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A new statistic for sampling design investigation : an application to length-structured landings sampling

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Measuring fish on a market or on board a vessel is the most common action taken by biologists all around the world to gather data for stock assessment. The samples coming from this kind of survey are of vector type and are not straightforward to analyse and compare. This paper proposes a generic tool that enables to investigate in any multinomial like sampling scheme. The use of this tool will be discussed based on examples from two different sampling designs. One is a sampling of commercial market categories and the other is a métier based sampling. The research of outliers, misallocated samples or potential bias, the stratification and the analysis of within and between strata variance will be discussed with the objective of constructing the best sampling design and insure the quality of the input data for stock assessment models. This statistic is easy to implement and should be considered as a mandatory step to validate the sampling data at an international level.

Keywords: market sampling, length structure, sampling design, stratification

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1. Introduction

The process of measuring fish in a market place or on board a vessel involves a lot of human power all around the world. It is obvious that this broad energy is useful to estimate the length distribution of the catch or the landings from a given stock on a particular time scale, let say on a yearly basis. The length distribution as it is or combined to an age-length key is used as input data to assess the state of the most important fish stocks. Inherent to any sampling procedure, the estimation of the length distribution may contain bias and uncertainties. The dissemination of input data errors or uncertainties in the assessment models have been studied by Kimura (1989), Restrepo *et al.* (1992), Pelletier (1991) and more recently by Patterson et al. (2001) and Reeves (2003) and are given to be significant on stock evaluations. The question arises then on what is the best sampling design and what is the optimal sampling intensity to certify the representativity of the length structure and achieve any targeted level of precision.

The question of sampling intensity has been largely studied, particularly to assess the best compromise between the length and the age numbers to sample to achieve a certain precision level (Lai 1987, Quinn and Deriso 1999). The question of the sampling design is more or less let at the sampling coordinators discretion. The sampling theory (Cochran 1977, Thompson 1992) applies to scalar estimators, not directly to a multinomial distributed estimator like the length structure. The purpose of this document is to propose an estimator resuming the information of the discrepancy between one vector-type sample and the overall vector coming from all the samples. This scalar-type estimator will be used on the particular frame of the market sampling for length and will enable the analysis of the sampling design following the common rules of the sampling theory. The population to sample is then the catch if the sampling is carried out on board a fishing vessel or the landings if the survey is a market sampling.

In sampling theory, the optimisation of a sampling design is based on a priori knowledge of the population to sample. This *a priori* knowledge coming usually from previous surveys with the same purpose or from a pilot study. In a yearly based recurrent sampling scheme like sampling for length in the fisheries landings, it is wise to use previous years knowledge to improve the next year sampling design. This continuous search of improvement and adequacy of the sampling scheme is not the reality, because no investigation tool is available.

When specifying a sampling design, the first idea that springs to mind is to split the population into strata. From Cochran (1977) we know that the stratification is appropriate when

1. data of known precision is wanted for certain subdivisions of the population (i.e. quarter, metier, …);
2. there are field constraints like sampling by different laboratories or countries;
3. biological differences between groups of the population has been identified in a previous survey or pilot study (i.e. offshore/inshore, North/South gradient, ….

Each of the three points given above are of importance when drawing a stratification for estimating the length structure of the catches or landings. Most of them require an a priori knowledge coming from the analysis of the previous survey. To enhance the sampling design and complete the analysis it is important to add

4. the search of patches to stratify in order to gain in precision. In our case, the patches should be referring to a biological explanation then addressed by point 3;
5. the search of outliers;
6. the adequation between sampling intensity, volume of landings and variance per strata if optimisation is seen through Neyman's allocation (Cochran, 1977);
7. the adequation between sampling intensity and the number of strata to investigate the problem of overstratification and poorly sampled strata.

It is important to stress here that stratifying to reduce variance is not the principal goal to achieve. A good sampling design should focus on reducing the potential bias (points 3 and 4) and defining a balanced field sampling between strata (points 6 and 7).

To carry out the complete sampling analysis, there is a need for an appropriate tool. In the literature, much is said on scalar-type estimators but very few on vector-type estimators. Recent workshops dealing with the problem of precision in the collection of data for stock assessment purpose (ICES 2004; ICES 2005a) have reviewed the way market and on-board sampling was organised in Europe. From this overview it comes that the stratification for length structure can be done in three dimensions, time, space and technical. Time is mostly quarterly divided, space is either integrated in the concept of stock or in the concept of métier when métier considers the location of fishing grounds (inshore/offshore, …). The technical dimension is either the commercial category or the family of gears used. From these considerations, it comes that the metier is a good candidate for stratification as it may include the three dimensions in a single denomination along with the definition given by the workshop on fleet segmentation (Anon.; 2005).

At a moment when harmonisation of sampling between countries is put forward (ICES, 2005b) it is time to investigate the broad sampling for length within the collection of fisheries data. In this paper we propose one statistic called Δ (Delta) directly derived from the analytical method for calculating the variance. It is possible to use Δ statistic to help in finding definition of strata such as metier or fishery that shows similar exploitation pattern.

Two case studies coming from the French market sampling will be used as support to the method. These are sole (*Solea vulgaris, L*) in Eastern Channel, ICES subdivision VIId and hake (*Merluccius merluccius, L*) in Eastern Atlantic, ICES Divisions VII and VIII. Sole in Eastern Channel is equally caught by trawlers and gillnetters and is split into steady and precise market categories. Hake in Eastern Atlantic is mainly caught by offshore trawlers divided in fishery units (Artexe *et al*., 2002).

2. Method

The methodology detailed in this section is mainly based on a practical analytical tool to investigate the adequacy of sampling designs regarding stratification assumptions. This tool could be used for any stratified sampling design. For practical reasons, it is presented through classical market sampling design stratified by time, space and fishing techniques. This sampling design aimed at providing an estimation of landings at length and/or age when possible for each stock. An estimator of the variance of total landings at length and at age can analytically derived.

Let the following notations :

- $\hat{D}$: the total landings estimator (in number)
- $\hat{D}_i$: the landings estimator at age *i* (in number)
- $\hat{p}_i$: the estimator of age *i* proportion of landings
- $\hat{D}_{ji}$: the estimator of the *j*th length class of landings within age *i*

The estimator of the landings at age is

$$\hat{D}_i = \hat{D}\hat{p}_i$$

and its variance estimator can be decomposed into three elements as described below.

$$\begin{aligned} Var(\hat{D}_i) &= Var(\hat{D}\hat{p}_i) \\ &= \hat{p}_i^2.Var(\hat{D}) + \hat{D}^2.Var(\hat{p}_i) + Var(\hat{D}).Var(\hat{p}_i) \\ &= V_1 + V_2 + V_3 \end{aligned}$$

The total landings estimator is

$$\hat{D} = \sum_j \hat{D}_j$$

and the estimator of the proportion of the landings at age *i* is :

$$\hat{p}_i = \frac{\sum_j \hat{D}_{ji}}{\hat{D}} = \frac{\sum_j \hat{D}_j . \hat{p}_{ji}}{\sum_j \hat{D}_j}$$

These estimators are calculated using the estimator of the landings at length, and the estimator of the proportion of landings of age i in the length class, estimated respectively from the length sampling and the age sampling.
In this paper, we focus on the variance estimation of landings at length. The sampling is a multi-stage sampling according the three dimensions

- stage1 : time (quarter, month, …)
- stage2 : space (ICES/GFCM subdivision, harbour sets, …)
- stage 3 : Technical (commercial categories, metier, gear, …)

In each technical stratum, a sample of the landings is collected and each individuals is then attributed to its length group (Figure 1).

Let consider some additional notations :

- k : k^{th} stratum
- K : the number of strata
- W_k : total landings of the k^{th} stratum in weight
- n_k : number of samples in the k^{th} stratum
- v : the v^{th} sample
- w_{kv} : the v^{th} sample weight in the k^{th} stratum
- J : the number of length classes
- j : the j^{th} length class
- d_{jkv} : the number of fish belonging to the j^{th} length class in sample v
- w_{jkv} : the weight of fishes belonging to the j^{th} length class in sample v

The variance estimator of the total landings is the following :

$$Var(\hat{D}) = \sum_j Var(\hat{D}_j) + \sum_{j \neq j'} Cov(\hat{D}_j, \hat{D}_{j'})$$

In this paper , we focus on $Var(\hat{D}_j)$

2.1. Variance of landings at length

From the sampling design of the landings at length, the estimator of the landings at length *j* may be decomposed as following :

$$\hat{D}_j = \sum_{k=1}^{K} \frac{W_k}{\sum_{v=1}^{n_k} w_{kv}} \left(\sum_{v=1}^{n_k} d_{jkv} \right) = \sum_{k=1}^{K} W_k \frac{\sum_{v=1}^{n_k} d_{jkv}}{\sum_{v=1}^{n_k} w_{kv}}$$

The estimate of the variance is

$$Var(\hat{D}_j) = \sum_{k=1}^{K} W_k^2 \operatorname{var}\left(\frac{\sum_{v=1}^{n_k} d_{jkv}}{\sum_{v=1}^{n_k} w_{kv}} \right)$$

and from Cochran (1977),

$$Var\left(\frac{\sum_{v=1}^{n_k} d_{jkv}}{\sum_{v=1}^{n_k} w_{kv}} \right) = \frac{1 - \frac{\sum_{v=1}^{n_k} w_{kv}}{W_k}}{\frac{1}{n_k}\left(\sum_{v=1}^{n_k} w_{kv} \right)^2} \frac{\sum_{v=1}^{n_k} \left(d_{jkv} - \frac{\sum_{v=1}^{n_k} d_{jkv}}{\sum_{v=1}^{n_k} w_{kv}} \right)^2}{n_k - 1} \tag{1}$$

2.2. Neyman's allocation

In stratified sampling, sampling intensity is driven by statistical rules but also by cost and practical constraints. In theory, an optimum allocation (minimizing the variance of the estimator for a fixed total size of sample *n*) is as follows

$$n_k = n \frac{N_k Var(\hat{D}_k)}{\sum_k N_k Var(\hat{D}_k)}$$

For practical reasons and lack of knowledge of the sampled population, this allocation is not easily operational.

2.3. Analytical tool for samples exploratory analysis

In a stratified sampling, each stratum is supposed to split the population into homogeneous subpopulation regarding to the estimated statistic. It is important to detect outlier samples and quantify their influence in the estimation of the statistic variance. We define an index, called Δ, which quantifies the discrepancy between the number at length in the sample and the adjusted mean number at length to the sample weight. This index of discrepancy can be used (i) to explore the samples of a stratum (either commercial category or métier) regarding (a) the length class or (b) over several or all length classes and (ii) to quantify the heterogeneity within a stratum.

With regards to these different cases, the formula of Δ is the following :

i. over all strata k
   a. given a length class j

$$\Delta_{jv} = d_{jkv} - \frac{\sum_k \sum_v d_{jkv}}{\sum_k \sum_v w_{kv}} w_{kv}$$

   b. over all length class

$$\Delta_v = \sum_j d_{jkv} - \frac{\sum_k \sum_v d_{jkv}}{\sum_k \sum_v w_{kv}} w_{kv}$$

ii. given a stratum k
    a. given a length class j

$$\Delta_{jkv} = d_{jkv} - \frac{\sum_v d_{jkv}}{\sum_v w_{kv}} w_{kv}$$

    b. over all length classes

$$\Delta_{kv} = \sum_j d_{jkv} - \frac{\sum_v d_{jkv}}{\sum_v w_{kv}} w_{kv}$$

Note that Δ_{jkv} matches with the last part of equation (1).

The different equations for Δ are centred on 0 and can show patterns, whereas the values of Δ^2 will be powerful to detect possible outliers.

3. Materials

Market sampling is done either by commercial categories, either by fleet or métier. Usually, sampling by commercial categories needs stability in the fish sorting process as a prerequisite. To represent both methodologies, North-East Atlantic Hake and Eastern Channel sole sampling scheme will be described and analysed.

3.1. North-East Atlantic hake

On the French Atlantic coast a large number of fleets lands hake using different fishing means: gillnets, trawls and lines. ICES working groups have defined Fishery Units (FU) to coordinate international sampling process. French sampling is based on these fishery units and landings are sampled within 5 of them : FU05 (inshore fish trawler in ICES area VII), FU09 (nephrops trawlers in ICES area VIII), FU10 (trawlers in ICES area VIII), FU12 (longliners in ICES area VIII) and FU13 (gillnetters in ICES area VIII). Sampling scheme is distributed among 6 harbours from south of Biscaye to south Britanny.
The length sampling objective is based on a number of fish to sample per FU and per quarter except for FU09 and FU10 based on a number of trips per month to sample.

- FU05 : 2000 fish
- FU09 : 10 trips per month
- FU10 :10 trips per month
- FU12 : 1000 fish
- FU13 : 500 fish

Age sampling scheme combines different methodologies

- item fish purchase : 10 fishes per length classes per quarter
- item Direct otoliths removal from market length sampling : 5 fishes per length classes per quarter with special attention to the largest fish
- Supplementary otoliths are provided by surveys (RESSGASC, EVHOE)

3.2. Eastern Channel sole

Sole landings are shared mostly between trawlers and gillnetters. Landings occur out of scallop season, i.e. from March to November. Regional landing distribution is about 30\% for

harbours between Cherbourg and Fecamp and 70\% for harbours between Dieppe and Dunkerque. The length sampling objective is based on commercial categories distributed among the principal harbours and quarter. At each sampling day, at least 3 samples from each commercial categories are sampled. One sample consists of measuring around 50 individuals, that is to say boxes with large number of small fish are split in two or three equal parts to avoid too much differences in the within category number of individuals sampled. On the other hand, boxes with very few number of individuals are skipped.
The age sampling is based on quarterly fish purchase. Once a quarter (usually in the middle), a fixed weight of each commercial categories is bought in order to have all the length classes range.

4. Results

4.1. Allocation of sampling effort

The precision level of a stratified sampling estimator depends mainly on the adequation between sampling effort and strata variance. Furthermore, a good way of minimising the variance is to chose Neyman's allocation, i.e. allow a sampling effort devoted to a stratum proportionally to the size and to the within variance of this stratum. In absence of *a priori* knowledge of the population heterogeneity a first view of the adequation between sampling effort and the size of the stratum can provide information on obvious discrepancies. Figure 2 proposed here on sole VIId shows a good correlation between sampling effort and landings and can therefore be considered as well established. Figure 3 shows that for sampling hake in Atlantic, fishery unit n°13 is not enough sampled when the temporal coverage is satisfactory.

4.2. Outliers and misallocated samples

The first analysis to perform on a sampling is to check if there is any outliers or misallocated samples. The assumption of sample representativity of the underlying population can be distorted by one or more samples taking most of the variance in one strata. Pointing out these samples has the same meaning as calculating the Cook's distance in a linear regression. The removing of such samples must be done in the most objective way as possible. In the example given figure 4A and after careful verification sample No 89151 is an outlier because of a mistake in the sample weight, sample N°85284 is misallocated and should be a sample of market category 50. Samples No 91346 and 92785 are not outliers and are kept in the data base. Figure 4B shows the sampling for sole VIId market categories after removing outliers and correction of the misallocation.

Sampling the metier, i.e sampling the total landings of a vessel trip that operates with a given gear on a given area and targeting a given (assemblage of) species is the alternative of sampling the market categories. The main difference between the two methods is that sampling the metier obliges to raise the sampling to the total landings to reconstitute the overall length structure landed. The values of Δ shown on the Y axis of the figures show this difference (figure 4 vs figures 5). Moreover, the raising process is done with an unknown uncertainty as very often only one box of fish is sampled by commercial category. The raising process tends to enhance the heterogeneity by mixing trips with low landings and trips with high landings. Figure 5 shows samples which are very different from the others but are not outliers.

4.3. Within strata heterogeneity

In figure 4B, the Δ values are sorted by commercial categories and it is obvious here that there is gradient between the category of the biggest fish (10) to the category of the smallest fish (50). The colouring feature shows that the sorting is similar in both North Eastern and South Western part of the Division VIId. The conclusion of this exercise is that it is possible to combine the samples from these areas and avoid the spatial dimension in the stratification. This only combination divides the number of strata by two, which can be of importance in the purpose of avoiding non sampled or poorly sampled strata. It is also noticeable that the division into 5 commercial categories is probably not the optimal division and splitting in two {10, 20, 30} and {40, 50} or three {10, 20}, {30} and {40, 50} would have given better results in term of precision for a given sampling effort. This draws the attention on the potential danger of setting too many commercial categories.

In figure 5, the most heterogeneous stratum is the FU13 which was shown figure 6 as being not enough sampled. This highlights the crucial need to increase sampling effort on this stratum to try to have a balanced sampling of all strata and reach a lower variance at a given sampling effort.

4.4. Between strata heterogeneity

For the smallest category of sole, are trawlers and gillnetters catching different length structures? When fishery units or metiers are defined, is it possible to combine some of them into a single sampling stratum to optimise the sampling design? Does different exploitation pattern in term of length structure of the catch makes a good stratifier for the definition of the fishery units or metier? the list of questions is as long as the number of scientists dealing with fisheries data. Heterogeneity within one stratum or within a specific group of strata is possible with the version Δ_{kv} of the statistic and enable to focus on a particular problem. The difference in fishing small or less small fish by a given gear can be scrutinized in the length structure of the smallest sole category, market category 50 (Figure 6A). To have more information, we have regrouped samples from 2002, 2003 and 2004. The result is that contrarily of what was expected, the gillnetters and the otter trawlers seems to have the same length structure but this structure is different from the beam trawlers. It is difficult to conclude that beam trawlers fish smaller soles with only 7 samples but this example shows what is possible with the Δ statistic. The area effect (figure 6B) is probably due to the beam trawlers that were sampled only in the North Eastern part of Division VIId.

One example of metier sampling is given here for Atlantic hake (ICES Division VII and VIII). Differences between vessels doing long trips (FU13) and vessels doing short trips appear very clearly (Figure 5). Concerning this sampling for hake, it is possible to focus more on the fishery units 09 and 10 and even to focus on these fishery units only in the fourth quarter on a reduced length range (figure 7). This figure points out a real difference between the landings of these two metiers raising the question to the hake biologists to find a possible explanation (recruitment caught by one metier and not by the other?).

5. Discussion

Market sampling for length is an extensive and time consuming process involving lots of human power all over the world. Sometimes considered as a good way to keep contact with the industry, the quantity of information is thought to be a good proxy for the quality of the data. The length samples raised to the total landings and combined to an age length key aim to be representative of the annual landings. In this process, the uncertainty on the volume of landings and the uncertainty on the information contained in the age length keys are preponderant on the length structure uncertainty (Gavaris, 1983). The issue can be more problematic for bias as a bias at the beginning of the three step process, indeed four steps if we consider international raising, will distort the final length/age structure estimates. The issue may also be problematic when considering technical measures based on gear selectivity or when considering assessment of a stock with only length structure. The Δ statistic proposed here is an easy and practical mean to investigate the sampling for length.

The only scrutiny on possible outliers makes the use of Δ statistic indispensable. Outliers or misallocated samples wrongly increase the variance and may sometimes distort the final result. When the sampling is aimed to provide data for assessment, it is much surprising to avoid such investigation and questioning on the catch at length/age structure as they are the main input data for the model. Moreover, the International combination is done on a yearly basis but the raising to International structure may probably be done at a more disaggregated level like métier or fishery unit and the use of Δ statistic would benefit to the global knowledge on the sources of variability of the data.

The sources of variability are particularly important to investigate at the moment of drawing a sampling plan. After compiling all sources at the scale of Europe, WKSCMFD (ICES, 2004) came to the conclusion that stratification for length should be done on a three dimensional basis, time, space and technical. Time strata points out the growth pattern affecting the individual length during a year. Quarterly stratification is the common way to deal with the issue, especially when length structure is combined to an age length key, but is quarter the best stratifier? Space strata is more optional and must be used only when metapopulation are proven to exist. It is often a source of confusion when the sampling design is drawn with a spatial component like harbours or landings areas to avoid bias or share the work between labs. There may be several groups of technicians measuring in different places in only one spatial stratum.

The technical stratification is probably the most problematic issue. There are mostly two sampling methods (i) sampling market commercial categories or (ii) sampling the landings of vessels belonging to a métier or fishery unit. Sampling market commercial categories makes the assumption that every vessel lands the same length structure within one category. The difference between raised length structure of different métiers remains in their absolute importance of market categories volume of landings. Métier based sampling makes the assumption that each métier has its own exploitation pattern and as a consequence, that each métier has a different exploitation pattern from the others. Δ statistic is useful here as it can be used on a certain range of lengths and explore whether metiers differ one from the others on the smallest and/or largest length classes. It can happen that two metiers have the same exploitation pattern and should be combined together. Much caution must be brought to such expertise as the similarity must be proven steady from year to year and have a certain biological sense. Market categories is a simplification of the métier sampling that allows less sampling intensity for the same precision. Δ statistic allows to test the assumption given above and it can be found that two métiers land different length structures within the smallest category and the same length structure within all the others. Considering length sampling all the assumptions can be tested with the Δ statistic and this kind of investigation is useful to draw sampling design that minimises the risk of overstratification.

The will to design many strata often comes from the unknowledge of the resulting length structure and from an attempt to estimate as many sampling strata as many existing sources of variability. Not only this leads to the problem of overstratification and poorly sampled strata but also there is a confusion between the estimation of the heterogeneity and the stratification. No length structure of one vessel's landings is similar to the other. The stratification must be a compromise between sampling intensity, *a priori* knowledge of the population heterogeneity, minimisation of bias and target precision. At a desired desegregation level, i.e. time span, a pure random sampling gives a good estimation of the overall length structure of the landings as the heterogeneity of the population is given to be represented in the samples. This should always be the basis of any sampling design and the stratification should be investigated at the light of the information contained in the primary samples.

The results of the Δ statistic need to be analysed with caution because it is based on a sum of positive and negative values. A low Δ value means that all lengths are close to the overall mean or that the positive and negative discrepancies cancel each other. To allow the Δ statistic to be representative of the reality, there is a need to be very confident on the sampled weight. This can be somehow problematic in the case of onboard sampling.

At a moment where fishery stakeholders and managers are willing to take into consideration the interactions between fishing industry, ecosystem changes and the available resources, the level of sampled information will strongly increase. At a moment where fishery scientists use more and more precise data, the sampled information must prove to be representative of the sampled population at the appropriate disaggregated level. It becomes critically urgent to investigate sampling design as a whole for fisheries data and this process begins with the investigation in the raw sampling data with a tool like Δ statistic.

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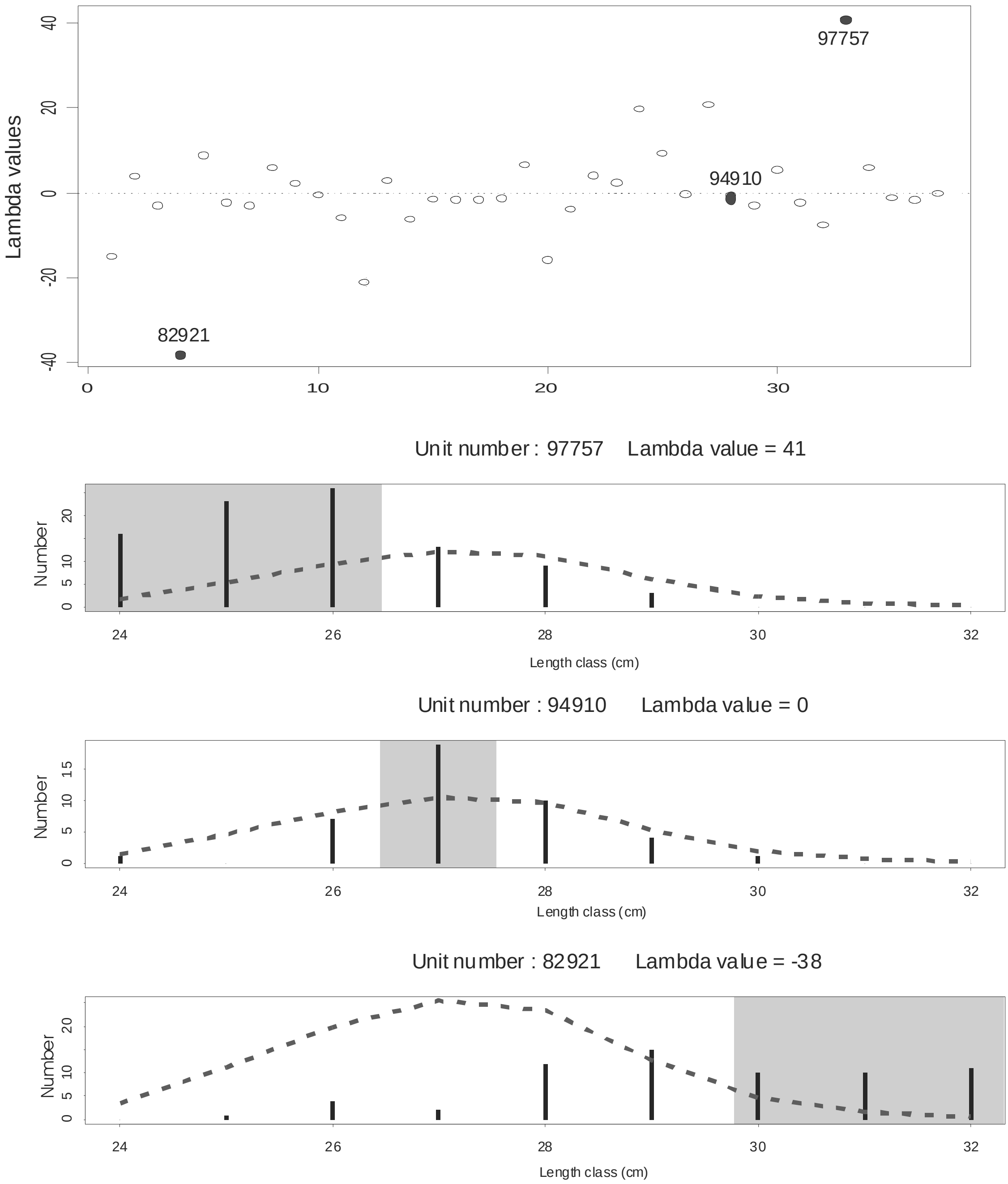


Figure 1 : Example of Δ statistic use, each point corresponds to a sampling unit (upper graph). Description of three units from the upper graph showing the length structure of the sample (thick line) and the averaged length structure rescaled to the sample weight (dashed line). the shaded zone corresponds to the length classes where the sampling unit is in excess compared to the average structure.

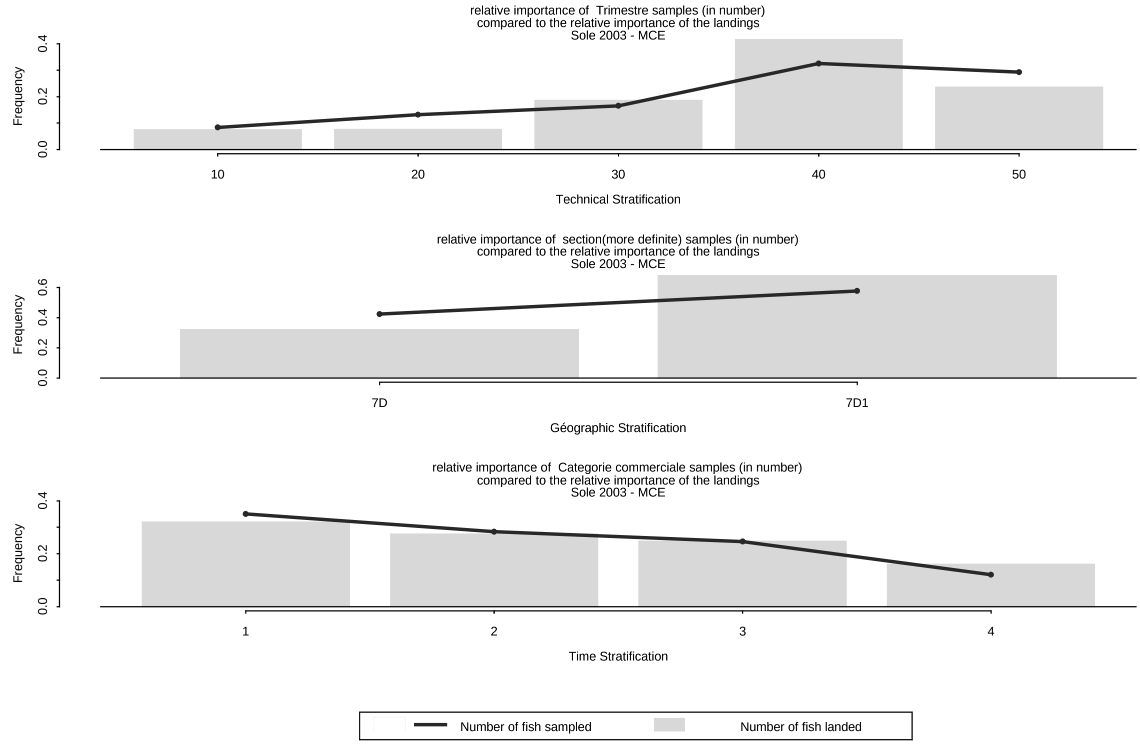


Figure 2: Sole VIId 2003 : Adequation between sampling and landings

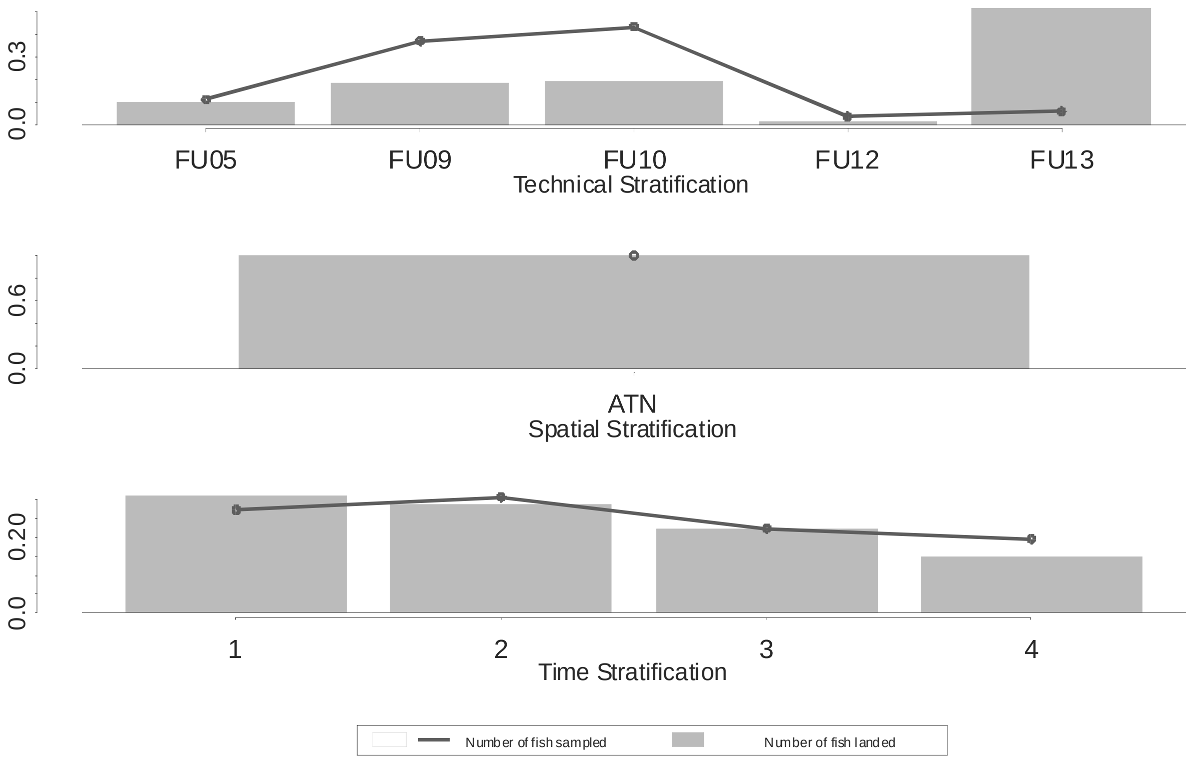


Figure 3 : Hake Atlantic 2003. Adequation between sampling and landings

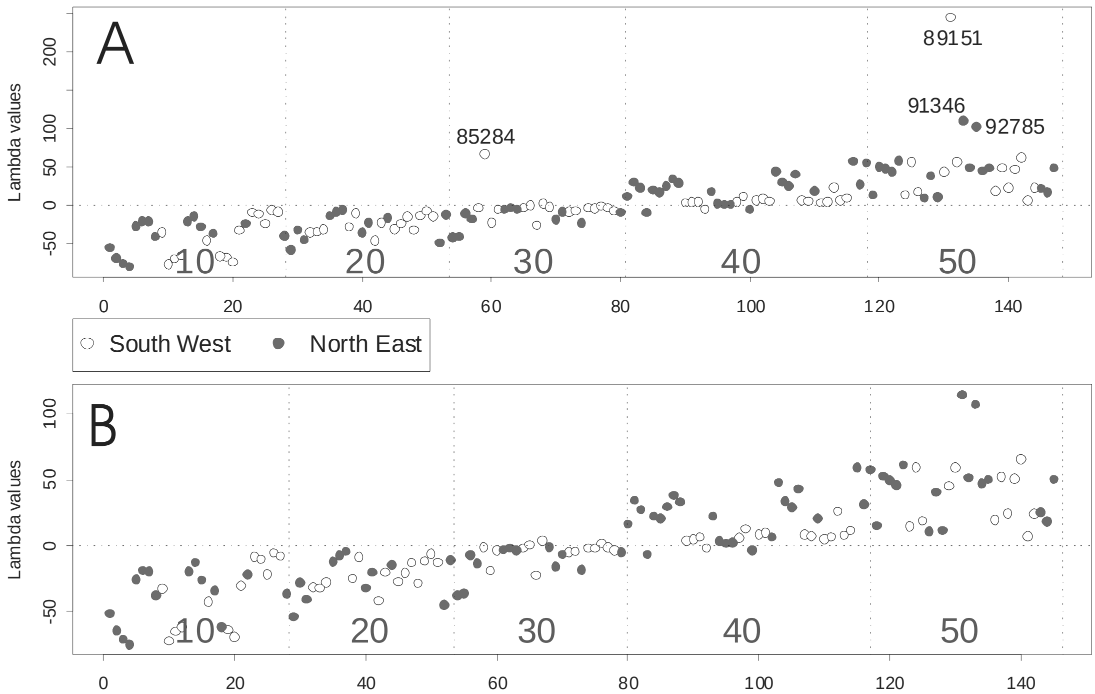


Figure 4 : Sole VIId 2003. Market category sampling. (A) all samples (B) after correction of the data set.

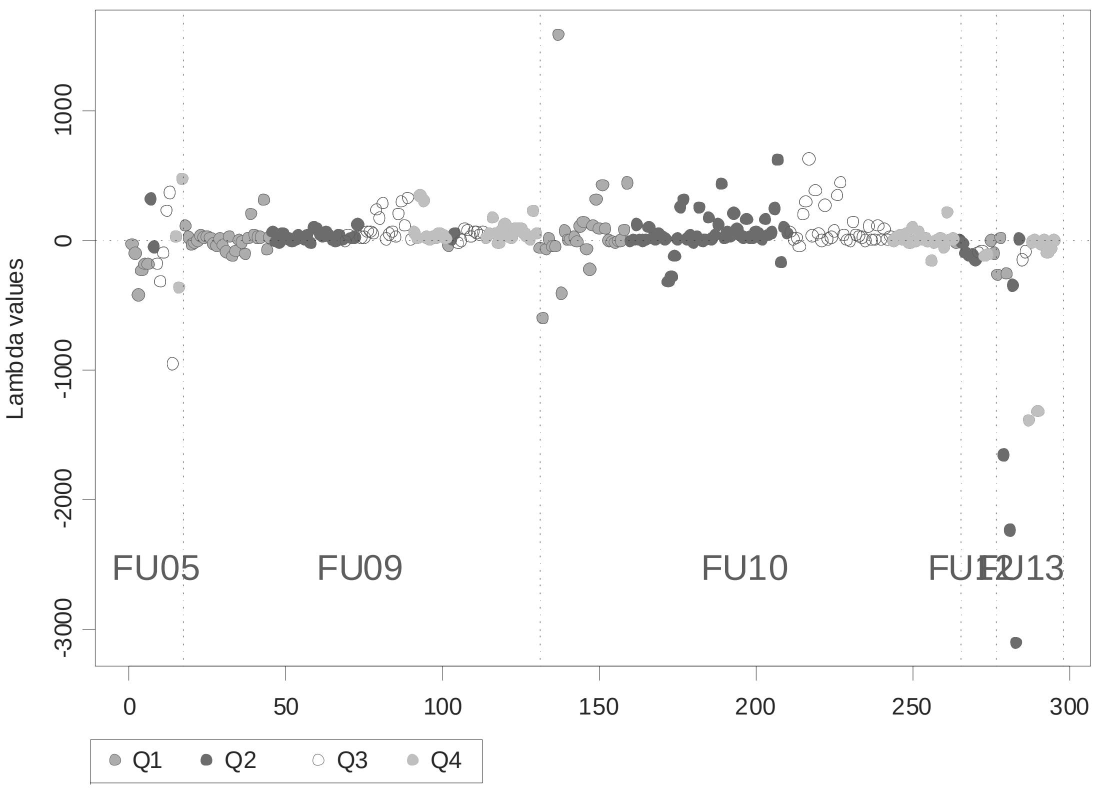
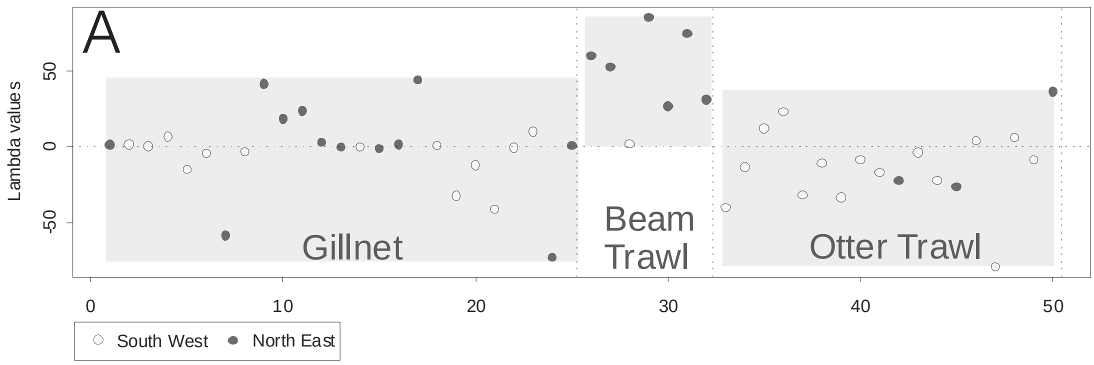


Figure 5 : Hake Atlantic 2003. Sampling ordered by Fishery units



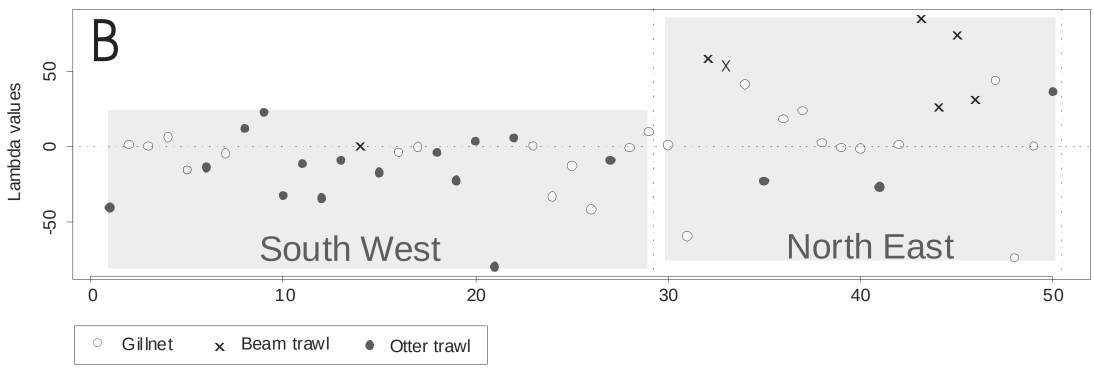


Figure 6 : Sole VIId 2002 – 2004 : Commercial category 50 (A) Gear effect (B) Area effect

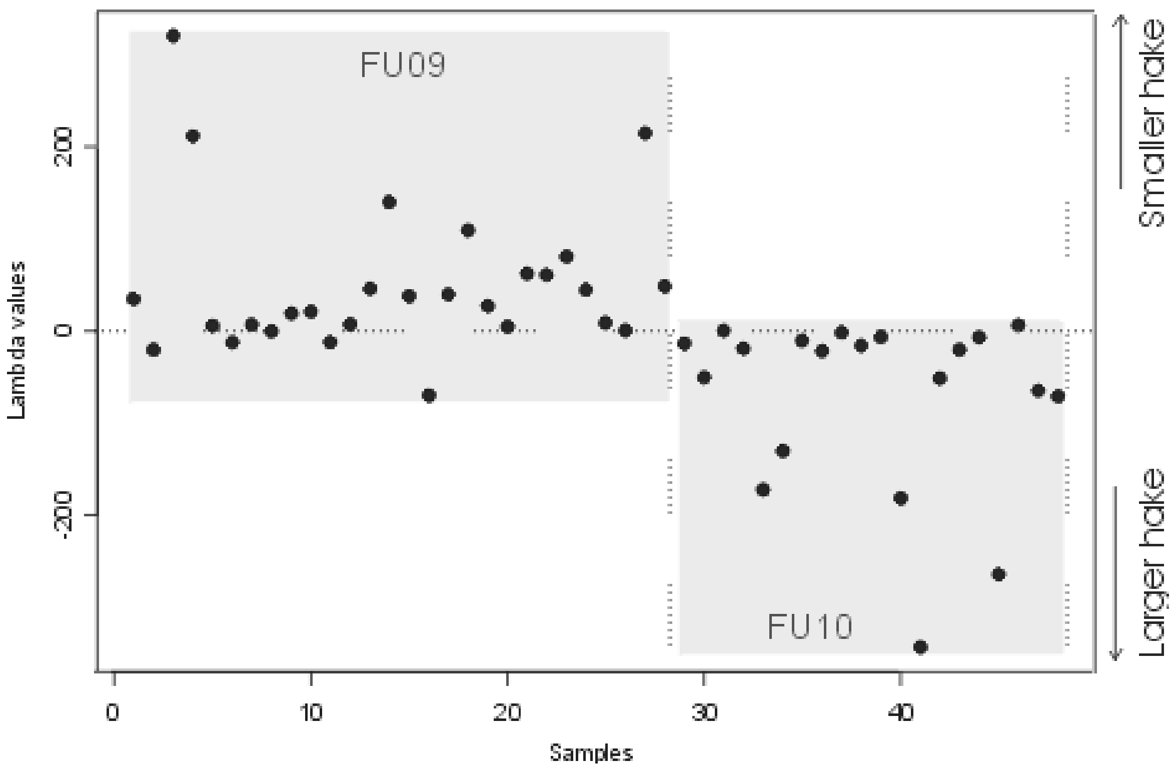


Figure 7 : Hake Atlantic 2003 : Focus on FU09 and FU10 during Quarter 4