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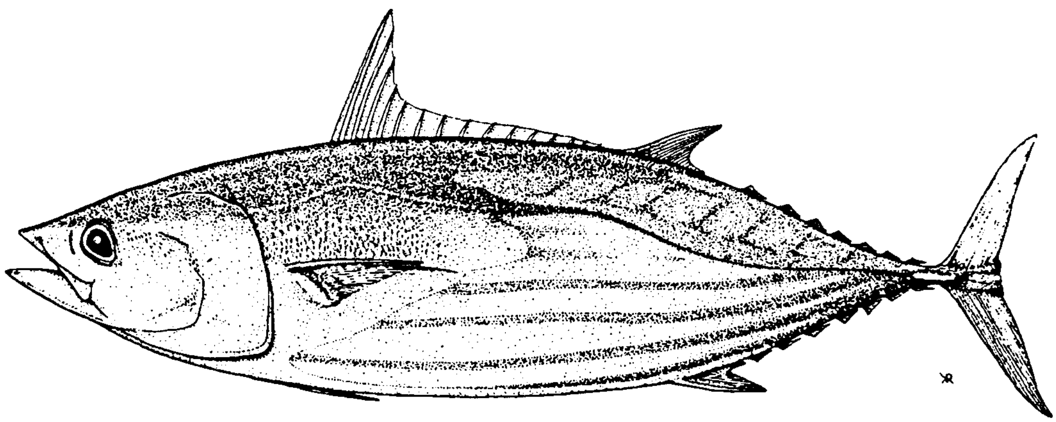

A review of length-based approaches to assessing fish stocks

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1. INTRODUCTION

Recently there has been a great upsurge in interest in length-based methods of assessing fish populations. The impetus for this has come from at least three sources - the increasing problems of applying the better known age-based methods (especially in tropical areas where fish do not carry easily-deciphered birth certificates on their scales or otoliths); the development of improved methods of analysing length data; and the increased availability of computers, especially desk-top microcomputers, that put within the reach of all the computational power needed to take advantage of some of the new methods.

This interest gave rise to a meeting in Mazara del Vallo, Sicily, organized by the International Centre for Living Aquatic Resources Management (ICLARM) and the Kuwait Institute for Scientific Research (KISR) in February 1985. This meeting brought together many of those working on length-based methods, and the report of the meeting (Pauly and Morgan, 1987) put on record many of the methods being used, some of which were previously available only in the grey literature.

From the meeting report it is clear that length-based methods have come of age, and represent a very valuable set of weapons for stock assessment scientists. They should not be considered as a second best alternative to age-based methods. Most length methods correspond very closely to similar age-based methods. They make the same assumptions about how fish populations behave, and depend to the same extent on the validity of those assumptions. Length methods have the operational disadvantage that they use an awkward time scale. Against this, the size of a fish may be more closely related to matters like food requirements or predation than its age. With the recognition of the usefulness of length-based techniques comes a corresponding need for some general guidance on how to set about using these methods.

In fact there are two needs. One is for technical guidance on how to apply one technique or another. This is now well provided for by the recent FAO manual (Sparre et al., 1989), based largely on the experiences of a number of FAO/DANIDA training courses. The other need is for a more general overview of the various techniques which can provide some guidance as to which methods to use. This report attempts to fill in this latter need. It is set out in four parts.

The first part deals with the collection of data. One of the main advantages of length-based methods is that the data are easy to collect. All that is needed is to go to the fish landing place with a measuring board and pencil and paper; and a major aim of this section is to encourage people to do more sampling and to collect length data from as wide a set of samples as possible in terms of types of gear, areas fished and times of year. To do this efficiently, guidance is given on sampling design, and on methods of recording and compilation.

The second part deals with the heart of length-based methods, i.e., the various techniques that have been used to estimate the vital parameters of fish population dynamics - the growth and mortality rates and the patterns of selection and recruitment. Each of the main methods are described, with their advantages and disadvantages, and enough information is generally given to enable the reader to apply the methods. However, to save space where the methods are complex and have already been described in published form, and especially where computer programs for using the method are available on request, only summary descriptions are given. This particularly applies to the ELEFAN suite of programs, where ICLARM has been very helpful in making these programs readily available to scientists in developing countries.

The third part deals with the actual work of assessment, i.e., bringing together these parameter estimates with other relevant information (especially statistical information from the fishery) in order to assess the state of exploitation of the fishery - is the stock heavily fished or not? - and to provide advice to fishery authorities on the potential for expansion or the need for management. Descriptions are also given for assessing the impact of possible management measures, such as increases in the size of first capture, some of which are particularly well handled by length methods.

Finally, guidance is given on what methods are likely to be most useful under different circumstances. Individual techniques are not equally useful in all fisheries, and in a given fishery only some (or in the worst case, none) of the methods are likely to be useful. This will depend on the pattern of growth and recruitment, the lifespan of the fish, and the selectivity of the fishery. Fisheries can be placed in different types, and a few length samples will show what type a given fishery is, and thus what methods should be considered. This final section also emphasizes the need, whatever method is used, for considering the reliability and precision of the estimates obtained, and the sensitivity of the results to the assumptions made and to the values of the inputs.

2. COLLECTION OF DATA

2.1 Background

The chief advantage of length-based methods is that the basic data are quick and easy to obtain. In the most recent review of the question of data acquisition, during the Sicily meeting on length-based methods (Morgan and Pauly, 1987), Hoenig et al. (1987) pointed out that these methods were often as demanding in sampling design and sampling effort as age-based methods. This is undoubtedly true as an observation of principle. Equally true as an observation of fact is that the difficulties of collecting age data in the volume, and with the spread in time and area that is desirable, are such that the age-data available for most fisheries are inadequate, even when there are no practical problems, e.g., in interpreting the rings on otoliths.

The observation of Hoenig et al., needs to be turned on its head. We may note that in many fisheries, given the variation in the sizes and ages of fish caught in different times and places, and the limited sampling facilities available, only with length-based methods is it likely to be practicable to collect statistically adequate information, i.e., data that take full account of the variability in the sizes (and ages) of fish caught at different times and places and with different gears. Collection of age data is often constrained by problems of interpretation, and collection of catch and effort data by the operational complications of the commercial fishery. The collection of length data (as representing what is caught, if not always what is in the sea) is less constrained, and the opportunities exist for setting up sampling systems for length data that are statistically efficient, and in which the resources deployed for the data collection work are in reasonable balance with, on the one hand the total resources available for all kinds of work, and on the other the contribution that length data can make to the general stock assessment programme.

Nevertheless, a superficial examination of data collection systems throughout the world suggests that in many places length samples are not being collected according to a careful statistical design, and in only very few has there been a full statistical analysis in order to determine the optimum design. Also, in many cases, comparatively few resources are allocated to this work, and one of the easiest ways to improve the assessments being made is to collect more length data (see for example Gulland, 1987, and Pauly's comment to this letter).

There are good reasons for this. Collecting length data is not a very interesting or challenging scientific task, even when it is done in comfortable conditions, and properly representative samples of fish catches can often be obtained only by working at fish markets in the early hours of the morning or on the deck of a fishing vessel at sea. The assessment scientist is usually very busy and has many tasks that are more obviously urgent, though not necessarily more important in the long run, than designing a good sampling scheme. This is reflected in the scarcity of published material dealing with the theory and practice of sampling commercial catches. A significant exception is the report of the Canadian workshop held in 1982 (Doubleday and Rivard, 1983) which contains much valuable material and is not confined to Canadian experience. Though the papers deal only with North Atlantic and North Pacific fisheries some of the situations faced, e.g., in the Newfoundland inshore fisheries, are similar to those of developing countries.

Sampling design and sampling intensity may be given some attention at the beginning of an investigation but at that time one is faced by the problem of the chicken and the egg. A good design cannot be set up until something is known about the variability of the data, what analyses can be made with the data, and how the precision and reliability of the answers are affected by the sampling errors and by other sources of uncertainty. However, these questions cannot be answered until data have been collected to show how length samples vary from place to place and from time to time, and some preliminary analyses have been made with the data.

At this point it is worth defining a few commonly used terms, all describing the attributes of a sampling scheme, or the estimates obtained from the scheme. There is an important distinction between terms that describe how close repeated samples will come to the same answer, and how close this answer comes (on average) to the true value. The first attribute is described by the variance of the attribute, and estimates with small variance are often described as having a high precision. The amount by which the average from repeated sampling departs from the true value is the bias, and a sample with small bias can be described as accurate.

Initially a sophisticated design cannot be expected. The first stage of any programme in which length data are likely to be important should be concerned merely with collecting as many data as can reasonably be done, making sure that there is as wide a spread as possible, with data being collected in all seasons (or all seasons in which significant fishing is done), from all areas, and from all types of fishing gear. Even at this stage some general principles can be followed. For instance, within-sample variance is likely to be much smaller than between-sample variance, and so it pays to collect many small samples rather than a few large ones. There are also general statistical procedures in randomizing the sampling, and strategies like cluster-sampling that can be used from the beginning.

The opportunities to design a fully efficient sampling scheme come when investigations have been going on for a few years. At some point it is desirable to make a special effort to answer such questions as:

- Is there a chance of bias?
- How big are the sampling errors?
- What is the contribution of these errors to the final outputs from the assessment studies, e.g., the value of next year's Total Allowable Catch (TAC) and to the various intermediate stages such as the current estimate of Z?
- How does this contribution compare with that of other sources of error and uncertainty, e.g., in the catch statistics, or of echo-surveys?
- How might the sampling work be modified to reduce variance and as far as possible eliminate the risk of bias?
- Should the proportion of the total resources allocated to collecting length-data be modified?

These questions should be part of regular reviews of research programmes, and are considered further in Section 5. For the present section it will be assumed in discussing sampling design, etc., that something is known about the variability of the population being sampled (usually the commercial catches) and the uses to which the data will be put.

2.2 The mechanics of length sampling

At first sight nothing could be simpler than sampling for length. It seems to be a matter of just going to some convenient point and measuring a proportion of the fish that are available. In practice, if later difficulties in using the data are to avoided, some practical points need to be carefully considered, including:

... what characteristic (e.g. total length) is to be measured, and in what units and with what precision?
... how are the measurements to be recorded?
... which fish are to be measured?
... how many fish are to be measured?

There are a number of quantities that may be referred to as the length of a fish - standard length, fork length, total length, etc. (for a fuller description of this and other practical aspects of collecting length data see Holden and Raitt, 1974, and Anon., 1981). As far as the application of length-based assessment methods is concerned it does not matter which length is used provided the same quantity is always used, and a record is kept of which is used. Special problems can arise with animals with odd shapes, e.g., shrimps or lobsters (carapace length is often used), or when some of the catch is partially processed (e.g., the heads removed) before it can be sampled. Bias can arise if processed fish are not sampled since only certain sizes may be processed. Sampling can then be done by using some other body measurement and converting.

Measurements should be done with reasonable precision, but very high precision need not be sought. For most applications the data will be grouped into length-classes - usually 20-40 groups - and much greater precision than this, e.g., 0.5 cm (for fish that range in size from 10 to 25 cm (giving 30 groups), will give little additional information. There are positive reasons for not attempting to make records with very great precision - it adds to the work, and can increase the chance of error. For instance, if attention is focused on whether a fish is 53.4 or 53.5 cm long, its length may be read or recorded as 63.4! In any case, a precision as high as this is unlikely to be achieved during large-scale sampling on the deck of a fishing vessel or on a fish market.

There are some applications, e.g., when trying to distinguish two adjacent modes, when finer divisions may be desirable, though there are limits to the extent to which they can help when the modes are close together. Thus it is often useful to measure fish to a greater precision than the groupings that will be used in most analyses. As a rule-of-thumb a precision of 1 cm is adequate for species for which most fish are 30 cm or bigger, with perhaps a few down to 20 cm; a precision to 0.5 cm at the time of measuring is fine for fish from 15 cm upwards, and so on for smaller animals. For example most cod, ranging in size from 30 to 100 cm plus are measured to the centimetre, but most length-frequencies are reported in 5-cm groups.

The point to be remembered is that for most purposes the precise length of any one individual fish is not of interest. There are exceptions, for example when relating different measurements for morphometric studies, or for length-weight studies, and for these purposes more precise measurements can be made. Usually we are interested in the size of a fish as being representative of the size of, say, 6-month old fish in a particular area at a particular time.

Whatever precision is used at the time of measuring, the boundaries of the groups should be clearly defined. The usual convention is that measurements are made to the unit below, e.g., a 20-cm fish means a fish whose length is between 20.00 cm and 20.99 cm, etc. This makes it easier to combine the data into wider groups (a 5 cm group will run from 20.00 to 24.99) - than if measurements are done to the nearest unit, i.e., a 20-cm fish means one between 19.50 and 20.49 cm. Confusion has arisen in the past when trying to combine measurements done according to different conventions. Whatever system is used it is convenient to have clear marks on the measuring board corresponding to the divisions of significance, e.g., at each centimetre, and to avoid any irrelevant markings, e.g., at the 0.5 centimetre.

The system of recording should be chosen so as to facilitate matters for those who are measuring the fish and for those who are to process the data, especially those who enter the data in whatever computer or other system is used. A well designed recording form will reduce the work, and make mistakes much less liable, or if they do occur, make it more likely that mistakes are detected early and corrected. Ideally there should be no intermediate step, other than perhaps a quick check that all data seem to be recorded, between recording the data on the fish market or on board the research vessel, and entering them in the computer system. Indeed, Pope (1988) points out the advantages of entering research vessel data on ship-borne systems at sea. If, as there should be, there are routine checks on the data as they are entered for such things as gross errors in sampling date, size of fish (no 120 cm anchovy), etc., and queries are raised over the ship's loudspeaker system, this incites a greater care with which data are recorded.

Examples of forms used in recording fish measurements are given by Holden and Raitt (1974), and in the updated version (Anon., 1981) and by Burns et al. (1983) in a useful review of the catch sampling programme in the northeastern USA. Experience suggests that it is not easy to design a form that will satisfy the ideal criteria above under all conditions, and that each data collection system will need slightly different forms to take account of the working conditions, the types of auxiliary information (name of ship sampled, its catch, etc.) needed and the system used to work up the data. Experience also indicates that design of the perfect form is not easy, and that nearly all forms need to be modified after a period of use. When a sampling scheme is introduced, therefore, one should look at forms used elsewhere, consult with those who are to record the data on the market and enter the data on the computer, to design what may seem from these discussions the best form, and then review it after a season's use (do not print a vast supply of a routine form at the first attempt).

Any form will consist of two parts, to record two kinds of information: the actual measurements, and the ancillary information about the source of the sample. There are various ways of recording the measurements. Most usually, measurers work in pairs, one handling the fish, and the other recording. The form should have the lengths already printed so that only numbers need to be noted. Hoenig et al. (1987) recommend the use of a stem and leaf diagram, which is useful if very precise records are needed; but a "window" system in which measurements are recorded in blocks of five is more usual and makes subsequent analysis easier. The ancillary information is most important for subsequent analysis and interpretation.

It should include:

.... date
.... place of sampling
.... name of vessel sampled
.... location of capture (if known; for large vessels making long trips, for which exact information may not be available, as much information as possible about the fishing grounds should be recorded)
.... date of capture (for vessels making long trips, for which this may differ significantly from the date of sampling)
.... gear used
.... target species (especially if different from the species measured)
.... total quantity landed (if the catch has been sorted into different market categories it is most important to record quantities of all categories)
.... sampler's name

The layout of the form and the details to be recorded should also take into account the procedures to be followed in the subsequent processing of the data, e.g., the database system to be used. This is discussed further in section 2.4.

The choice of which fish to measure is a matter of avoiding bias and reducing variance. Bias would be eliminated and variance would be small (though not necessarily a minimum) if each fish measured were chosen at random. This is impossible when sampling the landings of a commercial fishery. The choice of fish to measure is a hierarchical process involving most if not all of the following stages:

(a) Space

- different regions of the country

- different landing places/ports within a region

(b) Time

- seasons
- months/weeks
- days

This means that sampling will be done only at certain landing places on certain days during the year. On the occasions when sampling is done, further stages are involved;

(c) Sampling on one day

- landings by different vessels
- different size or other categories of fish
- boxes or other types of container within a category
- individual fish

The question of how to allocate available manpower and other resources in order to minimize variance is discussed in the following section on sampling design. Here we will look at the ways in which bias can occur.

Taking truly random samples (of vessels landing on one day, of fish in a box) will eliminate bias, but unless a formal randomizing process is followed, e.g., determining the vessels to be sampled according to the order in which they land, the numbers to be sampled being drawn from a set of random numbers, it is unlikely that the procedure is truly random. The absence of a conscious system, with sampling being done haphazardly, does not make sampling random. Almost inevitably some unconscious pattern will develop, and this can introduce bias.

Some biases are obvious. If a dozen fish are measured from a box of fish at the market, or from a pile of fish on the deck, they will usually be the larger fish. If the sampler is aware of this, he will probably avoid the biggest fish. To avoid bias, the general rule should be followed that any sample should consist of one (or more) complete boxes, or a complete pile of fish. If this would result in an unnecessarily large sample (more than 100-200 fish), then bias can be avoided by taking all the fish on one side of a box, or by dividing the pile of fish on deck in two or more piles before deciding which to sample.

Other sources of bias are less obvious. The landing places to be sampled will tend to be those that are close to the research institute, or otherwise convenient to reach. The vessels to be sampled will tend to be those landing at a time of day, or at particular position in the market that is convenient for sampling. These may correspond to particular fishing grounds (for example, those landing early in the day may have fished close to the port). In these cases the fish sampled may not be typical of the landings as a whole, and bias is possible. The procedures to avoid bias, involving some predetermined method for choosing which landing places, days or vessels should be sampled are similar to the sampling systems for determining total catches (see, for example, Bazigos, 1974).

2.3 Operational considerations

When designing a programme to sample the landings of a commercial fishery (commercial in this sense meaning any catches other than by research vessels) the scientist can be faced with a great variety of conditions which will affect the ease of sampling. Fish may be landed by a few large vessels at one or two major ports or by numerous small vessels at many points along a coast. The complete catch may be laid out for a time before being sold at auction, or the fish may be sold and taken away as soon as they are landed. Fish may be landed without any treatment a few hours after being caught or they may not be landed for days (even months in the case of some tuna longliners and other long-range vessels) and be processed in some way before landing. A single species of fish may be caught by several types of vessel, and each group of vessels may catch several different species of fish. Much of this variety can exist even in a fairly homogenous area, e.g., the northeast USA (Burns et al., 1983).

Given this variety of conditions it is clearly difficult to set out detailed guidelines on how the practical work of sampling for length should be carried out. So much depends on local conditions, and the details of the individual procedures will often have to be developed by trial and error. One early decision concerns the point in the progression from fisherman's net to consumer at which the measurements are made. The earlier the sampling is done the better, since this reduces the chance of any sorting or discrimination. The best point is usually as the fish are unloaded at the landing place, especially if there is a period (e.g., before the auction) when the catch is laid out and undisturbed.

Consideration should also be given to sampling at sea on board the fishing vessels themselves. This clearly gives high quality data, with exact data on position of capture, etc., and may be the only way of obtaining reliable data on the quantity and size of discards. It is however inefficient, since sampling will be concentrated at one place and not spread through the fishery. Baird and Stevenson (1983) and Zwanenberg and Smith (1983) have both compared at sea and in port samples. While the latter found some differences between port samples and at-sea samples from individual sets (which they ascribed to a variety of causes, including real differences between sets), the former concluded that the two sources were equivalent, with roughly equal variances for the same amount of sampling. However, both these studies were done in Canada. Different conclusions might apply in other fisheries in which there may be some sorting or processing before the fish are landed. Since much more sampling, spread more widely through the fleet can be done with port sampling, this seems best for routine work, though the opportunities for at-sea sampling, for example by observers sent to check on the compliance with regulations, should never be neglected.

Initially, before experience has built up, it is desirable that the research scientists who will be using the data in later analyses are themselves closely involved with the actual sampling and handling of the fish. There is nothing like a few hours on an exposed fish market before dawn in the winter at some North Sea fishing port to make one realize how errors can arise in the length sampling procedures! Later one can expect that most of the work will be done by less highly trained staff, and at that time it is desirable to set out the procedures to be followed in a detailed manual. Such a manual, as well as describing how the forms should be filled out, could include instructions on when and where to sample (e.g. measure fish from three landings whose position in the market are determined by a given set of random numbers). Fully detailed instructions should avoid many of the sources of bias that can arise when the choice is left to the sampler.

Some general principles can be set out to help develop the specific procedures for any particular fishery; the cooperation of the local fishermen and fish merchants and dealers must be assured. Once a programme is established they will usually come to accept scientists as a normal part of the landscape of the fish market. Initially care must be taken to explain what is being done, to avoid interfering with the normal activities of the landing place (almost inevitably measuring will have to be done when a lot of other things are going on), and not to damage or otherwise reduce the value of the fish measured (this will often mean arranging the fish in a box nicely with the biggest ones on top, if fish are measured prior to an auction). Sampling fish for scientific purposes should be kept completely distinct from possible examination of the catch for control purposes e.g., to check whether a size limit is being obeyed. The sampling should be done as soon as possible after the fish leave the fishing vessel, before there is much chance of sorting or selection. Even if there is no explicit sorting it is common for different markets or customers to prefer different sizes of fish.

In practice research and sampling will involve more than one species but this need not be a disadvantage. For example, if sampling of just one species largely, but not entirely, caught by one type of gear or one group of fishermen is being considered, then the minor landings are a nuisance. If they are not sampled then the estimates of, for instance, the size composition of the total landings may be seriously biased. If they are sampled, this may require special visits to distant areas, and involve a disproportionate amount of time in terms of the one species. However, in many cases the minor landings will consist of incidental catches in fisheries targeted on some other species. A few samples of the first species can then be easily taken as part of a programme directed primarily at those other species.

Sampling at sea, either on a research vessel or on a commercial vessel, presents its own problems, of which the physical difficulties of working in a confined space are often the biggest, and ones for which no general rules can be laid down. If the entire catch, say, in a trawl haul, can be measured the procedures are obvious. If less than the entire catch is measured then care must be taken to avoid bias. This may be done by dividing the catch into approximately equal piles or baskets. Alternatively the catch may be pre-sorted into species or species groups, and only some species measured. Here, as Pope (1988) points out, bias can be introduced if sampling is concentrated on the commonest species. This can mean that a species will be sampled only when large numbers are caught; these occasions may also be those when the dominant size groups are present, and the very big and very small fish may be under-represented. It is best if the species to be measured at each station of, for example, a routine trawl survey, should be predetermined as part of the survey design.

2.4 Processing of data

Few analyses will be made of the original measurements as they are made on the fish market. Before they are used to apply, for example, a length-based cohort analysis, they need to be processed in some way. The degree to which this processing should combine information from different sources, and the form in which the output should be presented, will depend on the type of analyses that are to be made. Generally what will be required will be the total numbers (or percentages) in each length group for the total catches (or landings) of a certain species during a year, or some sub-set of this, e.g., catches during a month, or at a certain port or by a certain type of gear.

The principles involved are best seen by considering the most complete form of analysis, i.e., to determine the year's catches in a complex fishery in several areas, several landing places, and several types of gears, in which it is only possible to sample a few of the vessels landing, at some of the landing places, at a few days each month. The logical steps for processing data, after the original measurements have if necessary been combined into suitable length-groups, are very simple. One step is, if only some elements in a set are considered (half of a box of fish, one box out of 30 landed by the sampled vessel, two vessels out of 15 landing on a particular day, etc.), the total for the box (or the vessel or the day) must be estimated by multiplying the numbers in the sample (the part box, or the sampled vessel) by a suitable raising factor (2 for the half box, 15 if one out of 15 vessels have been sampled). (NOTE: In some cases there can be a choice of raising factors. For example, if the 15 vessels have landed 164 boxes of fish, and the sampled vessel 10, an alternative raising factor is 164/10 = 16.4. The latter will usually be the most satisfactory, since it gives different weights to each vessel according to its contribution to the total catches).

If several samples have been taken within a set (several vessels sampled on one day, or several landing places in one area) the next step is for the numbers in different samples to be added together to give the total for the sampled units within the set (i.e., for all sampled vessels during the day). The process can involve a long sequence of these steps. For example, if a part-box has been sampled from each of several ships on each of several days during a month and sampling was done at some, but not all the landing places in each of several regions in a country, the steps to obtain the numbers in a certain length group landed in the whole country would be:

- raise the number measured to give the number in the box
- raise the number in the box to give the number in sampled ship (of that category, if the fish have been sorted)
- add, if necessary, to give total of all categories in sampled ship
- add to give numbers in all sampled ships on that day
- raise to give total for all ships on that day
- add to give total for all sampled days
- raise to give total for month (or other basic time period) at that landing place
- add to give total at all sampled landing places in a region
- raise to give total for whole region for month (or other basic time period)
- add to give total for country for month
- add to give total for year

It will be useful when the sizes taken are noticeably different (as in the case of tuna taken by longlines and surface gears) that they are kept apart until the final stage, i.e., separate annual totals are estimated for each gear and then added. With less pronounced differences the different groups may be combined earlier, e.g., when calculating regional totals for a month.

There is considerable choice over the details of how this process is carried out, for example, the length of the basic time period, or how data from different landings are grouped. The choice will depend on the uses of the data, and the interests that exist in the various intermediate totals. The total for a single vessel will seldom be of interest in assessments, though it will often be useful to compare different vessels when determining the intrinsic variation in the estimated length-composition. The greatest detail will probably be needed when following modal progressions to estimate growth. Then the time intervals should be fine enough that there is little growth during the interval. This may mean half-months or even weeks for fast-growing, short-lived species e.g. shrimp, while months or even quarters of the year may be sufficient for long-lived fish like cod.

2.4.1 Market categories

It is common for fish to be sorted into different categories, usually according to size, before they are sold. The consistency with which this is done varies from fishery to fishery; in some the big fish may be picked out and sold separately only for the better catches, and what is considered a big fish for this purpose can change from day to day; in tropical shrimp fisheries the products (at least for export) are graded into several categories, based on the number of shrimp per pound, that are the same virtually worldwide.

This sorting adds to the complications, but can mean that better estimates can be made of the size composition of the landings with little or no extra effort. For example, if most of a country's shrimp catch is exported, and the proportions in each size (count per pound) category is known, then quite a lot is known about the sizes of shrimp caught, even if no measurements are made. Care is needed in using category data, otherwise considerable bias can easily occur. For example, the shrimp that is not exported, and thus maybe not appearing in the size category data, is not a random sample of the catch, and in most cases will be only the smaller animals. Excluding them would give a serious overestimate of the mean size of the catch.

Discards are a special, and difficult, case of sorting by the fishermen of the fish before sale. Discarding is especially notorious in the case of many penaeid shrimp fisheries (see Gulland and Rothschild, 1984), where often all but the largest specimens of the demersal fish caught incidentally in the shrimp trawls are discarded, but discarding is a feature of many other fisheries. The existence of discards can complicate many assessments, especially of the results of changing the effective selectivity of the fishery, and make it very important to maintain the distinction between catches and landings. These problems, which are discussed by Saila (1983), are not specially related to length-based methods, though because discarding is often size-dependent length-based methods may be best suited to handling them.

2.5 Statistical design

2.5.1 How much sampling?

Some general guidance on the amount of sampling has been given by ICNAF (1974) and Hoenig et al. (1987). These are very different, reflecting the different purposes envisaged. The ICNAF recommendations, that at least one sample (of around 200 fish) should be taken from any stratum of a fishery (the fisheries in the Northwest Atlantic being stratified by gear type, area, and quarter of the year) in which 1 000 t or more of fish were taken, reflects the level of sampling necessary to monitor adequately a large industrial fishery, in which management measures were being actively considered. In Newfoundland, with a large and complex fishery following this standard (at least roughly) has resulted in some 1 072 000 fish being measured in 1980 (Muir, 1983).

In contrast Hoenig et al. (1987), following Pauly (1984), looking for minimum sampling levels that would provide data that could be used for simple length-based analyses, considered that sampling a total of 1 000-1 500 fish spread over 12 months was "excellent", and that even 500-1 000 fish spread over 6 months was "good". This difference largely reflects the different purposes. A sample of two or three hundred fish should be enough to identify one or two modes and, if the stock is nicely behaved, repeated samples at intervals of two or three months should show these modes progressing in a way that allows some sensible estimators of growth to be made. Such a level of sampling is, however, totally inadequate to provide reasonable estimates for next year's Total Allowable Catch (TAC). For regular monitoring of industrial-scale fisheries the ICNAF standards, which have now been in use for many years, and for which no significant modification has been proposed, appear the best.

The Pauly standards, however, even for simple applications, seem optimistic. They are perhaps useful if regarded as criteria for existing data, to judge whether it is worthwhile analysing them, e.g., to obtain a preliminary estimate of total mortality. Targets for collecting further data should be set higher. Sampling 1 500 fish in a year means, for a sample size of 250 fish, that only one sample is taken every other month. Such a frequency, involving only a few hours actually measuring fish each year, is barely adequate to cover seasonal variations, and will give no information about possible variability within a month, information that is vital in assessing the reliability of any estimates obtained.

Reasonably quantitative estimates of the amount of sampling that should be done can be obtained only after research is well advanced to the point at which the variability of the size composition of the catches is known, and it is clear how the data will be used, and how the sampling variance of the size data contributes to the precision of the final outputs, e.g., the level of the TAC. Prior to that, some general guidance can be offered, especially as regards the initial phase of an investigation:

... sampling should cover at least 14 months, i.e., the whole annual cycle with enough overlap the check on year-to-year differences

... unless the fishery is highly seasonal, when sampling may cease in the off-season, sampling should be done in each month

... though it may be found later that smaller, but more numerous, samples may lead to smaller variances in the estimates of annual length-composition, initially moderately large samples (200-300) are probably preferable in determining the length-composition of the catches at a particular time and place.

... unless there are practical problems in reaching the more distant landing places, samples should be spread through the whole area of the fishery

... samples should be taken from all the types of gear that take significant catches of the species

... there should be enough replication within strata, i.e., samples taken from the same gear in the same area in the same month to establish the level of within-strata variance, and hence the level of precision likely to be achieved.

Satisfying these criteria, with a minimum of replication, and not attempting to sample all gear/area combinations, will probably require some 20-30 samples. This is not a large amount of work, and the actual measuring may take 5 or 6 hours, and perhaps the same will be needed for checking, entering to the database and preliminary processing. The biggest demand on time is the need to make perhaps 15 or 20 separate visits to landing places, perhaps some way from the research institute. This would be unduly demanding if the visit was just to measure one sample of 200 fish of one species. In practice each visit to a landing place could involve measuring samples of other species, collecting biological samples for feeding studies, interviewing fishermen about where they had been fishing, and the effort expended.

This level of sampling, proposed for the period of initial study, is probably a reasonable first approximation to the sampling as part of a regular continuing programme of research. In due course it should be modified, being reduced if it seems that length-based methods are not very useful, or if there is little variation between months, gears or areas, and increased if it seems that length-based methods are likely to be a major part of the research programme. Ultimately calculations of the variance in the estimates of, e.g., the proportion of fish in each length-group, should allow the optimum level of sampling to be determined, though it seems that this can be a statistically complex procedure.

2.5.2 How should sampling be distributed?

Given a certain amount of resources - staff time, funds for travel to distant landing places - the question arises as to how this should be best allocated to obtain the best result (i.e., provide estimates that are unbiased and have the minimum variance). The greatest number of fish can be measured if as much time as possible is spent actually measuring fish, and little time "wasted" by moving from vessel to vessel or from port to port. In practice this would mean that sampling is concentrated at the most convenient landing places, and large numbers of fish are measured from each sampled vessel.

Such a sampling design is most unlikely to be optimum. It is very likely to be biased, since the fish landed at the more distant or inconvenient landing places will probably have different size-compositions from those landed at the nearer points. It will also have a high variance. The fish landed by one vessel (or at one port) tend to be much the same size, so two boxes of fish from the same vessel (or at the same port) will have more similar size-compositions than two boxes landed by different vessels (or at different ports). Thus once one box of fish from a vessel has been measured, measuring more boxes from the same ship will not, in general, tell us much more about the sizes of fish landed by other vessels. Our information about the sizes of fish in the landings as a whole will therefore be improved by sampling from more vessels (even if fewer fish are measured) than by increasing the size of the sample from any one vessel.

The question of optimum allocation in stratified and multi-stage sampling is discussed in standard statistical texts (e.g., Cochrane, 1953 and later editions), and the application to length sampling by Gulland (1966). The amount of sampling in a stratum (an area, landings by a given type of vessel, etc.) should be proportional to the contribution of that stratum to the total variability, i.e., greatest in those with the larger landings or with more variable sizes. The size of samples at different stages (the number of fish measured from one vessel, or the number of vessels sampled at one landing place on one day) will depend on the relative costs of taking more samples (sampling more vessels or at more landing places) or of taking bigger samples, and the relative sizes of the between-sample and within-sample variance.

Two samples of 150 fish will always give more information (provide estimates with smaller variance) than one of 300 fish, but will take more time. A sample size of 150 fish will be better than one of 300 fish, if a set of samples each of 150 fish (say 20 samples, or 3 000 fish in all) gives more information than a set of samples of 300 fish that takes equal time to collect (say 12 or 3 600 fish). General experience suggests that under typical conditions of commercial landings the optimum sample size is quite small, perhaps 50-150.

3. ESTIMATION OF PARAMETERS

3.1 Estimation of growth

3.1.1 General considerations

Individual differences

If we look at the length distribution of fish of a given year-class, all of approximately the same age, we will see that they are not all the same length. Typically the lengths will have something like a normal distribution about some mean length, with quite an appreciable standard deviation. Some of this spread will be because fish do not spawn at exactly the same time, and fish spawned at the beginning of the spawning season can be expected to be somewhat bigger than those spawned later. One element of the complete ELEFAN package uses this argument to obtain, essentially by extrapolating the observed distribution of length-at-age, an estimate of the distribution of the time of spawning through the year.

Differences in spawning time cannot be the whole explanation for differences in length-at-age, otherwise the spread of length would decrease as the fish grow older, and a few weeks difference in real age makes less difference to the length. Also information on growth increments, e.g., from tagging, show considerable differences. It is clear that there can be appreciable differences in the growth of individuals. A minor consequence of