Fisheries Research, 5 (1987) 287-302
Elsevier Science Publishers B.V., Amsterdam — Printed in The Netherlands

Effects of Ageing Errors on Estimates of Growth, Mortality and Yield per Recruit for Walleye Pollock (*Theragra chalcogramma*)

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ABSTRACT

Lai, H.L. and Gunderson, D.R., 1987. Effects of ageing errors on estimates of growth, mortality and yield per recruit for walleye pollock (*Theragra chalcogramma*). *Fish. Res.*, 5: 287-302.

The effects of ageing errors on estimates of growth, mortality and yield per recruit for walleye pollock (*Theragra chalcogramma*) were investigated by using Monte Carlo simulation. At current levels of normally distributed ageing errors (between and within reader), the bias in the von Bertalanffy growth parameters, L_∞ and K, and survival rate, S, were usually $<6\%$, yet the estimated optimum fishing mortality (F^*) was increased significantly. Although the biases in L_∞ and survival rate were $<10\%$ for the positively skewed ageing errors seen when comparing break-and-burn vs. otolith surface ageing methods, the estimated K, F^* and age at first capture (t_c^*) were substantially different. Systematic under-ageing error, associated with scale methods, resulted in a substantial bias in most parameters and overfishing would result if the estimated F^* and t_c^* were used in fishery management.

INTRODUCTION

Age of walleye pollock (*Theragra chalcogramma*) has routinely been determined by scales (Ogata, 1956; Yamaguchi and Takahashi, 1972), fin-rays (Chilton and Beamish, 1982) and otoliths (LaLanne, 1975). However, the differences in age readings made by these ageing methods are substantial (Lai, 1985). Because age determination provides the basic data for estimation of population parameters, variability in ageing walleye pollock would influence stock assessment and management of walleye pollock. This paper reports on a simulation study in which we demonstrate how estimates of growth, survival rate and yield per recruit of walleye pollock are affected by ageing errors.

0165-7836/87/$03.50

AGEING ERRORS AND SIMULATION METHODS

Errors in age determination of walleye pollock were examined for otoliths, dorsal and pectoral fin-rays and scales of 297 specimens collected from the eastern Bering Sea in 1983. Each fish was aged using each of these structures, with both surface and break-and-burn ageing methods being employed for otoliths. In addition, two independent readers aged each otolith.

In general, fin-rays and scales seemed to yield younger ages than otoliths. Break-and-burn and surface readings for otoliths were generally similar, although where discrepancies existed, the break-and-burn reading was usually highest. The break-and-burn ageing method often resulted in sections that were difficult to interpret, however, and further research will be required to determine the validity of this ageing method. Because of this and because the traditional data base for walleye pollock was derived through the otolith surface ageing method, surface readings were chosen as the reference ages.

To simulate ageing errors, a 1981 age–length key for walleye pollock from the eastern Bering Sea (Table I), aged by the otolith surface ageing method, was selected as a reference, against which the simulated population parameters could be compared. Von Bertalanffy growth parameters for the model $l_t = L_\infty(1-e^{-K(t-t_0)})$, estimated by non-linear regression (Lai, 1985) from the data in Table I were $L_\infty = 73.79$ cm, $K = 0.201$ and $t_0 = -0.154$. The survival rate, estimated by the method of Chapman and Robson (1960), was $S = 0.707$.

Three types of ageing error were encountered during the comparative study of ageing methods.

(1) Normally distributed ageing error without systematic differences between test (Y) and reference (X) ages. This type of ageing error was observed in between/within-reader comparisons using the otolith surface ageing method (Table II). The null hypotheses of zero mean differences between X and Y were not rejected at the 1% significance level. The standard deviation SD(Y) was linearly correlated with reference age, with an intercept of zero (Fig. 1).

(2) Positively skewed ageing error, but without systematic difference. This type of ageing error was observed when comparing ages determined by break-and-burn vs. otolith surface ageing methods (Table III). Although there were no significant differences (1% level) between test age (Y, by break-and-burn method) and reference age (X, by otolith surface ageing method), Y tended to be greater than X. The SD($\ln Y$) were linearly correlated with $\ln X$ (Fig. 1).

(3) Systematic ageing errors such as seen in comparisons of fin-ray or scale methods and the otolith surface ageing method (Fig. 2). The test ages (Y) determined by scales, dorsal and pectoral fin-ray methods were consistently younger than the reference age (X, by otolith surface ageing method) after age 3.

Simulation models of ageing variability were developed to reflect these types

TABLE I

Age-length key for walleye pollock collected from the eastern Bering Sea in 1981. Age of fish was estimated by the otolith surface ageing method

Length (cm)	Frequency	Age															
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
11	45	1															
12	76	4															
13	91	9															
14	94	7															
15	117	9															
16	128	12															
17	133	13															
18	123	11															
19	162	6	9														
20	226	8	11														
21	239		10														
22	255		10														
23	296		10														
24	270		9	3													
25	291		8	7	1												
26	273		11	4													
27	340		11	11	1												
28	291		14	9	1												
29	469		10	18	1												
30	489		8	15	2												
31	506		5	25	7												
32	494		1	27	5												
33	598		1	29	11	1											
34	597		1	27	7												
35	597			34	11	1											
36	571			29	15	1											
37	590			24	11												
38	560			27	15	2	1										
39	314			20	19												
40	304			11	16	4	1										
41	268			12	22	1	3										
42	286			2	25	4	1										
43	306			1	21	4	2										
44	281				24	8	3										
45	341				17	6	3	3									
46	333				20	9	4		1								
47	361				15	9	2	1	1								
48	351				3	6	4		1			1					
49	325				5	8	17	3			1						
50	226				7	11	7	5	2								
51	227				3	5	11	4	2	3	1						
52	194				2	6	10	4		2		1			1		
53	179					5	16	3	2								
54	165					6	10	8	3	2	1	1					
55	139				2	9	13	2	5	2	1						
56	138					5	11	4	4	4	1						
57	109				2	1	9	5	10			2		1			
58	73					1	7	6	2	3	2			1			
59	107					1	5	8	6	4	1	2					

TABLE I (continued)

Length (cm)	Frequency	Age															
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
60	52						3	6	6	6	4	3	2		1		
61	52					1	4	2	3	1	5	1	1				
62	64						2	5	8	1	2	1	1	2			
63	63					1	1	5	8	2	3	5		1			
64	40						3		10	4	2	2	1	2			
65	46							2	7	3	5	2	3		1		
66	42							1	2	4	5	2	1				
67	29						1	2	2	2	3	5		1		1	
68	14								2		4	6		3			
69	15								1	3		8		1			
70	12									1	3	4	3	2	1		
71	6								1	2	1	2	1	1		1	
72	9								2	1	2	2	3	2			1
73	5								1		2	1	2	2			
74	1												1	1			
75	3									2		1	1		1		
76	1												2	3		1	

of ageing error. Type (1) implied that test age was normally distributed with mean $=X$ and SD $=cX$. Thus, the constant, c, can be viewed as the coefficient of variation (C.V.) of ageing error. For the ith fish of age X_i in Table I, a normal random variate (R_i) was generated by the subroutine GGNML of the International Mathematical and Statistical Library (IMSL) (1982). The re-assigned age (Z_i) of this fish was calculated and rounded to the nearest integer by

$$Z_i = R_i \mathrm{SD} + X_i \tag{1}$$

C.V. was set at 0.1 and 0.2, respectively, the values observed in the within-reader and between-reader comparisons in Table II.

Type (2) implied that the distribution of Y could be represented by a log-normal distribution with mean$(\ln Y) = \ln X$ and SD $= c\ln X$. Thus, the constant, c, was the C.V. of ageing error on a logarithmic scale. C.V. was set at 0.1 and 0.15, respectively, to represent the variations of Reader A and Reader B in Table III. The subroutine in Naylor (1966) was used to generate log-normal random variates (Z_i) corresponding to the re-assigned age of the ith fish of age X_i in Table I.

Type (3) implied that type (1) governed ageing errors from age 1 to 3 and systematic ageing error occurred thereafter. Thus, moving the origin of the X and Y axes to (3,3), the linear relationship between Y and X was $(Y-3) = g(X-3)$, where g is the gradient of the systematic ageing error. The re-assigned age (Z_i) of the ith fish of age X_i in Table I could be obtained by generating a normal random variate, R_i, with

TABLE II

Comparisons of between/within-reader age determinations using the otolith surface ageing method (difference = test age(Y) − reference age(X))

1. Within reader

Difference	Otolith surface age											
	2	3	4	5	6	7	8	9	10	11	12	N
3									1	1	1	3
2			1		1	1	1	2		1	2	9
1	1	1	3	3	4	8	10	4	3	7	4	48
0	9	12	40	26	18	30	18	10	6	4	5	178
−1		1	4	2	3	10	8	6	5	4	5	48
−2					1	2	2	1	1		2	9
−3										1	1	2
N	10	14	48	31	27	51	39	23	16	18	20	297
Mean	0.100	0.000	0.021	0.032	0.037	−0.078	0.000	0.000	−0.063	0.278	−0.050	
SD(Y)	0.316	0.392	0.413	0.407	0.759	0.771	0.889	1.000	1.181	1.364	1.503	

$SD(Y) = -0.038 + 0.122X$; $R^2 = 96.1$; $S_a = 0.063$; $S_b = 0.008$.

2. Between reader

Difference	Otolith surface age											
	2	3	4	5	6	7	8	9	10	11	12	N
4									1		1	2
3						1	2	1	1	2	1	8
2			1	2	3	3	3	3	3	2	3	23
1	1		6	5	5	7	8	4	2	3	2	43
0	9	13	32	19	15	24	14	6	2	3	4	141
−1		1	8	4	4	9	7	5	3	5	3	49
−2			1		1	4	4	3	3	1	2	19
−3							1		1	2	2	6
−4											1	1
N	10	14	48	30	28	48	39	22	16	18	19	292
Mean	0.100	−0.071	−0.042	0.167	0.179	−0.021	0.513	0.091	0.188	0.000	−0.105	
SD(Y)	0.316	0.267	0.683	0.747	0.905	1.014	1.356	1.411	2.040	1.815	2.158	

$SD(Y) = -0.197 + 0.193X$; $R^2 = 95.6$; $S_a = 0.186$; $S_b = 0.193$.

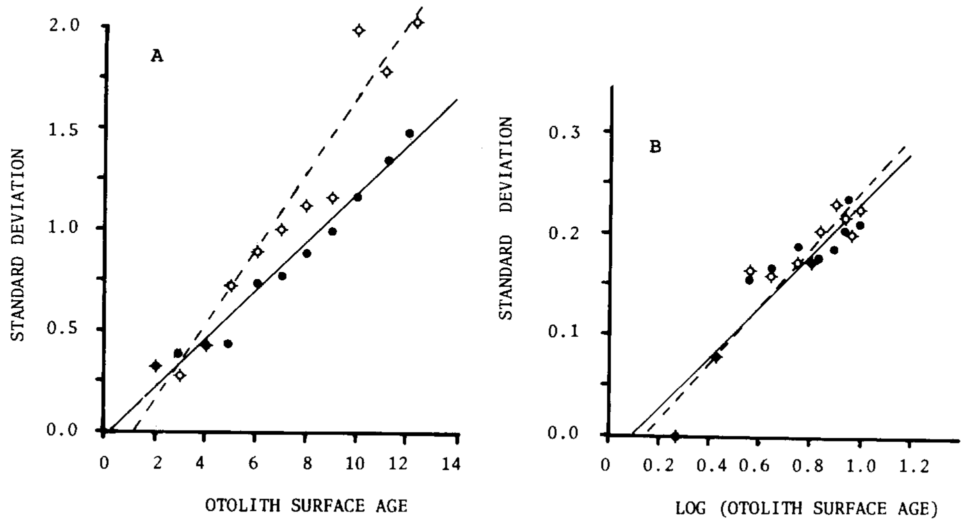

Fig. 1. Plot of standard deviation of test age against otolith surface age.
(A) Within-reader (—●—) and between-reader (--⊕--) comparisons using otolith surface ageing method. (B) Break-and-burn age vs. otolith surface age (—●—, Reader A; --⊕--, Reader B).

$$\begin{aligned} \text{mean} &= g(X_i - 3) + 3 && \text{for } X_i > 3 \\ &= X_i && \text{otherwise} \\ \text{and SD} &= c(g(X_i - 3) + 3) && \text{for } X_i > 3 \\ &= cX_i && \text{otherwise} \end{aligned}$$

We set C.V. to be 0.1 and 0.2 to reflect the real situations of under-ageing errors in Fig. 2. The re-assigned age, Z_i, was calculated as in eq. 1. We also included over-ageing in this study to obtain a generalized analysis of the effects of systematic ageing error. The gradient, g, was set from 0.2 to 1.5, whereas $g=0.4$ and 0.7 approximate the under-ageing errors of scale and fin-ray methods in Fig. 2.

The percentage deviation D (Majkowski and Hampton, 1983) was used to examine the effects of ageing error on the accuracy of the simulated population parameters. For example, D_i of the ith simulated von Bertalanffy growth coefficient, K_i, was calculated by

$$D_i = [100(K_i - K_0)/K_0]\%$$

where K_0 is the reference value. The mean of (D) D_i and its 95% confidence interval were calculated to describe average bias and variation in estimates due to ageing error.

Beverton and Holt's yield (Y) per recruit (R') model was used to examine

TABLE III

Comparison of ages of walleye pollock between otolith surface ageing and break-and-burn methods (difference = break-and-burn age (Y) − otolith surface age (X))
1. By Reader A

Difference	Otolith surface age											
	2	3	4	5	6	7	8	9	10	11	12	N
6										1	1	2
5								1	1	1	1	4
4						1	1	1			2	5
3				1	1	1	1	1	1	1	1	8
2			1	1	1	4	1	2	1	1	2	14
1		1	6	5	4	9	11	3	1	1	1	42
0	10	13	32	17	14	19	12	8	3	4	2	134
−1			9	6	5	11	5	4	5	3	3	51
−2					2	3	7	3	2	3	3	23
−3									2		1	3
N	10	14	48	30	27	48	38	23	16	15	17	286
Mean(Y)	0	0.071	−0.021	0.133	0.000	0.146	0.026	0.391	−0.250	0.533	0.882	
SD($\ln Y$)	0.0	0.077	0.159	0.166	0.179	0.169	0.175	0.185	0.208	0.200	0.212	

$\mathrm{SD}(\ln Y) = -0.029 + 0.103 \ln X$; $R^2 = 84.9$; $S_a = 0.027$; $S_b = 0.014$.

2. By Reader B

Difference	Otolith surface age											
	2	3	4	5	6	7	8	9	10	11	12	N
6											1	1
5									1		1	2
4						1	1	1	1	1		5
3				1	1	2	2	1	1	1	2	11
2			1	1	1	4	3	3	1	2	2	18
1			9	4	3	8	9	4	2	2	3	44
0	10	13	30	18	15	17	11	5	3	3	1	126
−1		1	8	6	6	13	6	5	4	2	2	53
−2					1	2	5	3	2	2	3	18
−3							2	1	1	1	1	6
N	10	14	48	30	27	47	39	23	16	14	16	284
Mean(Y)	0	−0.071	0.063	0.100	0.000	0.191	0.077	0.130	0.313	0.286	0.813	
SD($\ln Y$)	0.0	0.077	0.165	0.162	0.162	0.173	0.205	0.231	0.211	0.198	0.228	

$\mathrm{SD}(\ln Y) = -0.041 + 0.133 \ln X$; $R^2 = 87.0$; $S_a = 0.028$; $S_b = 0.015$.

the effects of ageing error on fishery management. The equation derived by Gulland (1969) was used in this study:

$$Y/R' = W_\infty g(1-c)^m \sum_{n=0}^{3} U_n (1-c)^n / (g+m+n)$$

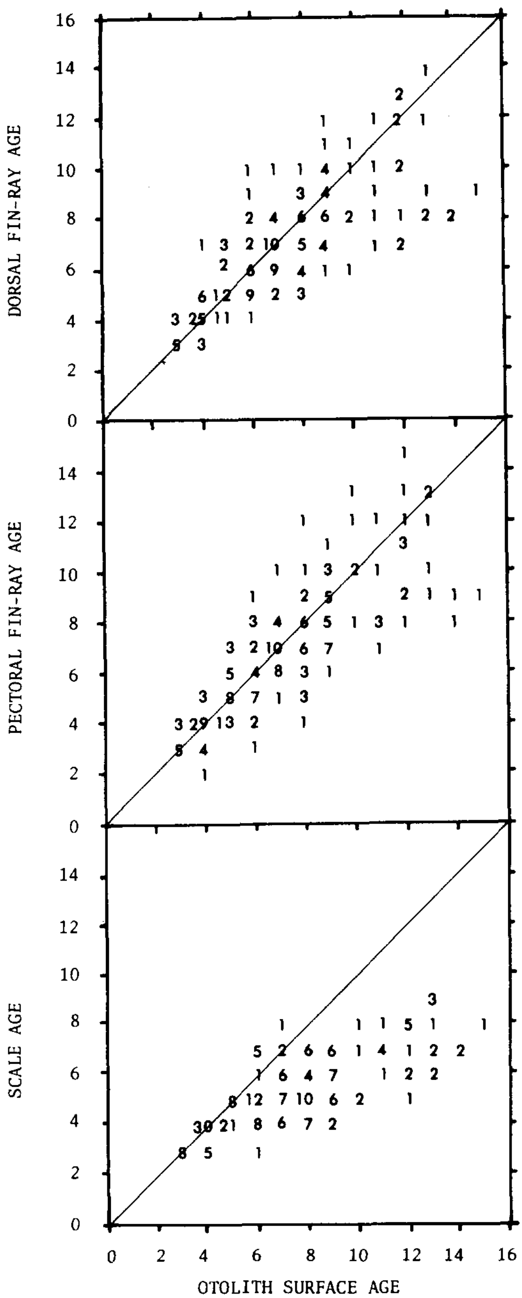

Fig. 2. Comparisons of ages determined by dorsal and pectoral fin-ray and scale methods vs. otolith surface ageing method.

where M = instantaneous natural mortality rate, F = instantaneous fishing mortality rate, Z = instantaneous total mortality rate, $m = M/K$, $g = F/K = Z/K - M/K$, $c = 1 - e^{-K(t_c - t_0)}$, t_c is the age at first capture, R' is the number of recruits entering the fishery and $U_n = 1, -3, 3, -1$, respectively, for $n = 0, 1, 2, 3$. W_∞ was estimated by using the weight–length relationship (Smith, 1979) $W = 0.0075L^{2.977}$. $W_\infty = 2.730$ kg corresponding to $L_\infty = 73.79$ cm.

It was difficult to estimate M with the limited data in this study. However, using the same ageing method and cohort analysis, Bakkala and Traynor (1984) reported that an average M of 0.30 best described the dynamics of the walleye pollock population in the Bering Sea. Therefore, we assumed M to be constant throughout the simulations.

The optimum fishing mortality rate (F^*) and optimum age at first capture (t_c^*) corresponding to maximum yield per recruit (Y^*/R') were estimated by the simplex method (Nelder and Mead, 1965). For simplicity, we only estimated F^* and t_c^* for the simulated mean values of the parameters at each C.V. level.

RESULTS

Based on 200 simulations of normally distributed and positively skewed ageing errors, the average mean length at age was generally over-estimated for ages 1–4, but under-estimated thereafter (Fig. 3). The magnitude of these changes increased with increasing C.V. of ageing error. These changes probably resulted from re-allocating the younger and smaller sized fish to older age classes and the older and larger sized fish to younger age classes.

The reference age composition was dominated by age 3 walleye pollock (Fig. 4). The kurtosis of the catch curve decreased with increasing C.V. of normally distributed and positively skewed ageing error. Lai (1985) reported that the proportions of age 1 and 2 fish increased drastically and became dominant if the C.V. was > 0.5 and > 0.25, respectively, for normally distributed and positively skewed ageing errors.

Table IV summarizes the effects of re-assigned estimates of growth and survival rate for normally distributed and positively skewed ageing errors. L_∞, K and survival rate did not deviate substantially from the reference values for the current levels of normally distributed ageing error. For the current levels of positively skewed ageing errors, the average bias was not substantial for L_∞ and S ($< 10\%$), but it was for K ($> 17\%$).

With current $t_c = 3$ years, reference F^* was estimated as 0.633 (Table V). F^* was over-estimated for the normally distributed and positively skewed ageing errors. The bias in F^* also increased with increasing C.V. level for both types of ageing error. Setting $F = 0.65$, t_c^* with simulated ageing errors were less than

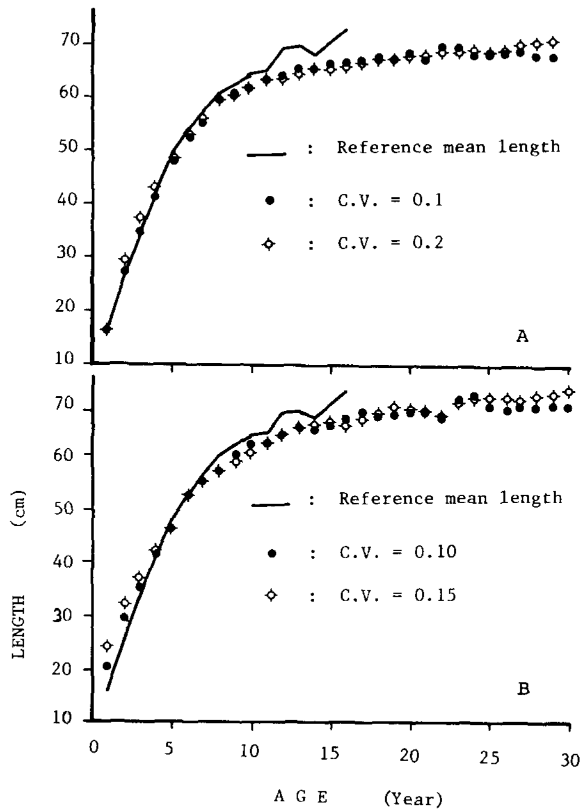

Fig. 3. Change of mean lengths at age subject to normally distributed (A) and positively skewed (B) ageing errors.

reference t_c^* and the bias increased with increasing C.V. of ageing error. These results indicate that increasing C.V. of ageing error could substantially affect management decisions, even in the case of normally distributed ageing error.

The growth curves became steeper with increasing under-ageing error and flatter with increasing over-ageing (Fig. 5). The influence of increased C.V. on the growth curves was the same as in normally distributed ageing error, i.e. an increase of mean lengths at younger ages and a decrease at older ages. Figure 6 shows that the proportion at age 3 decreased and the proportion of older ages increased with increasing over-ageing error.

Figure 7 shows that the bias of L_∞ was $<10\%$ in under- and over-ageing errors, but bias in K could be substantial ($>20\%$), with the current levels of under-ageing error. Survival rate (S) was substantially under-estimated with under-ageing error and slightly over-estimated with over-ageing error.

At $t_c = 3$ years, F^* generally increased with decreasing gradient, especially

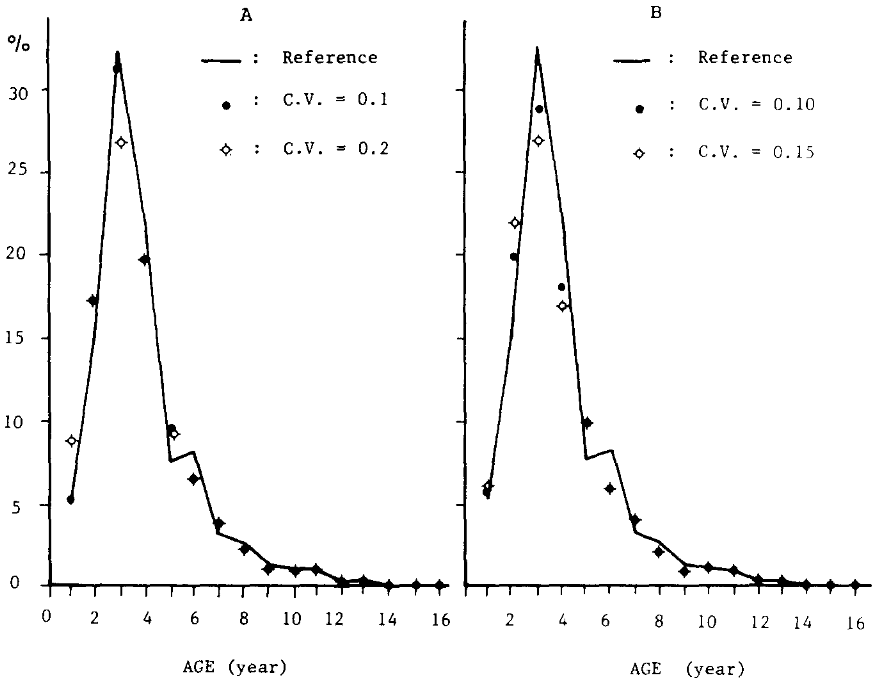

Fig. 4. Change of age composition subject to normally distributed (A) and positively skewed (B) ageing errors.

when C.V. = 0.2 (Fig. 8). If F^* was used to determine management policy, serious over-exploitation could result if scales ($g=0.4$) were used for age determination. Setting $F=0.65$, t_c^* increased with increasing gradient (Fig. 9). This

TABLE IV

Percentage deviation (D) and 95% confidence interval (in parentheses) of population parameters with normally distributed and positively skewed ageing errors

Ageing error	C.V.	L_∞	K	t_0	S
Normally distributed	0.1	−2.4% (−6.4%,1.6)	5.6 (−8.2,19.9)	1.0 (−98.7,100.7)	−0.1 (−0.7,0.4)
	0.2	−4.4 (−8.7,−0.1)	5.2 (−12.1,22.5)	165.9 (4.4,327.4)	0.9 (−0.1,1.9)
Positively skewed	0.10	−8.4 (−12.0,−4.9)	17.5 (−2.3,37.2)	102.7 (−81.6,287.0)	0.7 (−0.5,2.0)
	0.15	−8.8 (−12.2,−5.4)	17.1 (−3.1,37.3)	182.8 (−19.7,385.2)	−0.4 (1.7,38.3)

TABLE V

Estimated optimum fishing mortality rate (F^*, $t_c = 3$ years) and optimum age at first capture (t_c^*, $F = 0.65$) for walleye pollock, with normally distributed and positively skewed ageing errors

	C.V.	F^*	Y^*/R' (at F^*, $t_c = 3$)	t_c^*	Y^*/R' (at $F = 0.65$, t_c^*)
Reference	-	0.633	136.57	4.199	146.63
Ageing error					
Normally	0.1	0.674	139.85	4.088	148.49
distributed	0.2	0.748	133.11	3.905	138.55
Positively	0.10	0.861	142.25	3.705	144.98
skewed	0.15	0.928	141.05	3.601	142.23

effect would contribute further to the over-fishing that would result from the use of scales.

DISCUSSION

The effects of both normally distributed and positively skewed ageing errors on growth and catch curves are (i) an increase in the mean lengths of younger age classes and a decrease in the mean lengths at older age classes and (ii) a decrease in the proportion allocated to the dominant age classes. These effects will then affect the estimation of parameters describing the growth, mortality and yield per recruit from the fishery. The bias and variability of estimated parameters of growth and mortality may not be very severe under the current C.V. levels, but nevertheless have a significant impact when estimating Y/R',

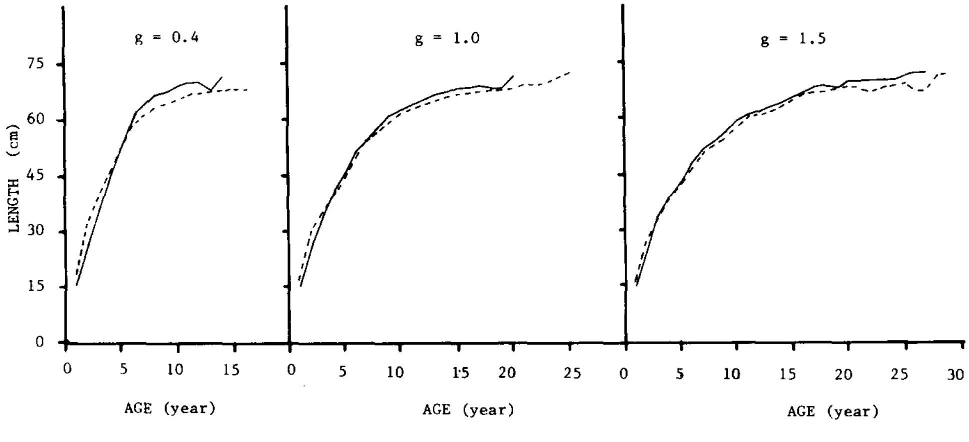

Fig. 5. Comparisons of mean lengths at age subject to under- ($g = 0.4$) and over-ageing ($g = 1.5$) errors. In the absence of systematic ageing error, $g = 1.0$. (—, C.V. = 0.1; -----, C.V. = 0.2.)

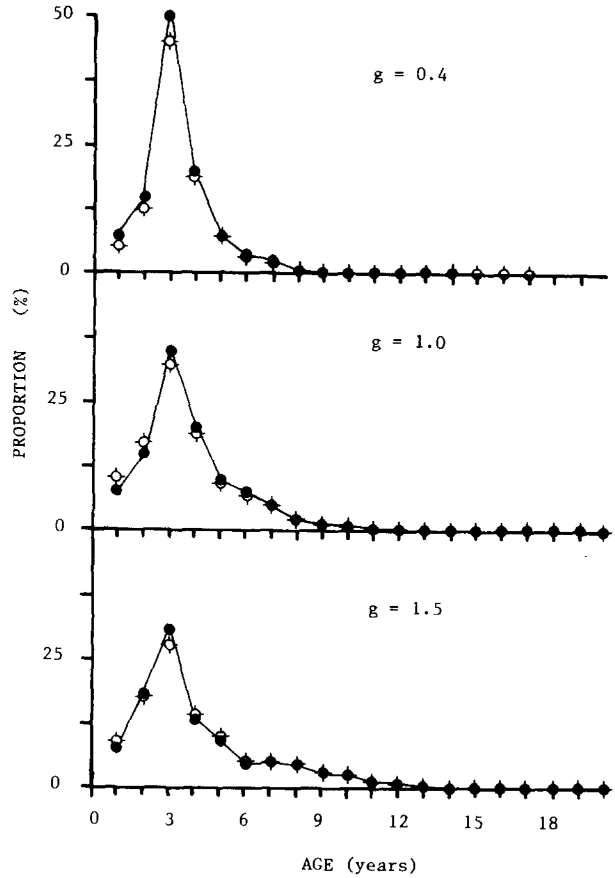

Fig. 6. Comparisons of age composition subject to under- ($g=0.4$) and over-ageing ($g=1.5$) errors. In the absence of systematic ageing error, $g=1.0$. (—●—, C.V. $=0.1$; ⊕, C.V. $=0.2$.)

F^* and t_c^*. This is particularly true in the case of the positively skewed ageing error that results from using break-and-burn as opposed to otolith surface ageing methods. The problem would be more serious if C.V. were higher.

It is noteworthy that the simulated mean lengths at age show similar trends for both normally distributed and positively skewed ageing errors. The magnitude of fluctuations in mean lengths are not substantial for the current C.V. levels in ageing errors, however, and as a result, plots of mean lengths against age or tests of von Bertalanffy growth curves are poor criteria for assessing the accuracy and precision of age determination. The most appropriate method for evaluating these problems is direct comparison of catch curves.

When systematic under- or over-ageing errors occurred, the bias in all parameters was most severe for under-ageing, especially for the estimated F^* and t_c^*. From the view point of fishery management, over-ageing error will result in a more conservative and lower risk management program, with a lower

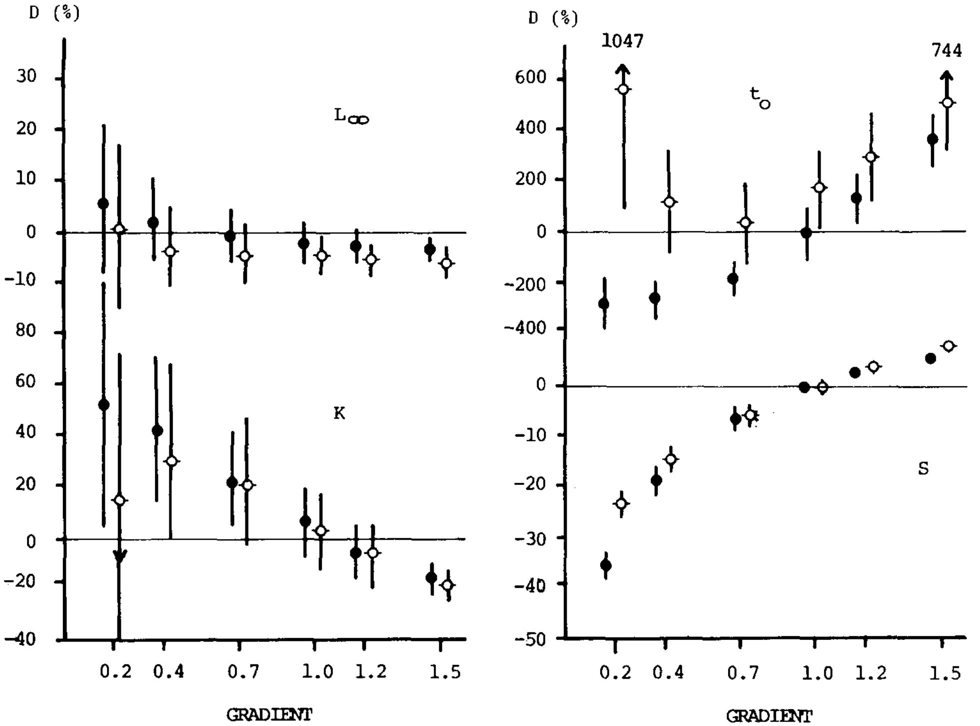

Fig. 7. Variations of population parameters (D and its 95% confidence interval) subject to under- and over-ageing errors. (●, C.V.=0.1; ⊕, C.V.=0.2; | =95% C.I.)

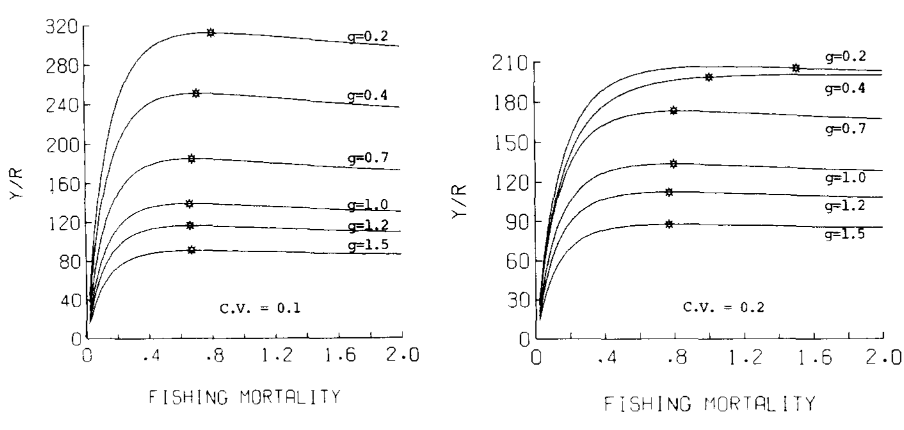

Fig. 8. Plot of Y/R' against fishing mortality for under- and over-ageing errors. ⊕ indicates the locus of maximum Y/R' on the yield curve. $t_c = 3$ years.

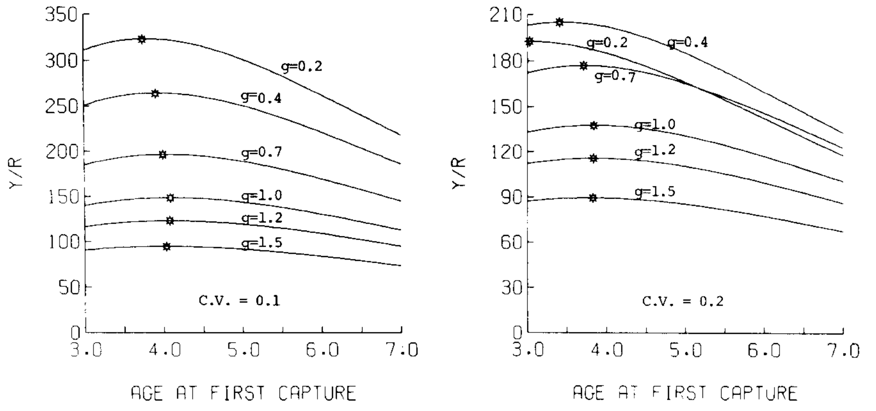

Fig. 9. Plot of Y/R' against age at first capture for under- and over-ageing errors. ⊕ indicates the locus of maximum Y/R' on the yield curve. $F=0.65$.

F^* and higher t_c^*. Unfortunately, under-ageing error usually prevails, especially where inappropriate ageing methods (e.g., scales) are used.

Because of the influence on stock assessments, the methods used in age determination should be improved upon wherever possible. It is essential to attempt to increase the precision and accuracy by standardizing and validating ageing methods. Any age-determination program should always check the consistency between and within readers (both past and current) and organize frequent exchanges and workshops between agencies. If precision is not improved, corrections must be employed in order to compensate for distortions caused by reader, method or agency-related error. If systematic ageing error occurs, a correction procedure such as that developed for Pacific cod (Lai, Gunderson and Low, in preparation) should be employed. Although these processes are time consuming, there will be long-term benefits in improved fishery management.

ACKNOWLEDGMENTS

This study was funded by the Northwest and Alaska Fisheries Center, National Marine Fisheries Service. The authors would like to express their thanks to Dave Somerton and Daniel Kimura for their discussions in the early stages of this study and to George Hirschhorn for providing the collection of walleye pollock otoliths.

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