilities at age in the Central North Pacific.

Estimates of Central North Pacific Male Swordfish Unfished Survival Probability at Age

Age Class (yr)	Male Length (cm)	Male Weight (kg)	Male Fraction Mature	Peterson & Wroblewski Male Natural Mortality	Hoenig Fish 1983 Male Natural Mortality	Hewitt and Hoenig Percent Rule Male Natural Mortality	Alverson and Carney Male Natural Mortality	Pauly Male Natural Mortality	Jensen BH Invariant 1 Male Natural Mortality	Jensen BH Invariant 2 Male Natural Mortality	Lorenzen Ocean Ecosystem Male Natural Mortality	Lorenzen Tropical Ecosystem Male Natural Mortality	Lorenzen Temperate Ecosystem Male Natural Mortality	Chen and Watanabe Male Natural Mortality
0.5	83	10.3	0.06	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
1	99	17.7	0.40	0.91	0.83	0.87	0.82	0.83	0.66	0.82	0.90	0.81	0.95	0.73
1.5	113	26.5	0.82	0.84	0.68	0.76	0.68	0.68	0.44	0.67	0.83	0.67	0.91	0.55
2	125	36.3	0.96	0.78	0.56	0.66	0.56	0.57	0.29	0.54	0.76	0.56	0.88	0.44
2.5	136	46.6	0.99	0.73	0.47	0.58	0.46	0.47	0.19	0.44	0.71	0.47	0.84	0.35
3	145	57.1	1.00	0.69	0.38	0.51	0.38	0.39	0.13	0.36	0.66	0.40	0.81	0.29
3.5	153	67.5	1.00	0.65	0.32	0.44	0.31	0.32	0.08	0.30	0.62	0.35	0.78	0.24
4	160	77.6	1.00	0.61	0.26	0.39	0.26	0.27	0.06	0.24	0.58	0.30	0.75	0.20
4.5	166	87.2	1.00	0.58	0.22	0.34	0.21	0.22	0.04	0.20	0.55	0.26	0.72	0.17
5	172	96.2	1.00	0.54	0.18	0.29	0.18	0.18	0.02	0.16	0.52	0.23	0.69	0.14
5.5	176	104.5	1.00	0.52	0.15	0.26	0.14	0.15	0.02	0.13	0.49	0.20	0.67	0.12
6	181	112.2	1.00	0.49	0.12	0.22	0.12	0.12	0.01	0.11	0.47	0.17	0.64	0.10
6.5	184	119.2	1.00	0.46	0.10	0.20	0.10	0.10	0.01	0.09	0.44	0.15	0.62	0.09
7	187	125.5	1.00	0.44	0.08	0.17	0.08	0.09	0.00	0.07	0.42	0.13	0.60	0.07
7.5	190	131.3	1.00	0.42	0.07	0.15	0.07	0.07	0.00	0.06	0.40	0.12	0.57	0.06
8	192	136.4	1.00	0.40	0.06	0.13	0.06	0.06	0.00	0.05	0.38	0.10	0.55	0.06
8.5	195	141.0	1.00	0.38	0.05	0.11	0.05	0.05	0.00	0.04	0.36	0.09	0.53	0.05
9	196	145.1	1.00	0.36	0.04	0.10	0.04	0.04	0.00	0.03	0.34	0.08	0.51	0.04
9.5	198	148.8	1.00	0.34	0.03	0.09	0.03	0.03	0.00	0.03	0.33	0.07	0.50	0.04
10	199	152.0	1.00	0.33	0.03	0.08	0.03	0.03	0.00	0.02	0.31	0.06	0.48	0.03
10.5	201	154.9	1.00	0.31	0.02	0.07	0.02	0.02	0.00	0.02	0.30	0.05	0.46	0.03
11	202	157.4	1.00	0.30	0.02	0.06	0.02	0.02	0.00	0.01	0.28	0.05	0.45	0.02
11.5	203	159.6	1.00	0.28	0.01	0.05	0.01	0.02	0.00	0.01	0.27	0.04	0.43	0.02

Table 3.1. Alternative estimates of female swordfish natural mortality at age (y^{-1}) in half-year increments.

Estimates of Eastern North Pacific Female Swordfish Natural Mortality at Age

Age (yr)	Female Length (cm)	Female Weight (kg)	Female Fraction Mature	Peterson & Wroblewski Female Natural Mortality	Hoenig Fish 1983 Female Natural Mortality	Hewitt and Hoenig Percent Rule Female Natural Mortality	Alverson and Carney Female Natural Mortality	Pauly Female Natural Mortality	Jensen BH Invariant 1 Female Natural Mortality	Jensen BH Invariant 2 Female Natural Mortality	Lorenzen Ocean Ecosystem Female Natural Mortality	Lorenzen Tropical Ecosystem Female Natural Mortality	Lorenzen Temperate Ecosystem Female Natural Mortality	Chen and Watanabe Female Natural Mortality
0.5	108	21.0	0.02	0.16	0.47	0.33	0.71	0.20	0.38	0.17	0.18	0.38	0.14	0.28
1	117	26.6	0.04	0.15	0.47	0.33	0.71	0.20	0.38	0.17	0.17	0.36	0.13	0.26
1.5	125	32.7	0.08	0.14	0.47	0.33	0.71	0.20	0.38	0.17	0.15	0.35	0.13	0.24
2	133	39.3	0.16	0.14	0.47	0.33	0.71	0.20	0.38	0.17	0.15	0.33	0.12	0.23
2.5	141	46.3	0.28	0.13	0.47	0.33	0.71	0.20	0.38	0.17	0.14	0.32	0.11	0.22
3	147	53.6	0.44	0.13	0.47	0.33	0.71	0.20	0.38	0.17	0.13	0.31	0.11	0.21
3.5	154	61.2	0.60	0.12	0.47	0.33	0.71	0.20	0.38	0.17	0.13	0.30	0.10	0.20
4	160	69.0	0.74	0.12	0.47	0.33	0.71	0.20	0.38	0.17	0.12	0.30	0.10	0.19
4.5	166	77.0	0.83	0.12	0.47	0.33	0.71	0.20	0.38	0.17	0.12	0.29	0.10	0.18
5	172	85.0	0.90	0.11	0.47	0.33	0.71	0.20	0.38	0.17	0.12	0.28	0.09	0.18
5.5	177	93.1	0.94	0.11	0.47	0.33	0.71	0.20	0.38	0.17	0.11	0.28	0.09	0.17
6	182	101.2	0.96	0.11	0.47	0.33	0.71	0.20	0.38	0.17	0.11	0.27	0.09	0.17
6.5	186	109.2	0.97	0.11	0.47	0.33	0.71	0.20	0.38	0.17	0.11	0.27	0.09	0.16
7	191	117.2	0.98	0.10	0.47	0.33	0.71	0.20	0.38	0.17	0.10	0.27	0.08	0.16
7.5	195	125.0	0.99	0.10	0.47	0.33	0.71	0.20	0.38	0.17	0.10	0.26	0.08	0.16
8	199	132.8	0.99	0.10	0.47	0.33	0.71	0.20	0.38	0.17	0.10	0.26	0.08	0.15
8.5	202	140.4	0.99	0.10	0.47	0.33	0.71	0.20	0.38	0.17	0.10	0.26	0.08	0.15
9	206	147.8	1.00	0.10	0.47	0.33	0.71	0.20	0.38	0.17	0.10	0.25	0.08	0.15
9.5	209	155.1	1.00	0.10	0.47	0.33	0.71	0.20	0.38	0.17	0.10	0.25	0.08	0.15
10	212	162.1	1.00	0.10	0.47	0.33	0.71	0.20	0.38	0.17	0.10	0.25	0.08	0.14
10.5	215	169.0	1.00	0.09	0.47	0.33	0.71	0.20	0.38	0.17	0.09	0.25	0.08	0.14
11	218	175.6	1.00	0.09	0.47	0.33	0.71	0.20	0.38	0.17	0.09	0.24	0.07	0.14
11.5	220	182.0	1.00	0.09	0.47	0.33	0.71	0.20	0.38	0.17	0.09	0.24	0.07	0.14
12	223	188.2	1.00	0.09	0.47	0.33	0.71	0.20	0.38	0.17	0.09	0.24	0.07	0.14
12.5	225	194.2	1.00	0.09	0.47	0.33	0.71	0.20	0.38	0.17	0.09	0.24	0.07	0.14

Table 3.2. Alternative estimates of male swordfish natural mortality at age (y^{-1}) in half-year increments.

Estimates of Eastern North Pacific Male Swordfish Natural Mortality at Age

Age (yr)	Male Length (cm)	Male Weight (kg)	Male Fraction Mature	Peterson & Wroblewski Male Natural Mortality	Hoenig Fish 1983 Male Natural Mortality	Hewitt and Hoenig Percent Rule Male Natural Mortality	Alverson and Carney Male Natural Mortality	Pauly Male Natural Mortality	Jensen BH Invariant 1 Male Natural Mortality	Jensen BH Invariant 2 Male Natural Mortality	Lorenzen Ocean Ecosystem Male Natural Mortality	Lorenzen Tropical Ecosystem Male Natural Mortality	Lorenzen Temperate Ecosystem Male Natural Mortality	Chen and Watanabe Male Natural Mortality
0.5	68	4.6	0.01	0.23	0.60	0.43	1.02	0.15	0.83	0.12	0.28	0.52	0.10	0.31
1	75	6.5	0.01	0.21	0.60	0.43	1.02	0.15	0.83	0.12	0.25	0.49	0.10	0.28
1.5	83	8.7	0.02	0.20	0.60	0.43	1.02	0.15	0.83	0.12	0.23	0.46	0.09	0.25
2	90	11.4	0.05	0.19	0.60	0.43	1.02	0.15	0.83	0.12	0.21	0.43	0.09	0.23
2.5	97	14.4	0.09	0.18	0.60	0.43	1.02	0.15	0.83	0.12	0.20	0.41	0.09	0.22
3	104	17.8	0.16	0.17	0.60	0.43	1.02	0.15	0.83	0.12	0.19	0.39	0.09	0.20
3.5	110	21.6	0.27	0.16	0.60	0.43	1.02	0.15	0.83	0.12	0.18	0.38	0.09	0.19
4	116	25.7	0.41	0.15	0.60	0.43	1.02	0.15	0.83	0.12	0.17	0.37	0.09	0.18
4.5	122	30.1	0.55	0.15	0.60	0.43	1.02	0.15	0.83	0.12	0.16	0.35	0.08	0.17
5	128	34.8	0.69	0.14	0.60	0.43	1.02	0.15	0.83	0.12	0.15	0.34	0.08	0.16
5.5	133	39.8	0.79	0.14	0.60	0.43	1.02	0.15	0.83	0.12	0.15	0.33	0.08	0.16
6	139	45.1	0.87	0.13	0.60	0.43	1.02	0.15	0.83	0.12	0.14	0.32	0.08	0.15
6.5	144	50.5	0.91	0.13	0.60	0.43	1.02	0.15	0.83	0.12	0.14	0.32	0.08	0.15
7	149	56.2	0.95	0.12	0.60	0.43	1.02	0.15	0.83	0.12	0.13	0.31	0.08	0.14
7.5	153	62.1	0.97	0.12	0.60	0.43	1.02	0.15	0.83	0.12	0.13	0.30	0.08	0.14
8	158	68.1	0.98	0.12	0.60	0.43	1.02	0.15	0.83	0.12	0.12	0.30	0.08	0.13
8.5	162	74.3	0.99	0.12	0.60	0.43	1.02	0.15	0.83	0.12	0.12	0.29	0.08	0.13
9	166	80.6	0.99	0.11	0.60	0.43	1.02	0.15	0.83	0.12	0.12	0.29	0.08	0.13
9.5	170	87.0	0.99	0.11	0.60	0.43	1.02	0.15	0.83	0.12	0.11	0.28	0.08	0.12
10	174	93.5	1.00	0.11	0.60	0.43	1.02	0.15	0.83	0.12	0.11	0.28	0.08	0.12
10.5	178	100.0	1.00	0.11	0.60	0.43	1.02	0.15	0.83	0.12	0.11	0.27	0.07	0.12
11	182	106.6	1.00	0.11	0.60	0.43	1.02	0.15	0.83	0.12	0.11	0.27	0.07	0.12
11.5	185	113.2	1.00	0.10	0.60	0.43	1.02	0.15	0.83	0.12	0.11	0.27	0.07	0.12

Table 3.3.

Estimates of Eastern North Pacific Female Swordfish Unfished Survival Probability at Age

Age Class (yr)	Female Length (cm)	Female Weight (kg)	Female Fraction Mature	Peterson & Wroblewski Female Natural Mortality	Hoenig Fish 1983 Female Natural Mortality	Hewitt and Hoenig Percent Rule Female Natural Mortality	Alverson and Carney Female Natural Mortality	Pauly Female Natural Mortality	Jensen BH Invariant 1 Female Natural Mortality	Jensen BH Invariant 2 Female Natural Mortality	Lorenzen Ocean Ecosystem Female Natural Mortality	Lorenzen Tropical Ecosystem Female Natural Mortality	Lorenzen Temperate Ecosystem Female Natural Mortality	Chen and Watanabe Female Natural Mortality
0.5	108	21.0	0.02	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
1	117	26.6	0.04	0.92	0.79	0.85	0.70	0.90	0.83	0.92	0.92	0.83	0.93	0.87
1.5	125	32.7	0.08	0.86	0.63	0.72	0.49	0.82	0.69	0.84	0.85	0.69	0.87	0.77
2	133	39.3	0.16	0.80	0.50	0.61	0.34	0.74	0.57	0.77	0.78	0.58	0.82	0.68
2.5	141	46.3	0.28	0.75	0.39	0.51	0.24	0.67	0.47	0.71	0.73	0.50	0.77	0.61
3	147	53.6	0.44	0.70	0.31	0.44	0.17	0.60	0.39	0.65	0.68	0.42	0.73	0.55
3.5	154	61.2	0.60	0.66	0.25	0.37	0.12	0.54	0.32	0.59	0.64	0.36	0.69	0.49
4	160	69.0	0.74	0.62	0.19	0.31	0.08	0.49	0.27	0.54	0.60	0.31	0.66	0.45
4.5	166	77.0	0.83	0.59	0.15	0.26	0.06	0.44	0.22	0.50	0.56	0.27	0.63	0.41
5	172	85.0	0.90	0.55	0.12	0.22	0.04	0.40	0.18	0.46	0.53	0.23	0.60	0.37
5.5	177	93.1	0.94	0.52	0.10	0.19	0.03	0.36	0.15	0.42	0.50	0.20	0.57	0.34
6	182	101.2	0.96	0.50	0.08	0.16	0.02	0.33	0.13	0.38	0.47	0.18	0.55	0.31
6.5	186	109.2	0.97	0.47	0.06	0.14	0.01	0.29	0.10	0.35	0.45	0.15	0.52	0.29
7	191	117.2	0.98	0.45	0.05	0.11	0.01	0.27	0.09	0.32	0.43	0.13	0.50	0.26
7.5	195	125.0	0.99	0.42	0.04	0.10	0.01	0.24	0.07	0.30	0.40	0.12	0.48	0.24
8	199	132.8	0.99	0.40	0.03	0.08	0.00	0.22	0.06	0.27	0.38	0.10	0.46	0.23
8.5	202	140.4	0.99	0.38	0.02	0.07	0.00	0.20	0.05	0.25	0.37	0.09	0.44	0.21
9	206	147.8	1.00	0.36	0.02	0.06	0.00	0.18	0.04	0.23	0.35	0.08	0.42	0.19
9.5	209	155.1	1.00	0.35	0.01	0.05	0.00	0.16	0.03	0.21	0.33	0.07	0.41	0.18
10	212	162.1	1.00	0.33	0.01	0.04	0.00	0.14	0.03	0.19	0.32	0.06	0.39	0.17
10.5	215	169.0	1.00	0.32	0.01	0.04	0.00	0.13	0.02	0.17	0.30	0.06	0.38	0.16
11	218	175.6	1.00	0.30	0.01	0.03	0.00	0.12	0.02	0.16	0.29	0.05	0.36	0.15
11.5	220	182.0	1.00	0.29	0.01	0.03	0.00	0.11	0.02	0.15	0.27	0.04	0.35	0.14
12	223	188.2	1.00	0.27	0.00	0.02	0.00	0.10	0.01	0.13	0.26	0.04	0.34	0.13
12.5	225	194.2	1.00	0.26	0.00	0.02	0.00	0.09	0.01	0.12	0.25	0.03	0.33	0.12
			Mean Generation Time (yr)	9.47	5.70	6.83	4.38	8.21	6.42	8.56	9.47	7.55	9.70	8.80

Table 3.4.

Estimates of Eastern North Pacific Male Swordfish Unfished Survival Probability at Age

Age Class (yr)	Male Length (cm)	Male Weight (kg)	Male Fraction Mature	Peterson & Wroblewski Male Natural Mortality	Hoenig Fish 1983 Male Natural Mortality	Hewitt and Hoenig Percent Rule Male Natural Mortality	Alverson and Carney Male Natural Mortality	Pauly Male Natural Mortality	Jensen BH Invariant 1 Male Natural Mortality	Jensen BH Invariant 2 Male Natural Mortality	Lorenzen Tropical Ecosystem Male Natural Mortality	Lorenzen Temperate Ecosystem Male Natural Mortality	Chen and Watanabe Male Natural Mortality
0.5	68	4.6	0.01	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
1	75	6.5	0.03	0.89	0.74	0.81	0.60	0.93	0.66	0.94	0.77	0.95	0.86
1.5	83	8.7	0.06	0.81	0.55	0.65	0.36	0.86	0.44	0.89	0.61	0.91	0.75
2	90	11.4	0.12	0.73	0.40	0.53	0.22	0.79	0.29	0.84	0.49	0.87	0.67
2.5	97	14.4	0.22	0.67	0.30	0.42	0.13	0.73	0.19	0.79	0.39	0.83	0.59
3	104	17.8	0.35	0.61	0.22	0.34	0.08	0.68	0.13	0.75	0.32	0.79	0.54
3.5	110	21.6	0.50	0.56	0.16	0.28	0.05	0.63	0.08	0.71	0.27	0.76	0.48
4	116	25.7	0.65	0.52	0.12	0.22	0.03	0.58	0.06	0.67	0.22	0.72	0.44
4.5	122	30.1	0.77	0.48	0.09	0.18	0.02	0.54	0.04	0.63	0.18	0.69	0.40
5	128	34.8	0.86	0.45	0.07	0.15	0.01	0.50	0.02	0.59	0.15	0.67	0.37
5.5	133	39.8	0.91	0.42	0.05	0.12	0.01	0.46	0.02	0.56	0.13	0.64	0.34
6	139	45.1	0.95	0.39	0.04	0.10	0.00	0.43	0.01	0.53	0.11	0.61	0.32
6.5	144	50.5	0.97	0.37	0.03	0.08	0.00	0.40	0.01	0.50	0.09	0.59	0.29
7	149	56.2	0.98	0.35	0.02	0.06	0.00	0.37	0.00	0.47	0.08	0.57	0.27
7.5	153	62.1	0.99	0.33	0.01	0.05	0.00	0.34	0.00	0.45	0.07	0.55	0.25
8	158	68.1	0.99	0.31	0.01	0.04	0.00	0.31	0.00	0.42	0.06	0.52	0.24
8.5	162	74.3	0.99	0.29	0.01	0.03	0.00	0.29	0.00	0.40	0.05	0.50	0.22
9	166	80.6	1.00	0.27	0.01	0.03	0.00	0.27	0.00	0.37	0.04	0.49	0.21
9.5	170	87.0	1.00	0.26	0.00	0.02	0.00	0.25	0.00	0.35	0.04	0.47	0.20
10	174	93.5	1.00	0.24	0.00	0.02	0.00	0.23	0.00	0.33	0.03	0.45	0.18
10.5	178	100.0	1.00	0.23	0.00	0.01	0.00	0.21	0.00	0.32	0.03	0.43	0.17
11	182	106.6	1.00	0.22	0.00	0.01	0.00	0.20	0.00	0.30	0.03	0.42	0.16
11.5	185	113.2	1.00	0.21	0.00	0.01	0.00	0.18	0.00	0.28	0.02	0.40	0.15

Figure 1. Swordfish mean size-at-age by sex in the Central North Pacific from DeMartini et al. (2007).

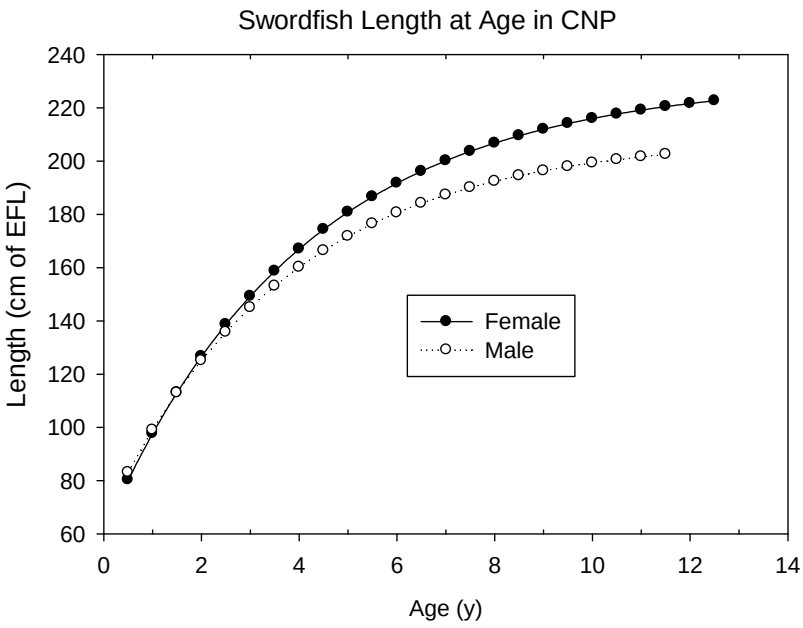


Figure 2. Swordfish mean weight-at-age by sex in the Central North Pacific from Uchiyama and Humphreys (2007) and DeMartini et al. (2007).

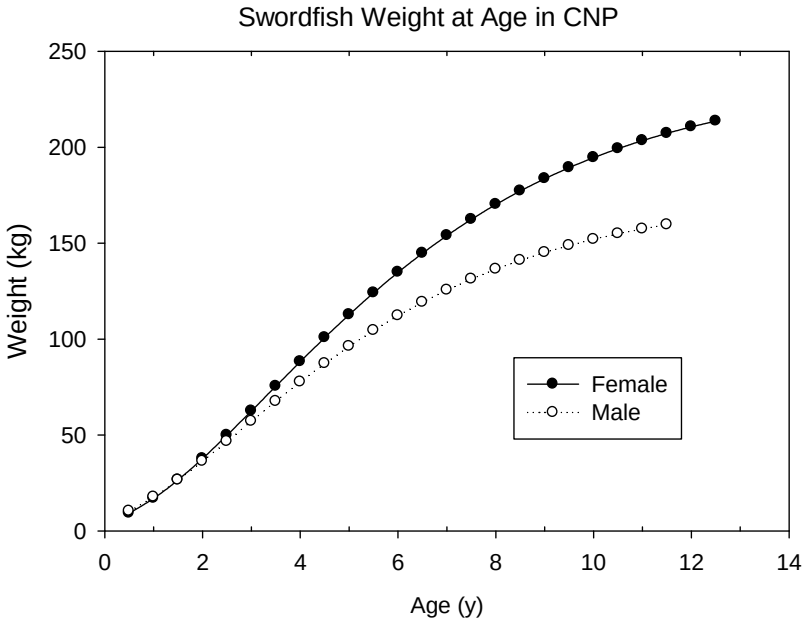


Figure 3. Swordfish average fraction mature at age by sex in the Central North Pacific from DeMartini et al. (2000).

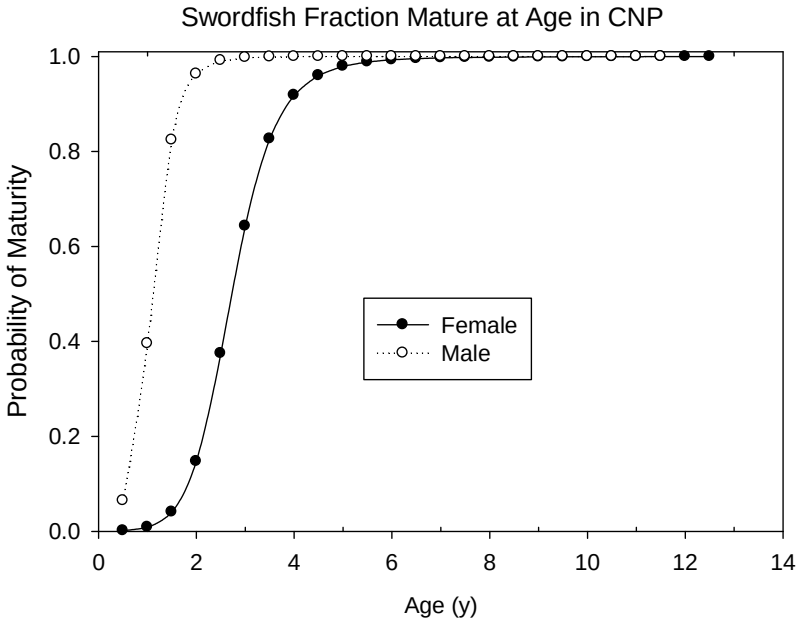
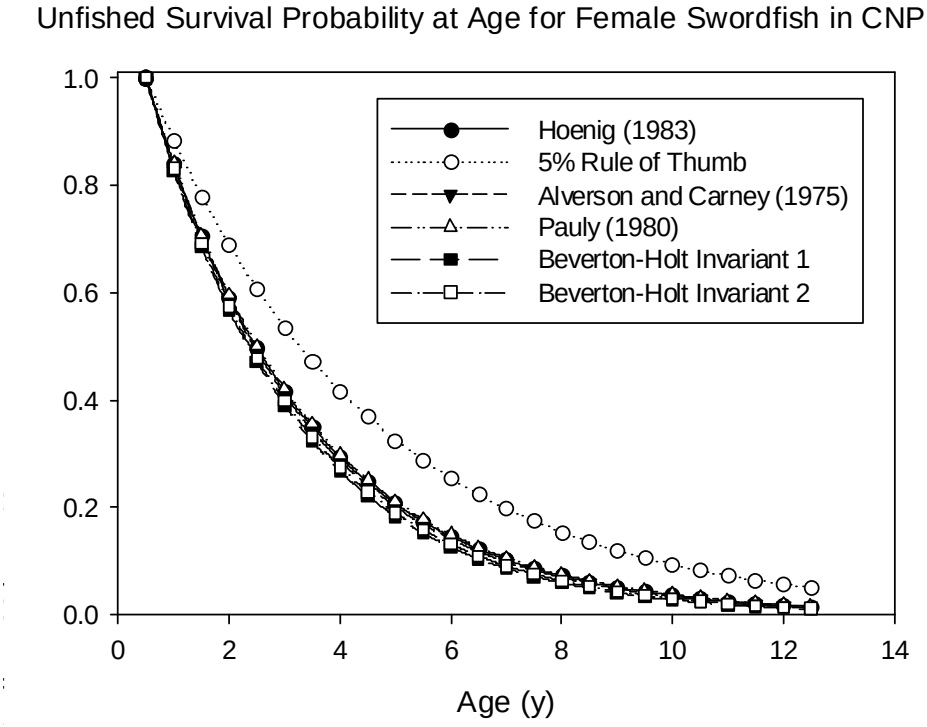


Figure 4.1. Unfished survival probabilities at age for female swordfish in Central North Pacific for constant and variable natural mortality estimators.



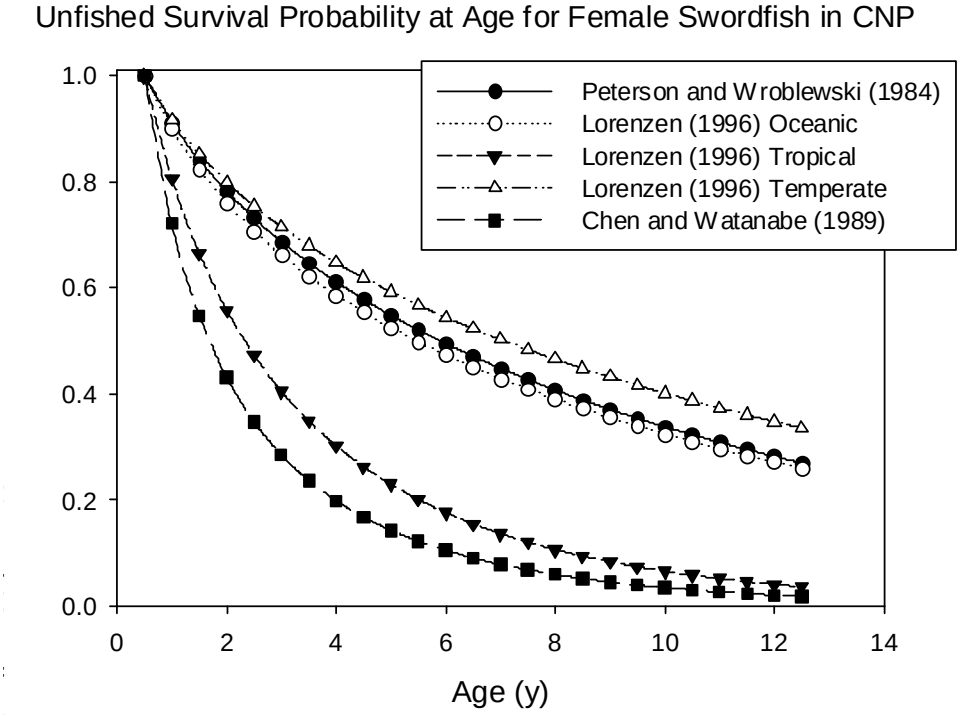


Figure 4.2. Unfished survival probabilities at age for male swordfish in Central North Pacific for constant and variable natural mortality estimators.