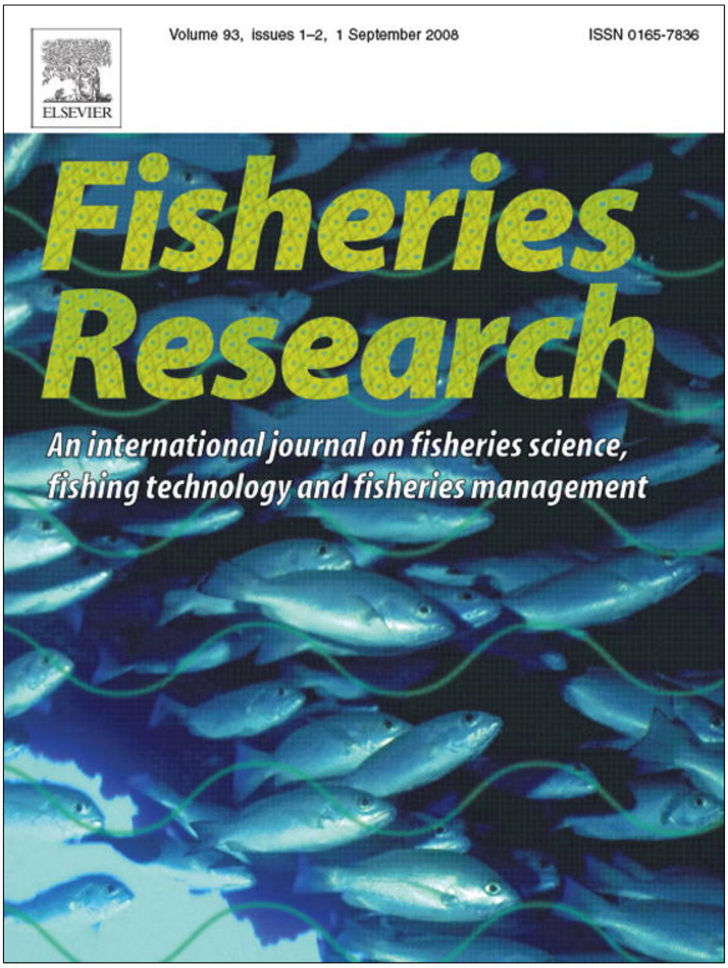
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Jackknife method for estimating the variance of the age composition using two-phase sampling with an application to commercial catches of swordfish (*Xiphias gladius*)

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ABSTRACT

An estimate of the age composition of a commercial swordfish catch and its variance was obtained using the replicate full jackknife estimator for two-phase sampling where the sampling units in the first phase are clusters (vessel-trips) and the units of the second phase are individual fishes. The jackknife variance estimator was compared with an analytical estimator of variance commonly used in fisheries studies which ignores the clustering, and assumes simple random sampling of individual fish. The application of these naïve estimators to the Chilean South Pacific swordfish fishery results in an underestimation of the variance. This is a consequence of using an inappropriate primary sampling unit of analysis in the first-phase sample where the vessel-trip unit is replaced by an individual fish unit, thus ignoring the intra-cluster correlation in age samples. The jackknife estimator of variance is an alternative useful for complex two-phase sampling designs.

1. Introduction

The classical method of two-phase sampling, also known as double sampling (Cochran, 1977; Särndal et al., 1992) is frequently used to collect length and age data for estimating the composition of a fish population. However, estimators of the variance in proportions at age (e.g., Ketchen, 1949; Southward, 1976; Kimura, 1977; Smith and Sedransk, 1982; Lai, 1993) often assume that individual fishes collected from each length class form a simple random sample. This assumption is rarely met in catch monitoring programs. It is common in fisheries that the sampling schemes include a first phase consisting of at least two-stages; a first-stage for obtaining a cluster sample (e.g. vessel-trips) and a second-stage to obtain a subsample of fishes within of each cluster. In the second phase these fishes are restratified by length and a final sample of fishes is selected for aging. Analytical variance estimators commonly adopted by researchers for estimating the variance of the age composition are often based on the strong assumption that the fishes selected from the vessel-trips in the first-phase sample came from a simple random sample of individual fishes from the study population (Lai, 1993). The implication of simplifying the sampling design to a selection of individual fishes that forms a simple random sample is that the classic method tends to underestimate the variance of the age–catch composition (Pennington and Volstad, 1994; Helle and Pennington, 2004).

An approach is presented in this paper where in the first phase a random sample of clusters without replacement is selected, and where the length is measured for every fish in the cluster, resulting in a single-stage cluster sampling. Therefore, if every fish in the selected cluster is surveyed, it is possible to postulate a two-phase sampling where in the first phase a sample of clusters is selected, and in the second phase a sample of individual fishes is selected for aging. In this sampling design (where the primary and secondary phase units do not coincide) we used a full jackknife estimator of variance (Wolter, 1985; Kott and Stukel, 1997; Kim et al., 2000; Kim and Sitter, 2003), considering the vessel-trip as the cluster unit in the first-phase sample. The full jackknife variance estimator is compared with an analytical variance estimator. As an example, an application is made based on data obtained from the Chilean swordfish (*Xiphias gladius*) fishery.

It is important to clarify, in this study, it is not the purpose to estimate the variance age composition of catch of this particular fishery, only is to evaluate how one specific estimator which ignores the clustering (assumes simple random sampling of individual fish) will affect the variance estimates.

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2. Materials and methods

2.1. Commercial sampling

The data used in this paper were collected in 2005 from the swordfish fishery carried out in oceanic waters of the SE Pacific off the coast of Chile. The sampling program of the Chilean fisheries gathers swordfish samples from the commercial catch obtained by longline vessels. Intensive samples from vessel-trips are taken monthly and all the fishes are measured in length; in 2005 the mean catch was 13 individuals/haul. Spines from the anal fins are collected for age determination according to the procedures of Berkeley and Houde (1983) and Ehrhardt (1992). Age determinations are made from the spines of 100 fishes monthly at the laboratory of the Instituto de Fomento Pesquero (IFOP) to construct an annual age–length key (ALK). Note that the sampling scheme for the swordfish is fit to a two-phase sampling where the first-phase sample included units of clusters (vessel-trips) and the second-phase sample included units of individual fishes (Kim and Sitter, 2003).

The swordfish data came from 53 trips sampled in the first phase, in which a total of 17,132 fishes were caught and measured in length. The analysis of length included classification of the fishes into 5-cm intervals (except for the extreme length), producing a total of 39 length classes (≤120, 121–125, 126–130,. . ., ≥311 cm) (Fig. 1). In the second-phase sample the fishes were randomly selected from each length class, assigning an age class (1–15 years); a total of 961 fishes were analyzed.

In spite of that the fraction of sampling vessel-trips in this fishery is unusually high (around 80% of trips), in order to exemplify the effect in the variance estimates of age composition when it is ignored that the data come from cluster samples in the first phase, we assumed that the sampling fraction is sufficient small such as occurs in the most fishery monitoring programs.

2.2. Estimation

The aim of the present study centered on estimation of the variance of the age composition of the catch from a fishery, using a two-phase sampling. The parameter to be estimated was the proportion of fishes in the catch which had an age class e ($e = 1, 2, \ldots, T$). The estimators were proposed for a particular stratum of the zone, period, or some combination of these which could be extended to a greater number of strata.

Two estimators were used for calculating the variance. For the two-phase sampling with cluster sampling units in the first phase and individual fish in the second phase, the variances were estimated using the replicated full jackknife method (Kim et al., 2000; Kim and Sitter, 2003), and for the two-phase design with individual fish sampling units in the first and second phases, we employed the classic method of estimating the analytical variance for two-phase sampling with stratification (Cochran, 1977; Kimura, 1977).

For comparative purposes, estimations were made of each age class based on (a) proportion of catch at age class p_e; (b) standard error S.E.; (c) coefficient of variation CV, defined as the quotient between S.E. and p_e, and (d) relative design precision RV, defined as the ratio between the estimations of variances obtained with the jackknife and analytical estimators.

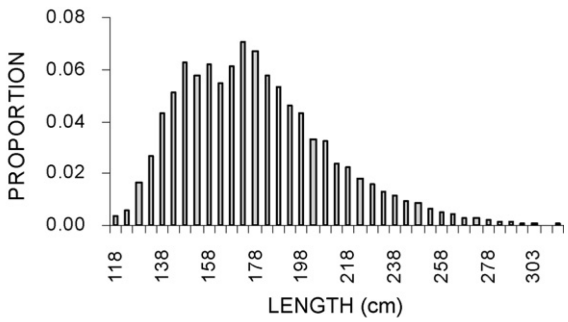

Fig. 1. Estimated length (lower jaw fork) frequency distribution of swordfish in the Chilean commercial catch taken by the longline fleet, 2005.

2.3. Two-phase sampling: cluster sampling units in first phase and individual fish in second phase

In this sampling design the sampling units of the first and second phases do not coincide. The first-phase sample units are clusters (vessel-trips), and in the second-phase sample the units are individual fishes. We assume that a random sample without replacement of n clusters is selected with equal probability from N clusters in the first-phase sample. We also assume that all the fishes within the cluster are measured. Let M_i be the size of cluster i. From the selected first-phase sample, we observe $x_{ij} = (x_{ij1}, x_{ij2}, \ldots, x_{ijG})$, where x_{ijg} takes the value 1 if the fish j in the cluster i belongs to length class g, and takes the value 0 otherwise. There are $m_g = \sum_{(ij)\in A_1} x_{ijg}$ fishes in length class g, where A_1 represents the set of indices of the fishes selected in the first-phase sample. For the second phase, a sample of $r_g \geq 2$ fishes is selected without replacement with equal probability independently across the g length classes (Kim and Sitter, 2003).

An unbiased estimator of the proportion of fishes at age class e is given by

$$p_e = \frac{\sum_{g=1}^{G}\sum_{(ij)\in A_2} w_i w_{ijg} y_{ijge}}{\sum_{g=1}^{G}\sum_{(ij)\in A_2} w_i w_{ijg}} \tag{1}$$

where $w_i = n^{-1}N$ is the first-phase weighting factor of cluster i and $w_{ijg} = r_g^{-1} m_g$ is the second-phase sampling weight in length class g. Let A_2 be the set of indices of the fishes selected for aging in the second phase. The age variable y_{ijge} takes the value 1 if fish j of length class g in cluster i belongs to age class e, and takes the value 0 otherwise.

The numerator of estimator (1) is known as the direct expansion estimator of a total (Kott and Stukel, 1997) or as the π^*-estimator (Särndal et al., 1992). The numerator can also be considered as a re-weighted expansion estimator (Kott and Stukel, 1997; Kim et al., 2000; Kim and Sitter, 2003) because the weight of the first-phase $w_i = n^{-1}N$ is constant.

An estimator of replicated full jackknife variance (Kim et al., 2000) is given by

$$\hat{V}_J(p_e) = \sum_{k=1}^{L} \frac{n-1}{n}(p_e^{(k)} - p_e)^2 \tag{2}$$

where $p_e^{(k)}$ is kth version of p_e based on the observations of the kth replicate, L is the number of replications, which in this study would be equal to the number n of clusters and

$$p_e^{(k)} = \frac{\sum_{g=1}^{G}\sum_{(ij)\in A_2} w_i^{(k)} w_{ijg}^{(k)} y_{ijge}}{\sum_{g=1}^{G}\sum_{(ij)\in A_2} w_i^{(k)} w_{ijg}^{(k)}} \tag{3}$$

The full jackknife method for the first phase successively deletes one cluster and adjusts the weight of the remaining clusters by $n/(n-1)$. The replicate weight for the first phase of cluster i, is defined by

$$w_i^{(k)} = \begin{cases} 0, & i = k \\ \dfrac{n}{n-1} w_i, & i \neq k \end{cases} \quad (4)$$

and the full jackknife replicated weights for the second phase are

$$w_{ijg}^{(k)} = \begin{cases} 0, & i = k \\ \dfrac{m_g - m_{kg}}{r_g - r_{kg}}, & i \neq k \end{cases} \quad (5)$$

where $m_{kg} = \sum_{j=1}^{M_k} x_{kjg}$ is the number of first-phase sample fishes in cluster k that belong to length class g and $r_{kg} = \sum_{(j) \in A_2} x_{kjg}$ is the number of second-phase sample fishes in cluster k that belongs to length class g.

2.4. Two-phase sampling: individual fish sampling units in the first and second phases

In this sampling design the primary sampling units of the first and second phases are individual fishes. In the first phase we do not distinguish the cluster units from which the sample individual fishes are selected, and therefore, for the validity of this sampling design, it is assumed that the sample of fishes selected within the cluster in the first phase came from an simple random sample of individual fishes from the population under study. Under these conditions, in the first phase, a sample of n individual fishes is selected. These fishes are stratified into g length classes. In the second phase, and conditionally on the preceding sample, a random subsample of $n' < n$ fishes is selected across the g length classes, for aging.

From the fishes selected in the first-phase sample we observe the auxiliary variable $x_j = (x_{j1}, x_{j2}, \ldots, x_{jG})$, where x_{jg} takes the value 1 if the fish j belongs to length class g, and takes the value 0 otherwise. In the first-phase sample there are a total of $n = \sum_{(jg) \in A_1} x_{jg}$ fishes and $n_g = \sum_{(j) \in A_1} x_{jg}$ fishes in length class g. Let A_1 be the set of indices of the fishes selected in the first-phase sample.

An unbiased estimator of the proportion of fishes at age class e is given by

$$p_e = \sum_{g=1}^{G} q_{ge} p_g \quad (6)$$

where the estimator $p_g = n_g/n$ represents the proportion of fishes of length class g obtained from the first-phase sample; this expression is equivalent to an estimator of relative weight of the length classes in the population, whose magnitudes are not known for any fishery. The estimator q_{ge} represents the ALK obtained from the second-phase sample, which is an expression of the proportion of fishes at age class e conditioned to the length class g given by

$$p(e|G = g) = q_{ge} = \frac{n_{ge}^*}{n_g^*} \quad (7)$$

where $n_g^* = \sum_{(j) \in A_2} x_{jg}$ is the number of second-phase sample fishes for aging that belong to length class g and $n_{ge}^* = \sum_{(j) \in A_2} x_{jg}$ is the number of fishes of age class e in the sample n_g^*. Let A_2 be the sets of indices of the fishes selected in the second-phase sample.

The approximate analytical expression most frequently used for the variance of the estimator (Kutkuhn, 1963; Southward, 1976; Kimura, 1977; Lai, 1987) of the age composition, is given by

$$\hat{V}(p_e) = \sum_{g=1}^{G} \left[p_g^2 \frac{q_{ge}(1 - q_{ge})}{n_g^*} + p_g \frac{(q_{ge} - p_e)^2}{n} \right] \quad (8)$$

2.5. A simulation study

A simulation study is used to illustrate which is the behaviour of the jackknife and analytical variance estimator. A data set of 30 vessel-trips was used, in which a total of 11,593 fishes were caught and measured in length and 951 were aged. With this data we obtained the age frequency distribution (P_e), which represents the parameter of interest.

For the simulation, combinations of samples were drawn from a population according to the following two-phase design: at the first-phase 20 vessel-trips were selected using a simple random sampling with replacement. All individual fishes within selected first-phase vessel-trips units were selected, resulting in a single-stage take-all cluster sample. At the second phase, all selected first-phase individual fishes were restratified into nine length strata (<135, 136–155, 156–175, 176–195, 196–215, 216–235, 236–255, 256–275, and ≥276 cm) and second-phase units (individual fishes aged) were drawn according to simple random sampling within each length classes, where the overall second-phase sample sizes were 600 and 800 fishes aged. For each sampling scenario, 4000 simulation runs were conducted.

For each of the 4000 samples of the different scenarios we estimated the proportion and variance at age, given in Eqs. (1) and (2) for the jackknife method and Eqs. (6) and (8) for the analytical method, respectively. We calculated as indicators the percent relative bias of the estimated proportion at age with respect to the population value (P_e) and the percent relative bias of the variance estimator with respect to the estimated true mean square error (MSE) (Stukel and Kott, 1996).

The percent relative bias of the proportion estimator of the age composition, is given by

$$\mathrm{RB}(p_e) = \frac{E(p_e) - P_e}{P_e} \times 100 \quad (9)$$

where

$$E(p_e) = \frac{1}{4000} \sum_{r=1}^{4000} p_{er} \quad (10)$$

p_{er} is the value of proportion at age class e for sample r.

The percent relative bias of the variance estimator of the age composition, is given by

$$\mathrm{RB}(\hat{V}(p_e)) = \frac{E(\hat{V}(p_e)) - \mathrm{MSE}_e}{\mathrm{MSE}_e} \times 100 \quad (11)$$

where

$$E(\hat{V}(p_e)) = \frac{1}{4000} \sum_{r=1}^{4000} \hat{V}(p_{er}) \quad (12)$$

and

$$\mathrm{MSE}_e = \frac{1}{4000} \sum_{r=1}^{4000} (p_{er} - P_e)^2 \quad (13)$$

and $\hat{V}(p_{er})$ is the value of variance of the proportion at age class e for sample r.

3. Results

The estimations of the age–catch composition of swordfish using Eqs. (1) and (6) were equal. Commercial catches of swordfish were dominated by the 1–6-year-old age classes, with the presence of individuals over these age classes not exceeding 9% (Fig. 2). In general when using the analytical expression for estimating the

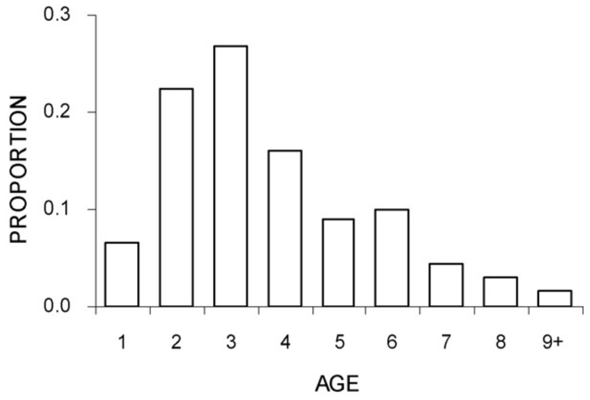

Fig. 2. Estimated age frequency distribution of swordfish in the Chilean commercial catch taken by the longline fleet, 2005.

variance of age composition, which assumes a random selection of fishes in both phases of the two-phase sampling, it was observed that the coefficient variation (CV) was lower in all the age classes when compared with results obtained with the replicate full jackknife variance, which takes into account the cluster (vessel-trip) as a primary sampling unit (Table 1). The age class 3, which was the dominant group in the commercial swordfish catch, shows a minimum level of CV with values of 0.048 for the analytical variance estimator and 0.083 for the jackknife variance estimator, in contrast with the age class 9+ which appeared at very low levels in the catch, and with the greatest CV estimated using both estimators (0.138 and 0.255). The mean CV value estimated was 0.096 for the analytical variance estimator and 0.146 for the jackknife variance estimator. The relative precision (RV) was greater than 1 for all ages and presented fluctuations around a mean value of 2.5 (Table 1), signifying that the jackknife variance estimator is 2.5 times greater than the analytical variance estimator, a difference that is attributable to the inappropriate of the primary sampling unit of analysis in the first-phase sample of the classic method of two-phase sampling.

Comparing these results with respect to age classes having high ($P_e \geq 5\%$) and low ($p_e < 5\%$) presence, it was observed that the first six age classes gave an estimated mean CV of 0.076 for the analytical variance estimator and 0.123 for the full jackknife variance estimator, with a mean RV value of 2.7, which was higher than the overall mean. In the other group, with all fishes 7 years and older, the CV tended to converge toward higher values for both methods, the mean value of which was 0.136 for the analytical variance estimator and 0.191 for the full jackknife variance estimator. The mean value of RV for this group of greater age classes reached a value near 2.

Table 1
Estimated proportions of swordfish at age class, standard error (S.E.) and coefficient of variance (CV) resulting from the application of two estimators of variance, and relative design precision (RV), representing a quotient between the jackknife and analytical variances

Age class	Proportion	Estimators				RV
		Analytical		Jackknife		
		S.E.	CV	S.E.	CV	
1	0.0670	0.0069	0.1035	0.0111	0.1663	2.583
2	0.2248	0.0117	0.0522	0.0222	0.0988	3.583
3	0.2685	0.0128	0.0477	0.0223	0.0829	3.025
4	0.1604	0.0114	0.0710	0.0140	0.0875	1.518
5	0.0897	0.0089	0.0994	0.0157	0.1751	3.105
6	0.0999	0.0082	0.0824	0.0126	0.1264	2.353
7	0.0436	0.0052	0.1202	0.0065	0.1481	1.518
8	0.0297	0.0045	0.1510	0.0050	0.1697	1.263
9+	0.0164	0.0023	0.1379	0.0042	0.2548	3.415

Table 2
Percent relative bias of the proportion at age class for two variance estimators (For samples of 20 vessel-trips in first phase, with 600 and 800 fishes aged in second phase)

Age class	600		800	
	Jackknife	Analytical	Jackknife	Analytical
1	4.6%	−70.4%	4.5%	−77.5%
2	4.9%	−71.2%	3.1%	−78.3%
3	2.9%	−71.4%	0.2%	−79.1%
4	3.1%	−63.3%	3.5%	−72.1%
5	2.0%	−60.9%	3.8%	−70.8%
6	2.8%	−52.9%	2.3%	−63.6%
7	2.1%	−38.0%	4.4%	−49.5%
8	7.3%	−30.9%	8.7%	−41.7%
9+	8.4%	−45.2%	8.9%	−51.1%

The results from the simulation showed that the bias estimated of the age proportion was small, with the biases range from −3.1 to 0.1. The biases were similar for the two estimators as expected, because the estimations of proportion at age from Eqs. (1) and (6) are equal. Furthermore, the differences from the two sampling scenarios (600 and 800 fishes aged) were small. In Table 2 is summarized the bias of variance of proportion at age class. The bias was consistently small for jackknife procedure in the two sampling scenarios, was positive and none exceeded 9%, while for analytical method the bias was highly negative, with the absolute biases range from 30.1% to 79.1%. For the last method the variance estimates tend to be more biased as the sample size in the second phase increase, to difference of jackknife that not presented clear trends of the results by age.

The mean values of RV obtained from the simulation reached a value near 3, confirming that the variance from jackknife estimator is greater than the analytical estimator.

4. Discussion

The performance of relative precision by age class indicated that the variance estimated using the replicate full jackknife method was more two times greater than the variance estimated using the analytical estimator. This result seems to indicate that the analytical variance estimator was more precise than the jackknife variance estimator. Nevertheless, the analytical variance did not take into account the characteristics of the clusters in the first-phase sample since it assumes that the fishes in the first-phase sample are a simple random sample of individual fishes from the population. The fishes within a cluster which present the most similar characteristics are the least informative if these come from a simple random sample of individual fishes of the study population (Pennington and Volstad, 1994; Pennington et al., 2002). The omission of the possible dependence of the fishes within the cluster leads to a general underestimation of the precision of the age classes (Aanes and Pennington, 2003; Helle and Pennington, 2004).

The resampling simulation applied to assess the behaviour of the two estimators used to calculate the variance of the age composition, supported the results of a lower estimation of variance from classical analytical ALK method. In the jackknife method for all ages the estimate of variance was consistently higher and the bias in the variance was consistently lower. In the case of the analytical method there was a general tendency to largest bias in the variance with negative sign. This confirms that the estimate of variance of the age composition from this classic estimator is likely to be an underestimation for true variance.

It is common practice in the study of marine populations to estimate the variance of the age composition when a complex two-phase sampling scheme is applied. An adaptation of the classic method of sampling is used assuming equal primary sampling units (individual fishes) in the first and second phases. This leads to obtaining less conservative estimates of variances, which is confirmed by the results obtained in the present analysis. It should be noted that this problem has received little attention in the fisheries literature, and it appears that the use of empirical methods is a more useful procedure in that it allows evaluation of the effect of the clusters in the estimation of the variance. Therefore, the method of estimating variance using the jackknife procedure could be a useful alternative for complex two-phase sampling schemes, particularly if the cluster can be completely measured.

The general conclusion, based on observations on the swordfish fishery, is that the analytical variance using the classic method tends to underestimate the variance of the age composition of the commercial catch, since it ignores the clusters underlying in the sampling scheme. This indicates that when all the fishes are measured for length on the trips sampled, it is preferable to employ the empirical estimator of jackknife variance. In the case when the first-phase subsampling of fishes is carried out within the clusters, and the within-cluster variance is small, the jackknife method will continue being a good approximation for estimating the variance of the age composition. Another alternative for estimating variance (not evaluated in the present study) would be the use of the bootstrap method with the clusters treated as resampling units.

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