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Statistical Assessment of the Age–Length Key

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Since 1934 when Fridriksson originated the age–length key, it has been widely used by fisheries biologists to estimate age distributions of populations. In recent years, there has been a general recognition that often the key has little value, or even worse, gives biased results. The analysis presented here indicates why the age–length key is so susceptible to bias. More importantly, a criterion is presented for determining whether the age–length key should be used in a particular situation. If the key is to be used, results from examples indicate that random age subsamples (i.e. the number of specimens aged from each length category proportional to the number in each length category) are superior to fixed age subsamples (i.e. a constant number of specimens aged from each length category). Generally, small increases in the age sample will likely increase the accuracy of an age-distribution determination more effectively than relatively large increases in the length sample.

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Introduite en 1934 par Fridriksson, la clé âge–longueur a été depuis largement utilisée par les biologistes des pêches pour estimer la distribution des âges dans une population. Depuis quelques années toutefois, on admet généralement que la clé a souvent peu de valeur ou, ce qui est pire, donne des résultats biaisés. L'analyse que nous présentons ici explique pourquoi la clé âge–longueur est si susceptible de biais. Ce qui est plus important, nous donnons un critère permettant de décider si la clé âge–longueur doit être utilisée dans une situation particulière. Dans les cas où la clé doit être utilisée, des exemples indiquent que les sous-échantillons d'âges pris au hasard (i.e. le nombre de spécimens dont l'âge est déterminé dans chaque catégorie de longueur étant proportionnel au nombre de poissons dans chaque catégorie de longueur) sont supérieurs à des sous-échantillons d'âges fixes (i.e. un nombre uniforme de spécimens dont l'âge est déterminé dans chaque catégorie de longueur). Généralement, des petites augmentations dans l'échantillon d'âges résulteront probablement en une détermination plus précise de la répartition des âges que ne le feraient des augmentations relativement grandes de l'échantillon de longueurs.

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ONE of the fundamental problems of fisheries biologists is to estimate the age distribution of a population. Sampling for ages may be accomplished by either taking a simple random sample, or by using Fridriksson's (1934) age–length key. The biologist must decide if the gains made by using the age–length key justify its use. There appears to be little in the literature to help him make this decision. In this paper, a criterion is presented for determining whether the key should be used in a particular situation.

If the age–length key is to be used, the biologist must decide whether the age subsample should be random (i.e. the number of specimens aged from each length category proportional to the number in each length category) or fixed (i.e. a constant number of specimens aged from each length category). In the literature, one can find proponents of random and fixed age subsamples. Ketchen (1949), in an early paper, felt that fixed age subsamples were superior. Southward (1976) found that random age subsamples were more efficient. The analyses and examples presented in the following sections show that from a statistical point of view random age subsamples are more efficient.

Age–Length Key

Suppose the proportions of a population of age $i = 1, \ldots, n_a$ are $p_1, \ldots, p_{n_a}$. Suppose also that the distribution of lengths at each age is given by q_{ij}, $j = 1, \ldots, n_l$.[1] Here,

$$\sum_{j=1}^{n_l} q_{ij} = 1$$

for all i. The proportion of length j is then

$$l_j = \sum_{i=1}^{n_a} p_i q_{ij}.$$

Of the j length fish, the proportion of fish of age i is $q_{ij}' = (p_i q_{ij})/l_j$. Therefore,

$$\sum_{i=1}^{n_a} q_{ij}' = 1$$

for all j. The quantities directly estimable from sample data are l_j and q_{ij}'. If a random sample of N_l length frequencies is taken and n_j are of length j, and if n_j^* of the n_j fish are aged, of which m_{ij} are of age i, then $\hat{l}_j = n_j/N_l$ and $\hat{q}_{ij}' = m_{ij}/n_j^*$ are unbiased estimates of l_j and q_{ij}'. Since

$$p_i = \sum_{j=1}^{n_l} l_j q_{ij}',$$

it follows that

$$\hat{p}_i = \sum_{j=1}^{n_l} \hat{l}_j \hat{q}_{ij}'$$

provides an unbiased estimate of p_i. This is the usual application of the age–length key. It should be noted that q_{ij}' is dependent on the p_i's. This means that the age–length key will give biased results if applied to a population where the age composition differs from that of the population from which the age–length key was drawn.

The value of this key can be assessed directly by calculating the variance of the estimates of the various p_i's. Any gains from increasing the length-frequency sample should be reflected in the variance of the $\hat{p}_i$'s. Since we are concerned with the overall variance of the $\hat{p}_i$'s, the total variance

$$\text{Vartot} = \mathrm{E} \sum_{i=1}^{n_a} (\hat{p}_i - p_i)^2 = \sum_{i=1}^{n_a} \text{var}(\hat{p}_i)$$

[1]It should be noted that n_a and n_l actually refer to the number of categories. The ages and lengths are assumed to be coded so that the smallest values are one.

seems an appropriate error index. Using this error index, the efficiency of the age–length key may be assessed, as compared with increasing the age sample. Also, it may be determined whether the age subsample should be random or fixed.

Derivation of the Variance of the $\hat{p}_i$'s

The variance for the $\hat{p}_i$'s estimated from the age–length key may be derived by straightforward methods. However, for simplification, the following assumptions are made concerning n_j^*, the subsample from length category j which is aged. For the case of fixed age subsample sizes, the variance is conditioned on $n_j^* = n_s/n_l$, where n_s is the total sample to be aged and n_l is the number of length categories. The weakness of this approach is that n_j, the number of specimens of length j, may be actually less than n_j^*. When N_l is large compared with n_s, this should not be a problem. For the case of random age subsamples, it is assumed that $n_j^* = sn_j$, where $s = n_s/N_l$. Hence, this variance is not conditioned on n_j^*.

The variance of $\hat{p}_i$,

$$\begin{aligned}\mathrm{Var}(\hat{p}_i) &= E(\hat{p}_i - p_i)^2 \\ &= E\sum_{j=1}^{n_l}(\hat{l}_j\hat{q}'_{ij} - l_jq'_{ij})\sum_{j'=1}^{n_l}(\hat{l}_{j'}\hat{q}'_{ij'} - l_{j'}q'_{ij'}) \\ &= \sum_{j=1}^{n_l}\sum_{j'=1}^{n_l}E(\hat{l}_j\hat{q}'_{ij}\hat{l}_{j'}\hat{q}'_{ij'} - l_jq'_{ij}l_{j'}q'_{ij'})\end{aligned} \quad (1)$$

The expectations can most easily be evaluated by breaking them into the cases $j = j'$ and $j \neq j'$. When $j = j'$ the expectation gives a different result under fixed and random subsampling.

Case 1a. $j = j'$ subsample fixed

$$\begin{aligned}E(\hat{l}_j\hat{q}'_{ij}\hat{l}_j\hat{q}'_{ij}) &= E\left(\frac{n_j}{N_l}\frac{m_{ij}}{n_j^*}\frac{n_j}{N_l}\frac{m_{ij}}{n_j^*}\right) \\ &= \underset{n_j}{E}\frac{n_j}{N_l}\frac{n_j}{N_l}\left(\frac{q'_{ij}(1-q'_{ij})}{n_j^*} + q'^2_{ij}\right) \\ &= \left[\frac{l_j(1-l_j)}{N_l} + l_j^2\right]\left[\frac{q'_{ij}(1-q'_{ij})}{n_j^*} + q'^2_{ij}\right]\end{aligned}$$

Case 1b. $j = j'$ subsample random

$$\begin{aligned}E(\hat{l}_j\hat{q}'_{ij}\hat{l}_j\hat{q}'_{ij}) &= E\left(\frac{n_j}{N_l}\frac{m_{ij}}{sn_j}\frac{n_j}{N_l}\frac{m_{ij}}{sn_j}\right) \\ &= \underset{n_j}{E}\frac{n_j}{N_l}\frac{n_j}{N_l}\left[\frac{q'_{ij}(1-q'_{ij})}{sn_j} + q'^2_{ij}\right] \\ &= \frac{l_jq'_{ij}(1-q'_{ij})}{n_s} + q'^2_{ij}\left[\frac{l_j(1-l_j)}{N_l} + l_j^2\right]\end{aligned}$$

Case 2. $j \neq j'$ subsample fixed or random

$$\begin{aligned}E(\hat{l}_j\hat{q}'_{ij}\hat{l}_{j'}\hat{q}'_{ij'}) &= E\left(\frac{n_j}{N_l}\frac{m_{ij}}{n_j^*}\frac{n_{j'}}{N_l}\frac{m_{ij'}}{n_{j'}^*}\right) \\ &= \underset{n_j,n_{j'}}{E}\left[\frac{n_j}{N_l}\frac{n_{j'}}{N_l}q'_{ij}q'_{ij'}\right] \\ &= q'_{ij}q'_{ij'}\left[\frac{-l_jl_{j'}}{N_l} + l_jl_{j'}\right]\end{aligned}$$

Substituting the appropriate expectations back into (1), and simplifying, yields the following variance formulas:

a) $\mathrm{Var}\,(\hat{p}_i) = \dfrac{p_i(1 - p_i)}{n_s}$ (random sample)
ages only

b) $\mathrm{Var}\,(\hat{p}_i) = \sum_{j=1}^{n_l} \left[\dfrac{l_j(1 - l_j)}{\mathrm{N}_l} \dfrac{q'_{ij}(1 - q'_{ij})}{n_j^*} + \dfrac{l_j^2 q'_{ij}(1 - q'_{ij})}{n_j^*} + \dfrac{l_j q'^2_{ij}}{\mathrm{N}_l} \right] - \dfrac{p_i^2}{\mathrm{N}_l}$
age subsample fixed

c) $\mathrm{Var}\,(\hat{p}_i) = \sum_{j=1}^{n_l} \left[\dfrac{l_j q'_{ij}(1 - q'_{ij})}{n_s} + \dfrac{l_j q'^2_{ij}}{\mathrm{N}_l} \right] - \dfrac{p_i^2}{\mathrm{N}_l}$
age subsample random

Note that $\mathrm{Var}\,(\hat{p}_i)$ and $\mathrm{Vartot} = \sum_{i=1}^{n_a} \mathrm{Var}\,(\hat{p}_i)$ have the following forms:

a) $\mathrm{Vartot} = \dfrac{a_1}{n_s}$
ages only

b) $\mathrm{Vartot} = \dfrac{b_1}{\mathrm{N}_l n_j^*} + \dfrac{b_2}{n_j^*} + \dfrac{b_3}{\mathrm{N}_l}$
age subsample fixed

c) $\mathrm{Vartot} = \dfrac{c_1}{n_s} + \dfrac{c_2}{\mathrm{N}_l}$
age subsample random

The form of these Vartot expressions allow us to easily calculate the asymptotic value of Vartot as N_l goes to infinity. This value of Vartot would be that given by an age–length key when an infinite length sample was taken. We can then calculate the asymptotic percentage reduction in Vartot (ages only), which would then represent an upper bound to the value of using the key. An important property of this percentage reduction is that it is independent of the actual value of n_s. In other words, the gain in using the age–length key is the same when $n_s = 100$, or $n_s = 1000$, when measured in this way.

The asymptotic variances can be written as

$$\lim_{\mathrm{N}_l \to \infty} \begin{matrix}\text{Vartot}\\ \text{age subsample}\\ \text{fixed}\end{matrix} = \frac{b_2}{n_j^*} = n_l \frac{b_2}{n_s}$$

and

$$\lim_{\mathrm{N}_l \to \infty} \begin{matrix}\text{Vartot}\\ \text{age subsample}\\ \text{random}\end{matrix} = \frac{c_1}{n_s}$$

The percentage reduction in Vartot (ages only) that can be achieved when age subsamples are fixed is then

$$\gamma_{\mathrm{F}} = \frac{\dfrac{a_1}{n_s} - n_l \dfrac{b_2}{n_s}}{\dfrac{a_1}{n_s}} \times 100 = \frac{a_1 - n_l b_2}{a_1} \times 100$$

Since $p_i = \sum_{j=1}^{n_l} l_j q'_{ij}$ implies $a_1 = c_1 + c_2$, it may be deduced that Vartot ages only = Vartot age subsample random

when $N_l = n_s$ (i.e. when the length observations are taken from specimens that are aged). Therefore, the percentage reduction in Vartot (ages only) that can be achieved when age subsamples are random is

$$\gamma_R = \frac{\frac{a_1}{n_s} - \frac{c_1}{n_s}}{\frac{a_1}{n_s}} \times 100 = \frac{c_2}{a_1} \times 100$$

The age–length key, when age subsamples are random, cannot do worse than a random sample of ages without lengths. However, when age subsamples are fixed, the age–length key may do worse than a random sample of ages even if an infinite length sample were taken. In the following section, an example is given in which this is the case.

Examples

As examples of how the preceding analyses can be used, age–length data were compiled from biological market samples for the following two species:

a) Species: Pacific ocean perch
(*Sebastes alutus*)
Location: Queen Charlotte Sound
Time: May–June–July 1975
Sex: male
Ages: 9–20 yr
Lengths: 32–43 cm

b) Species: Pacific cod
(*Gadus macrocephalus*)
Location: miscellaneous
Time: February–March 1974
Sex: male
Ages: 3–5 yr
Lengths: 53–77 cm

From the data presented in Tables 1 and 2, estimates of p_i and q_{ij} were made which were then assumed to be the true parameters of the population. The coefficients for Vartot were then calculated from the formulas given in the preceding section. The calculated coefficients are as follows:

Pacific ocean perch	Pacific cod
$a_1 = .85135$	$a_1 = .54270$
$b_1 = .66564$	$b_1 = .25866$
$b_2 = .09106$	$b_2 = .01798$
$b_3 = .09465$	$b_3 = .26605$
$c_1 = .75670$	$c_1 = .27665$
$c_2 = .09465$	$c_2 = .26605$
$\gamma_F = -28\%$	$\gamma_F = +17\%$
$\gamma_R = +11\%$	$\gamma_R = +49\%$

From the γ_F value, it is seen that for Pacific ocean perch, Vartot (ages only) increases 28% when an age–length key is used with fixed age subsamples. This means that the age determination is worse

TABLE 1. Age-length data for Pacific ocean perch (*Sebastes alutus*).

Length (*cm*)	Age (*yr*) 9	10	11	12	13	14	15	16	17	18	19	20
32	10	5										
33	15	13	13	1								
34	14	27	27	19	4	1						
35	26	36	59	32	3	2						
36	5	48	74	67	18	3	1					
37	3	23	51	37	20	7		1				
38		6	23	40	27	12	2		2			
39			5	10	13	23	9	6		2		1
40			1	1	12	13	14	18	6	2	1	
41				1	5	9	11	18	11	3	6	1
42						5	7	7	7	9	6	5
43						1	2	1	2	1	1	4

TABLE 2. Age-length data for Pacific cod (*Gadus macrocephalus*).

Length (*cm*)	Age (*yr*) 3	4	5
53	5		
54	3		
55	6		
56	13	3	
57	11		
58	14	3	
59	18	4	
60	20	2	
61	18	2	
62	15	10	
63	13	1	
64	8	9	1
65	6	14	
66	3	13	
67	1	13	
68	1	8	2
69		13	4
70	1	7	
71		4	2
72			2
73			2
74		1	
75			2
76			1
77			2

than a simple random sample of ages even if an infinite length sample is taken. From the γ_R value, it is seen that Vartot (ages only) decreases 11% when an age-length key is used with random age subsamples. The age-length key is apparently of marginal value in this case.

For Pacific cod, $\gamma_F = 17\%$ and $\gamma_R = 49\%$. The age-length key may be of significant value. Again, random age subsamples are favored over fixed age subsamples. Tables 3 and 4 give values of Vartot at various sampling levels. For consistency, sample sizes were rounded to integers. From these tables, it appears that random samples are generally favored over fixed samples. For populations

TABLE 3. Values of Vartot for Pacific ocean perch. F and R refer to fixed and random age subsamples.

Aged sample	Length sample = aged sample	Total length sample 100 F	100 R	200 F	200 R	300 F	300 R	400 F	400 R	500 F	500 R	1000 F	1000 R
50	.01703	.02538	.01608	.02407	.01561	.02364	.01545	.02342	.01537	.02329	.01532	.02303	.01523
100	.00851	.01316	.00851	.01227	.00804	.01198	.00788	.01183	.00780	.01174	.00776	.01156	.00766
150	.00568			.00773	.00552	.00749	.00536	.00737	.00528	.00730	.00523	.00715	.00514
200	.00426			.00603	.00426	.00580	.00410	.00569	.00402	.00562	.00397	.00549	.00388
250	.00341					.00476	.00334	.00465	.00326	.00459	.00322	.00446	.00312
300	.00284					.00405	.00284	.00395	.00276	.00389	.00271	.00376	.00262
350	.00243							.00343	.00240	.00338	.00235	.00326	.00226
400	.00213							.00305	.00213	.00299	.00208	.00287	.00199
450	.00189									.00262	.00187	.00251	.00178
500	.00170									.00239	.00170	.00228	.00161

TABLE 4. Values of Vartot for Pacific cod. F and R refer to fixed and random age subsamples.

Aged sample	Length sample = aged sample	Total length sample 100 F	100 R	200 F	200 R	300 F	300 R	400 F	400 R	500 F	500 R	1000 F	1000 R
50	.01085	.01295	.00819	.01097	.00686	.01031	.00642	.00998	.00620	.00978	.00607	.00939	.00580
100	.00543	.00780	.00543	.00615	.00410	.00560	.00365	.00532	.00343	.00516	.00330	.00483	.00303
150	.00362			.00454	.00317	.00403	.00273	.00377	.00251	.00362	.00238	.00331	.00211
200	.00271			.00374	.00271	.00324	.00227	.00299	.00205	.00284	.00192	.00255	.00165
250	.00217					.00277	.00199	.00253	.00177	.00238	.00164	.00209	.00137
300	.00181					.00246	.00181	.00222	.00159	.00207	.00145	.00179	.00119
350	.00155							.00200	.00146	.00185	.00132	.00157	.00106
400	.00136							.00183	.00136	.00169	.00122	.00141	.00096
450	.00121									.00156	.00115	.00128	.00088
500	.00109									.00146	.00109	.00118	.00082

of different age structures, the analysis could change significantly. However, these changes can be examined by the method presented here.

In addition to the analysis presented here, the variance formulas can be used to examine each $\hat{p}_i$ on an individual basis. For example, the coefficient of variation of each $\hat{p}_i$ may be calculated. This type of analysis tends to be voluminous when many sampling levels are being examined.

Finally, the variance of the $\hat{p}_i$'s estimated from the actual use of an age–length key may be estimated by simply substituting the appropriate parameter estimates into the var($\hat{p}_i$) formula for the case where the age subsample is fixed. The derivation of this formula only required that the n_j*'s were fixed constants, not necessarily equal.

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