12. THE STOCK/RECRUITMENT RELATIONSHIP

The stock and recruitment problem may be considered as the search for the relationship between parental stock size and the subsequent recruitment in numbers or the year class strength (cf. Section 8.3). This is a central problem of fish population dynamics, since it represents nature's regulation of population size, whether or not the populations are being exploited.

This chapter presents some considerations on the stock/recruitment (S/R) relationship problem although it does not present methods to solve actual problems. The reason why the S/R relationship is given this kind of treatment is not that the subject is less important, but rather that really convincing models to handle the problem have not yet been developed.

The following essay on the S/R relationship is based on Beyer and Sparre (1983) and Pauly (1984). Discussions of the S/R relationship with special reference to tropical fish stocks are given in, among others, Murphy (1982) and Pauly (1984).

To present the S/R relationship an exceptionally clear example has been chosen (Fig. 12.0.1). It deals with the false trevally *(Lactarius lactarius)* in the Gulf of Thailand (Pauly, 1980a). In this case there appears to be a well defined relationship between recruitment and spawning stock size. However, as already mentioned in Section 8.3 (Fig. 8.3.2) this is not a typical example of an S/R plot.

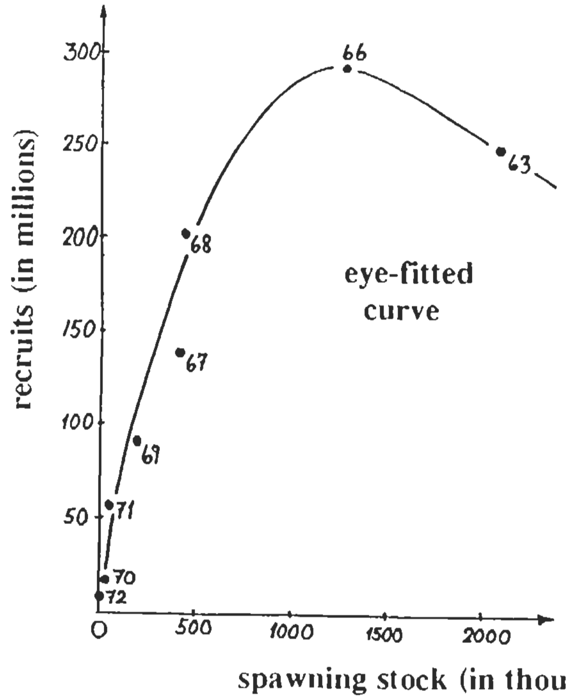

Fig. 12.0.1 **Stock and recruitment plot for the false trevally (*Lactarius lactarius*) in the Gulf of Thailand (from Pauly, 1980a)**

Fig. 12.0.2 shows the S/R plot for herring (*Clupea harengus*) in the North Sea for the years 1949-1978. The estimates of stock sizes and recruitment (numbers of one year old fish) are derived from VPA (cf. Section 5.1). This example is more representative for S/R plots in general.

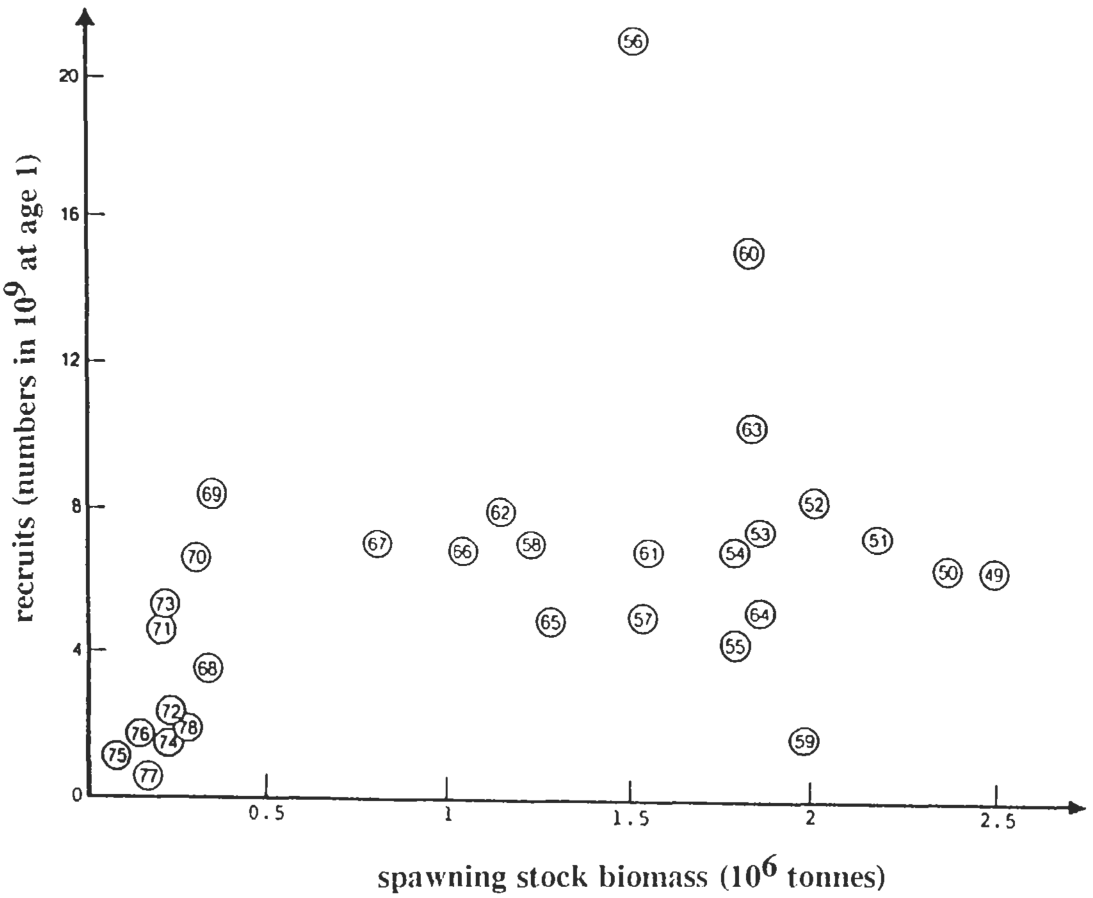

Fig. 12.0.2 **Stock and recruitment plot of North Sea herring (*Clupea harengus*). Number of one year old herring vs spawning stock biomass. Data derived from VPA (reproduced from Beyer and Sparre, 1983)**

Obviously, there can be no recruits if no adult fish are left to mature, spawn and produce eggs which hatch and grow to become recruits. The females of most fish species are extremely fecund, producing thousands, even millions of eggs during their adult life. This enormous fecundity has led many fishery biologists to believe that even a very small parental stock should be able to rebuild the stock after each spawning season. It was assumed that features of the abiotic environment (e.g. oceanographic conditions) were the major factors determining how many of the spawned eggs would survive to become recruits. They believed that the spawning stock biomass (biomass of mature fish) was virtually an irrelevant factor for the determination or recruit numbers, except in cases of stock sizes close to zero. This lack of an S/R-relationship was suggested, for example by Beverton and Holt (1957) (see also Beverton, 1963). Later works (e.g. Parrish, 1973 and Saville, 1980) suggest that many fish stocks do display an S/R-relationship. It has been suggested that most of the fish stocks that collapsed in recent decades suffered from recruitment overfishing (cf. Section 8.3) (Murphy, 1966, 1977; Saville, 1980).

However, S/R relationships generally cannot be established directly by plotting the number of recruits (or some index of recruitment) on spawning stock biomass. Rather, it is necessary to simultaneously account for an S/R relationship and the biotic and/or abiotic factors which may affect it. Csirke (1980) demonstrated a strong effect of oceanographic conditions on the recruitment of the Peruvian anchovy.

12.1 CLASSICAL S/R CONSIDERATIONS

It has been observed for many fish stocks that the mean recruitment level is almost constant in a large intermediate domain of variation of the parental stock (see Figs. 12.0.2 and 12.1.1). In the case of the North Sea herring (Fig. 12.0.2) it has been estimated that this intermediate range comprises at least an interval corresponding to 10^{12}-10^{13} eggs. The mean recruitment level is about $8*10^9$ one year old fish. Thus the probability of an egg developing into a one year old recruit is about 0.0001.

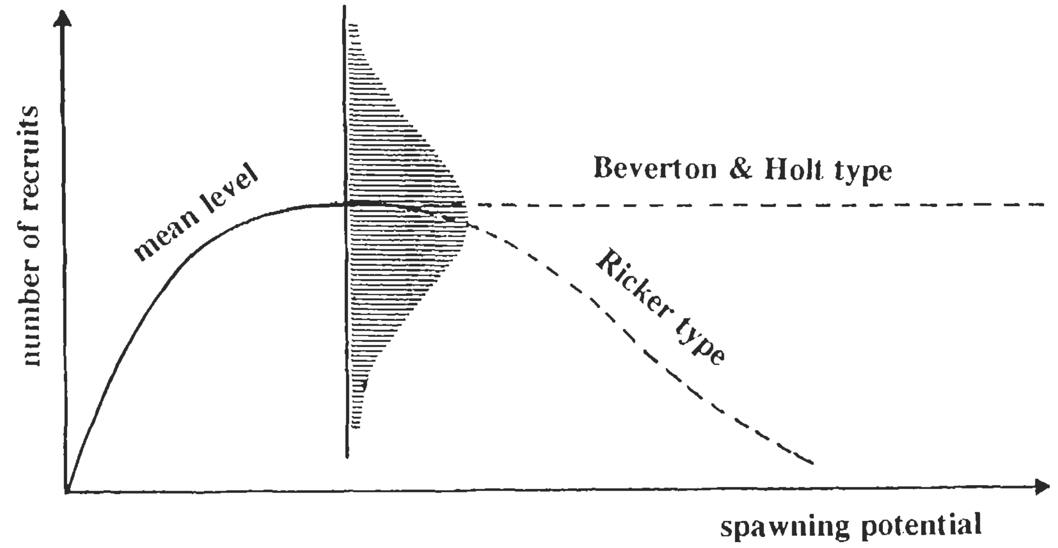

Fig. 12.1.1 **The basic form of a recruitment curve. The shaded distribution indicates variation in recruitment about the mean level**

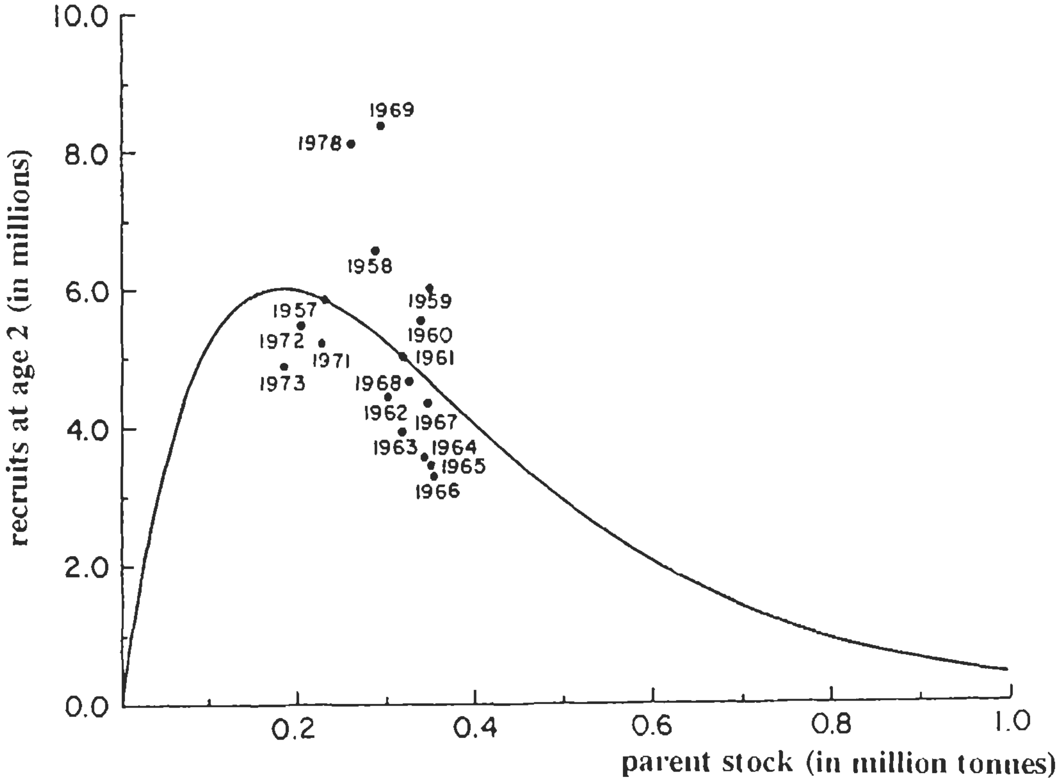

Fig. 12.1.2 **Ricker curve fitted to the spawning stock biomass and recruitment of southern bluefin tuna. Data derived from cohort analysis (reproduced from Murphy, 1982, with permission)**

It should be noted that this low rate of survival has nothing to do with fishing, since we are considering mortality in the pre-exploited stage of the life-history (the fish younger than Tr, cf. Section 4.1). The effect of fishing is a reduction of the spawning potential (i.e. growth overfishing, cf. Section 8.2), not of the recruitment. It is only when the rate of fishing is increased beyond a certain level that recruitment is affected (i.e. recruitment overfishing, cf. Section 8.3). In the case of North Sea herring, such a transition from growth overfishing seems to have taken place somewhere in the seventies. But, in principle, we do not know very much about the proper location of this transition zone in the recruitment graph. There is only one thing that is known for certain and that is the point of extinction. We know little about the other extreme of the recruitment curve. Beverton and Holt (1957) suggest the following type of S/R relationship:

$$R = \frac{E}{E + g*Rmax}*Rmax \qquad (12.1.1)$$

where g is a parameter and where the number of recruits, R, increases towards an asymptotic level, Rmax, when the egg production, E = (number of females) * (average egg production), increases. This model is derived from a simple density-dependent mortality model:

$$dN(t)/dt = -M(t)*N(t) \quad \text{and} \quad M(t) = m1 + m2*N(t) \qquad (12.1.2)$$

where N(t) is the number of survivors at age t, M(t) the rate of natural mortality of juveniles and m1 and m2 are parameters. Thus, the more survivors there are at age t, the higher their mortality. This mechanism evens out the differences in survival caused by other, biotic or abiotic, factors.

It can be shown (Beverton and Holt, 1957) that Eq. 12.1.1 is the solution to the differential equation 12.1.2.

This is an example of a model describing "density dependent mortality". Density dependent mortality may be explained by food competition. If food is limited the number of starvation deaths becomes a function of the number of specimens which have to share the food.

The characteristic shape of the Beverton and Holt S/R curve is shown in Fig. 12.1.1. The S/R plot of Fig. 12.0.2 is difficult to describe by a curve, but if a curve were fitted it would be of the Beverton and Holt type.

Ricker (1954) suggested a different mathematical model for the S/R-relation-ship (see Fig. 12.1.1):

$$R = R1*E*\exp(-R2*E) \qquad (12.1.3)$$

where R1 and R2 are parameters.

In this model the number of recruits decreases from a maximum level (of R1/(e*R2) when E = 1/R2) towards zero as the production of eggs, E, increases. The recruitment decline is explained by cannibalism of the young by the adults. These matters are described more fully by Ricker (1954, 1975).

The eye-fitted curve in Fig. 12.0.1 is a Ricker type of S/R relationship. However, the descending part of the curve is based on only one point. A few more observations for large spawning stocks may change the picture. Fig. 12.1.2 shows a Ricker curve fitted to data for southern bluefin tuna (*Thunnus maccoyii*) (Murphy, 1982). This example also illustrates the difficulties often encountered when trying to fit an S/R curve. As Murphy (1982) says about this plot: "there appears to be an underlying density dependent relationship overlaid by considerable environmental variability".

Essentially, the Beverton and Holt model says that above a certain level of spawning stock there is no relationship between parent stock and recruitment, whereas the Ricker model says that this relationship exists for all sizes of the spawning stock, and that there is an optimum spawning stock size (cf. Fig. 12.1.1).

Deriso (1980) and Schnute (1985) suggested a general stock/recruitment model:

$$R = R1*E*[1 - R2*R3*E]^{1/R3}$$

where R1, R2 and R3 are parameters. For large values of the "shape" parameter R3, the above model reduces to the Ricker model as we then get

$$R = R1*E*\exp(-R2*E)$$

If R3 = -1 we get the Beverton and Holt model by redefining the parameters to R1 = 1/g and R2 = 1/(g*Rmax) as

$$R = R1*E/[1 + R2*E] = (R1/R2)/(E + 1/R2)$$

Most available data on stock and recruitment refer to the medium range of variation in the spawners. It is here that most species appear to maintain a constant mean recruitment level and this constitutes the motivation for the assumption of constant recruitment in classical fish population dynamics. The most remarkable fact, perhaps, is that recruitment shows only relatively small variations about this mean level considering the great reduction in numbers from the egg stage until maturity (Ursin, 1982)

12.2 THE STABILITY OF RECRUITMENT

Table 12.2.1 gives relative recruitment variations for eleven commercially important North Sea species in the period 1963-75 (Ursin, 1982). The table is derived from VPAs from various ICES working group reports. We see for example, that the cod year classes show a factor of six in their variation from the weakest to the strongest.

To consider this variation range in the light of the range of population reduction of cod during the first year of life we may apply the following consideration as an approximation of the situation in the seventies. The mature stock comprises about 200,000 tonnes of cod, half of which are females. Once a year each female spawns 10% of her body weight as eggs, giving a total annual production of 10,000 tonnes of eggs or $2*10^{13}$ eggs, since each egg weighs about 0.5 mg wet weight. The mean recruitment level, however, is only $2*10^{8}$ one year old fish. Thus on the average only one egg out of 100,000 survives and grows into a one year old cod. The factor of six in recruitment variation implies that the probability of a fish dying in the first year of life at most changes from 0.999,997 for a bad year class to 0.999,983 for a good year class, or in other words the probability of a fish surviving changes from 0.000,003 to 0.000,017.

We could also consider stability in terms of recruitment to the mature stock. During her life-time a female cod must produce an average of one mature female and one mature male. Only extremely small deviations from this magic number 2 are feasible if the cod stock is to remain at approximately the same level, as it apparently has done for the last 150 years or more.

Table 12.2.1 **Recruitment variation in North Sea fish stocks 1963-1975. Numbers adjusted to a value of 100 for the most outstanding year class of each species. "Ratio" is the ratio between the numbers in the strongest and the weakest year class (after Ursin, 1982)**

	gadoids				flatfish			clupeids		others	
year class	cod	haddock	whiting	saithe	Norway pout	plaice	sole	herring	sprat	sand eel	mackerel
1963	52	1	14	17	4	100	100	100	-	-	10
1964	49	1	26	23	6	29	21	53	-	-	26
1965	70	2	30	18	0.5	28	11	47	-	-	43
1966	63	12	37	50	7	25	11	66	59	-	62
1967	20	100	100	51	-	21	18	65	62	-	10
1968	19	6	33	55	2	27	9	36	37	-	16
1969	82	2	30	29	-	32	26	78	41	-	100
1970	100	14	33	29	45	25	6	62	20	100	11
1971	18	21	68	30	7	20	14	41	19	21	17
1972	35	4	90	40	16	62	19	19	46	47	4
1973	31	21	63	100	100	40	18	47	91	28	15
1974	51	40	92	27	38	25	7	-	100	86	11
1975	27	9	37	50	18	37	22	-	79	41	4
Ratio	6	100	7	6	200	5	17	5	5	5	25

This approximate one-for-one replacement between successive generations holds at least as long as the mature stock is within the medium range of variation as referred to above. Thus, whether we are considering a situation of heavy fishing , where the mature female cod on the average lays about two million eggs in its short lifetime, or whether we are considering an average production of 40 million eggs per female at a low fishing level, the number 2 still holds.

We do not know what causes this enormous reduction in numbers from the egg stage and leads to the fine adjustment of the number of recruits to the number of mature fish. Note in passing that the North Sea haddock and Norway pout show a remarkable instability in recruitment (see Table 12.2.1). It could be that stabilizing mechanisms do not exist in the North Sea for these two species.

12.3 TOWARDS MODELLING RECRUITMENT

It is difficult to attack the recruitment problem in a sensible way by means of statistical tools only because of the small amount of useful data that in general seem to be available. We only achieve one new data point per species each year. Thus, to explain recruitment variability such as the occurrence of extremely strong year-classes, we may advance a great variety of conflicting hypotheses, all of which lead to different conclusions but none of which can be rejected on the basis of the available data.

The situation is no better with respect to explanations of recruitment stability. It is not possible to discriminate between empirical recruitment models such as those given by Eqs. 12.1.1 and 12.1.3. Neither is it possible beforehand to sort out irrelevant mechanisms of mortality regulation by means of data. Apparently we need to build more biological knowledge on the causes of natural mortality in the first year of life into the recruitment models. See also Sinclair (1988).

13. DEMERSAL TRAWL SURVEYS

Bottom trawl surveys are widely used for monitoring demersal stocks when only an index of abundance is required. From unfished stocks (or stocks for which no or few data on the fishery are available) biomass and annual yield estimates may also be derived by bottom trawl surveys. The estimation of total biomass from the catch per unit of effort (or unit area), however, involves several crucial assumptions, leaving such estimates rather imprecise.

The mean catch (either in weight or in numbers) per unit of effort or per unit of area is an index of the stock abundance (i.e. assumed to be proportional to the abundance). This index may be converted into an absolute measure of biomass using the so-called "*swept area method*" (Section 13.5). This method falls under the so-called holistic methods (cf. Section 1.8).

Reviews of the theory are given in, for example, Gulland (1975), Saville (1977), Troadec (1980), Doubleday (1980) and Grosslein and Laurec (1982). These reviews also give guidelines for conduct of surveys (planning, design, data collection, data recording, analysis and reporting), some of which are summarized in Sections 13.2 to 13.4), see also Butler *et al.* (1986), ICOD (1991) and Strømme (1992).

This Chapter gives first a short description of demersal trawl survey planning and a few guidelines for data recording and for field work (Sections 13.1 to 13.4). For more detailed descriptions of these subjects the reader is referred to, among others, Alverson and Pereyra (1969), Alverson (1971), Mackett (1973), FAO/UNDP (1975), Gulland (1975), Saville (1977), Flowers (1978), Doubleday (1981), Grosslein and Laurec (1982) and Fogarty (1985). The remainder of the Chapter (Sections 13.5 to 13.8) is a short account of the theory necessary to perform a stock assessment based on trawl survey data.

13.1 THE BOTTOM TRAWL

The bottom trawl (Fig. 13.1.1) is a conical net bag with a wide mouth fitted with weights on the ground-rope and floats on the head-rope. When the vessel is under way the net is kept open by two otter boards, wooden or iron structures which are towed by the warps attached forward of their centre so they tend to diverge. The two otter boards are connected to the net by bridles. These may be up to 200 m long and sweep the sea bed over a wide area. They frighten the fish towards the advancing net and so increase its effectiveness. The shape of net varies depending on the kinds of fish to be caught and on the types of bottom. The ground-

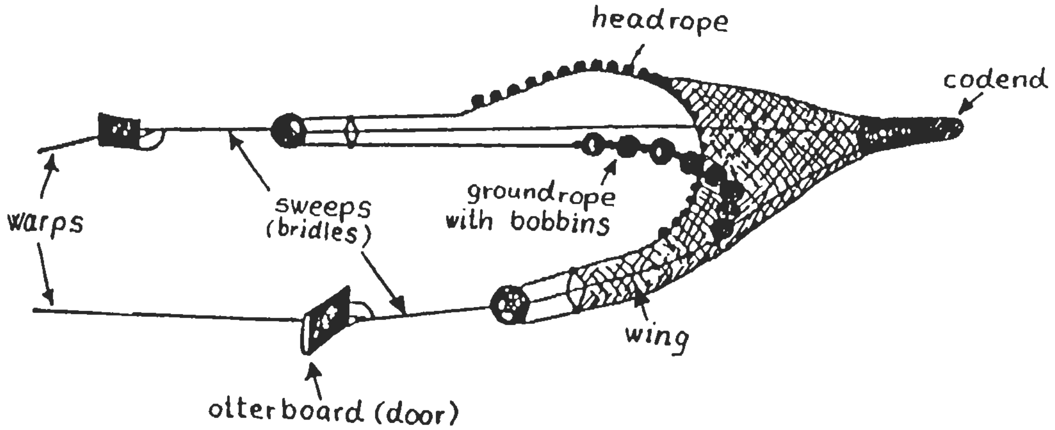

Fig. 13.1.1 Bottom trawl

rope may be fitted with roller gear (bobbins) so that the trawl can be used on stony bottom without being damaged. The tail end of the gear from which the captured fish are removed is called the "*codend*". This is where most of the size selection takes place. In most cases a relatively small mesh size is required in the codend, in order to obtain a representative sample for the entire size range of the species under investigation (see Section 13.2).

13.2 PLANNING A DEMERSAL TRAWL SURVEY

Below is a list of some important items to consider before conducting a survey.

Definition of objectives

The objective(s) should be specified. Examples of objectives are:

1. Estimation of the total biomass and catch rates
2. Estimation of the biomass of selected species
3. Collection of biological data (e.g. length-frequencies) for estimation of growth and mortality parameters
4. Collection of environmental data

Information about the survey area

Information about depth and bottom conditions to point out trawlable areas and decisions on strata may be obtained from a preliminary survey with echo- sounding. Information from local fishermen may be valuable. Information on seasonal winds, currents and migration patterns of fish stocks are important as well.

Choice of gear

The design of the trawl should fit with the expected bottom conditions and the vessel used. If rough bottom is prevalent the gear should be fitted with bobbins in order to avoid damage to the gear. If semi-pelagic species are common a high-opening trawl should be used. The mesh size in the codend should be chosen so that the entire size range of the fishable part of the stock is retained by the trawl. Often 10-20 mm stretched mesh is appropriate. The mesh size used for assessment surveys is usually much smaller than the size used by the commercial fisheries, because samples of small fish are important for assessment methods based on length-frequencies.

If different trawls are used parallel or alternate hauls should be carried out in order to estimate correction factors for pooling of data.

Survey design

A procedure for the selection of stations should be decided on. A fixed grid of stations ensures maximum information on the distribution throughout the area, but not necessarily the most precise estimate of biomass. For estimation of stock sizes a completely randomized design or a stratified random sampling design should be preferred. In most cases a stratified sampling design should be chosen because fish are seldom uniformly distributed and in most cases abundance is related to depth. Stratified sampling often gives a much more precise estimate for the same (or even lower) cost than simple random sampling (cf. Sections 7.2 and 13.7).

Allocation of hauls (stratification)
Strata are basically constructed in accordance with the density distribution of the fish, so that areas with high/medium/low densities are separated. To do so, some information must be available before the survey. Perhaps the first survey (or the first part of the survey) should have a completely randomized survey design, or the trawl hauls might be evenly spaced. But in the next part of the programme some information on densities and standard deviations of density estimates will be available, and that information can be used for stratification. The standard deviation of catch per unit area (CPUA) is often found to be proportional to the CPUA and will therefore be higher in areas with high abundance.

The optimum allocation of a given number of hauls between strata will be to sample each stratum in proportion to its standard deviation multiplied by the stratum size (cf. Sections 7.2 and 13.7). The distribution of hauls within strata should preferably be at random, but often practical matters dictate the sample design. For example, obstacles on the bottom may not allow a proper random distribution of stations.

Possible number of hauls
To estimate how many hauls it is possible to make in a given period the following information should be available:

Total number of days available	N
Time spent going to and from the fishing ground (hrs)	t1
Duration of one haul (hrs)	t2
Time used for shooting and hauling the trawl (hrs)	t3
Time to cover distance between stations (average, hrs)	t4
Number of hours available per day (depending on crew, behaviour of investigated species, navigation, etc.)	T
Time used for preparations: loading of ice, food, water, repair of gear and equipment (days)	t5

Except for the first and the last day of a cruise, when T should be reduced by t1, the number of hauls per day can be calculated from:

(number of hauls per day) = T/(t2+t3+t4)

(Total number of hauls) = (N-t1-t5)*(number of hauls per day)
+ (hauls made first and last day)

It is important to **standardize** the length of a haul throughout the survey, since the catchability of species and sizes often depends on the duration of the haul. For survey purposes hauls of 0.5 hour or 1 hour are usually the most adequate (see also Section 13.6).

13.3 DATA RECORDING

When setting up a plan for a trawl survey a crucial point is to decide on the data items to be recorded, the required precision and how often they should be recorded.

The data items to be recorded are determined by the models by which the objectives of the survey can be achieved, e.g. the swept area method (cf. Section 13.6), length-frequency analysis (cf. Chapter 3), mortality estimation (cf. Chapter 4). Such data items would usually include specifications of the gear used, and for each haul the time and position at start and at end of the haul, wire length, wingspread, bottom type and depth. The catch record should include total weight, species composition by weight and length-frequencies (for selected species).

The required precision depends on the subsequent use of the data. However, often the precision of a trawl survey is controlled by the number of hauls, which limits our ability to decide on the precision.

It must be known how the data are going to be processed before data recording takes place, particularly in cases where data reduction takes place before the recording stage. Consequently, before you can design appropriate log sheets you must have a rather precise idea of how data will subsequently be processed. When designing a log sheet, practical considerations are important, e.g. where the data are entered, on the bridge, in the laboratory or on the deck.

It is important that the data are well organized to facilitate processing, e.g. by computer. This is especially the case when data from more than one vessel have to be combined. Properly designed recording documents will make the correct recording much easier and more dependable. Several documents are usually required to record all the information collected during a survey. These are in the following categories:

1. A log which summarizes the whole cruise.

2. Details of individual stations (or hauls), the "*fishing log*", which will generally provide information on the vessel's position, time of start and end of haul, gear rigging etc. Summary information on the catch such as total weight and weight composition by species should also be recorded on the fishing log.

3. Detailed information on the catch. This may be in terms of length, weight, sex, maturity stage etc. for each specimen, or samples of length-frequency distributions.

A detailed description of a data processing system for demersal trawl surveys is given in Flowers (1978) who reproduces forms suitable for the work specified as 1 to 3 above.

13.4 DECK SAMPLING AND CATCH RECORDING PROCEDURES

It is important, before the survey begins, to make sure that the equipment and working conditions are such that the sampling can be carried out easily and without risk. Also, the crew must be instructed not to remove any part of the catch before the sampling has been completed.

The following steps pertain to methods for sorting the catch of a fishery research vessel such that the catch composition, both by weight and by number of each species (species group) can be established. The procedure outlined here is from Pauly (1980, adapted from Losse and Dwiponggo, 1977).

Step 1: Remove all sea snakes and other venomous or otherwise dangerous animals. Also remove turtles, and if alive, return these to sea. Record number and kind of animals removed.

Step 2: Remove inorganic debris and plant material. Record type of material removed.

Step 3: Remove the larger fish that are readily visible and place them in a box.

Step 4: Wash the remainder of the catch (of small fish) if necessary, and mix with shovels.

Step 5: Put the mixed catch in boxes, while continuing to remove larger fish and putting them into the box mentioned in Step 3. The boxes should be filled simultaneously, not one after the other, and it should be made certain that all boxes contain approximately the same weight of fish.

Step 6: Count the number of boxes with small fish and record.

Step 7: A rule of thumb is to take one box out of every five at random for subsampling. Record number of boxes taken for subsampling as B1, B2, B3, ... etc.

Step 8: The box(es) taken for sub-sampling is (are) then treated as follows:

- Weigh the total catch in B1 and record.

- Place fish of B1 on a sorting table and sort to species level as far as food fishes and valuable crustaceans (e.g. shrimps) are concerned, and to taxonomic groupings as well-defined as possible (e.g. genus, family, etc.) for other groups (the non-edible fish and miscellaneous crustaceans).

- Repeat procedure, if appropriate, for the other boxes, B2, B3, ... etc.

Step 9: If more than one box was sorted, compute, for each species (or higher taxonomic group) the total weight and number in all sorted boxes.

Step 10: Multiply the numbers and weight of fish and invertebrates by species (or higher taxonomic group) by the ratio of the number of unsorted to sorted boxes.

Step 11: Weigh and count the larger fish mentioned in Steps 3 and 5, by species (very large fish should be weighed individually and measured).

Step 12: Add, when there is an overlap (when the fish of a certain species occurred both in the sorted boxes of small fish and in the large fish box) the weights and numbers obtained in Step 11 to the weights and numbers in Step 10.

Step 13: Step 12 (as well as Step 11, when there is no overlap) provides estimates of total catch, both in weight and number, by species or higher taxonomic groups. Record the total, both in weight and numbers into an appropriate fishing log and convert to catch per unit if fishing time was less or more than an hour. During surveys, this step must be completed after each haul, or every evening at the latest, to preclude loss of information.

Step 14: In addition to catch sampling, identifying and recording, the work of the fishery scientist generally includes among other things:

- Collecting length-frequency data
- Collecting miscellaneous biological information on the fish caught, e.g., concerning their weight and maturity
- Collecting and preserving specimens for further studies onshore
- Collecting oceanographic data.

It is important to sort and sample the catch to the greatest extent possible. The extra cost involved in sorting and sampling all the edible species is usually only a fraction of the total costs of the survey.

13.5 THE SWEPT AREA

From Fig. 13.5.1 it appears that the trawl sweeps a well defined path, the area of which is the length of the path times the width of the trawl, called the "*swept area*" or the "effective path swept". The swept area, a, can be estimated from:

$$a = D*hr*X2, \qquad D = V*t \tag{13.5.1}$$

where V is the velocity of the trawl over the ground when trawling, hr is the length of the head-rope (see Fig. 13.5.1), t is the time spent trawling. X2 is that fraction of the head-rope length, hr, which is equal to the width of the path swept by the trawl, the "wing spread", hr*X2 (see Fig. 13.5.1).

For southeast Asian bottom trawls values of X2 from 0.4 (Shindo, 1973) to 0.66 (SCSP, 1978) are reported. Pauly (1980) suggests X2 = 0.5 as the best compromise. In the Caribbean a value of X2 = 0.6 was used by Klima (1976).

For the estimation of biomass we use the catch per unit area (CPUA), as will appear in the next section. It is estimated by dividing the catch by the swept area (in square nautical miles or square kilometers). This estimate thus depends on how accurately the swept area is estimated. The swept area as defined in Fig. 13.5.1 assumes that the bridles have no herding effect, which they are in fact known to exhibit. The wing spread is calculated as the fraction X2 of the head rope length. The wing spread varies with hauling speed, weather conditions, current velocity and direction and warp length and is therefore not well defined. It can be accurately measured by special devices, but an approximate value can be calculated from measurements of the distance between the warps at the gallows and at say, 1 m, towards the net.

When exact positions of the start and the end of the haul are available the distance covered can be estimated in units of nautical miles (nm), by:

$$D = 60 * \sqrt{(Lat1-Lat2)^2 + (Lon1-Lon2)^2*\cos^2(0.5*(Lat1+Lat2))} \tag{13.5.2}$$

where

Lat1 = latitude at start of haul (degrees)
Lat2 = latitude at end of haul (degrees)
Lon1 = longitude at start of haul (degrees)
Lon2 = longitude at end of haul (degrees)

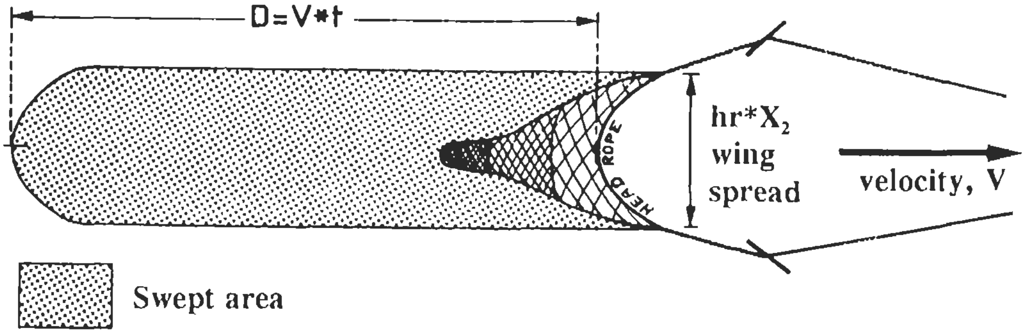

Fig. 13.5.1 Swept area (cf. Fig. 4.3.0.1)

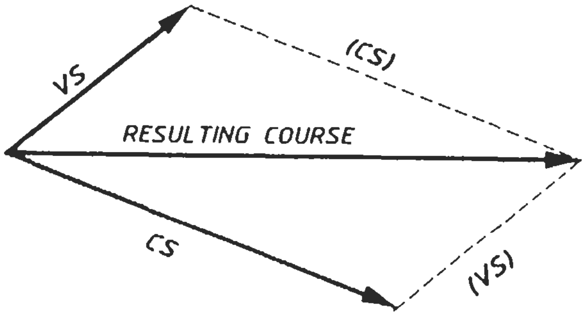

Fig. 13.5.2 Vector addition of vessel and current course and velocity

If exact positions are not available, but only the velocity of the vessel and its course together with direction and speed of the current, then the distance covered per hour can be calculated from:

$$D = \sqrt{VS^2 + CS^2 + 2*VS*CS*\cos(dirV-dirC)} \quad (nm) \qquad (13.5.3)$$

where

VS = velocity of vessel (knots = nm/hr)
CS = velocity of current (knots)
dirV = course of vessel (degrees)
dirC = direction of current (degrees)

Eq. 13.5.3 is an application of "vector addition" (see Fig. 13.5.2).

13.6 BIOMASS ESTIMATION BY THE SWEPT AREA METHOD

Let Cw be the catch in weight of a haul. Then Cw/t is the catch in weight per hour, when t is the time spent hauling (in hours). Let a be the area swept (cf. Eq. 13.5.1). Then a/t is the area swept per hour, and

$$\frac{Cw/t}{a/t} = \frac{Cw}{a} \quad kg/nm^2 \qquad (13.6.1)$$

becomes the catch in weight per unit of area. Let X1 be the fraction of the biomass in the effective path swept by the trawl which is actually retained in the gear and let $\overline{Cw/a}$ be the mean catch per unit area of all hauls. Then an estimate of the average biomass per unit area, b, is:

$$\bar{b} = \overline{(Cw/a)}/X1 \quad kg/nm^2 \qquad (13.6.2)$$

Let A nm^2 be the total size of the area under investigation. Then an estimate of the total biomass, B, in this area, A, is obtained from:

$$B = \frac{\overline{(Cw/a)}*A}{X1} \qquad (13.6.3)$$

It is difficult to estimate which proportion of the fish that is present in the area swept by the trawl gear is actually retained by the gear, in other words it is difficult to give a precise estimate of X1. Underwater television recordings show that the reaction of fish to trawls varies markedly between species. The value of X1 is usually chosen between 0.5 and 1.0. For trawlers in southeast Asia a value of X1 = 0.5 is commonly used in survey work (Isarankura, 1971, Saeger, Martosubroto and Pauly, 1980). Dickson (1974), on the other hand, suggests X1 = 1. The difference between these two values of X1 is difficult to resolve. Using X1 = 0.5 doubles the estimate of biomass compared to that obtained by using X1 = 1.0.

The duration of the haul is proportional to the distance covered so the duration should have no direct influence on the catch per unit of area. However, the catchability, X1, of different species may vary according to the duration of the haul because some species, when herded by the trawl get tired soon and get captured while other species are able to swim in front of the trawl for a long period and thus avoid being caught. It is therefore important to standardize the duration of the haul so that results from different hauls can be compared. To investigate the dependence of catchability on haul duration, parallel hauls of different duration (e.g half an hour and one hour) could be made.

The total area surveyed can be estimated from a mercator projection by means of a planimeter. Another method is to copy the area on transparent paper which then is cut out and weighed. Then the weight of the paper is compared to the weight of a piece of similar paper which corresponds to a known area. This method is not very precise.

13.7 PRECISION OF THE ESTIMATE OF BIOMASS

Let the biomass estimate in Eq. 13.6.3 be obtained from n hauls, and let Ca(i) be the catch (in weight) per unit of area of haul no. i, where i = 1,2,...,n. The estimate of B then becomes:

$$B = \frac{A}{X1} * \frac{1}{n} * \sum_{i=1}^{n} Ca(i) = \frac{A}{X1} * \overline{Ca} \qquad (13.7.1)$$

and the variance (cf. Eq. 2.1.2):

$$VAR(B) = \left[\frac{A}{X1}\right]^2 * \frac{1}{n} * \frac{1}{n-1} * \sum_{i=1}^{n} [Ca(i)-\overline{Ca}]^2 \qquad (13.7.2)$$

Thus, a higher precision (a smaller variance) can be obtained by increasing the number of hauls, n (cf. Section 7.1, Fig. 7.1.1). Another way of reducing the variance is to apply stratified sampling (cf. Section 7.2). Suitable stratification may reduce the variance considerably for the same number of hauls and thus improve survey efficiency for the available research vessel time. The distribution of many fish species is determined by depth and bottom type. Therefore stratification based on these factors is widely used. Fig. 13.7.1 shows an example of stratification based on depth.

The areas of the four strata in Fig. 13.7.1 are A1,A2,A3 and A4 and the total area A = A1+A2+A3+A4. Let B(i) be the estimated biomass in stratum no. i calculated by Eq. 13.7.1. Then the estimate of the total biomass of the total area, A, becomes:

$$B = B(1)+B(2)+B(3)+B(4) \qquad (13.7.3)$$

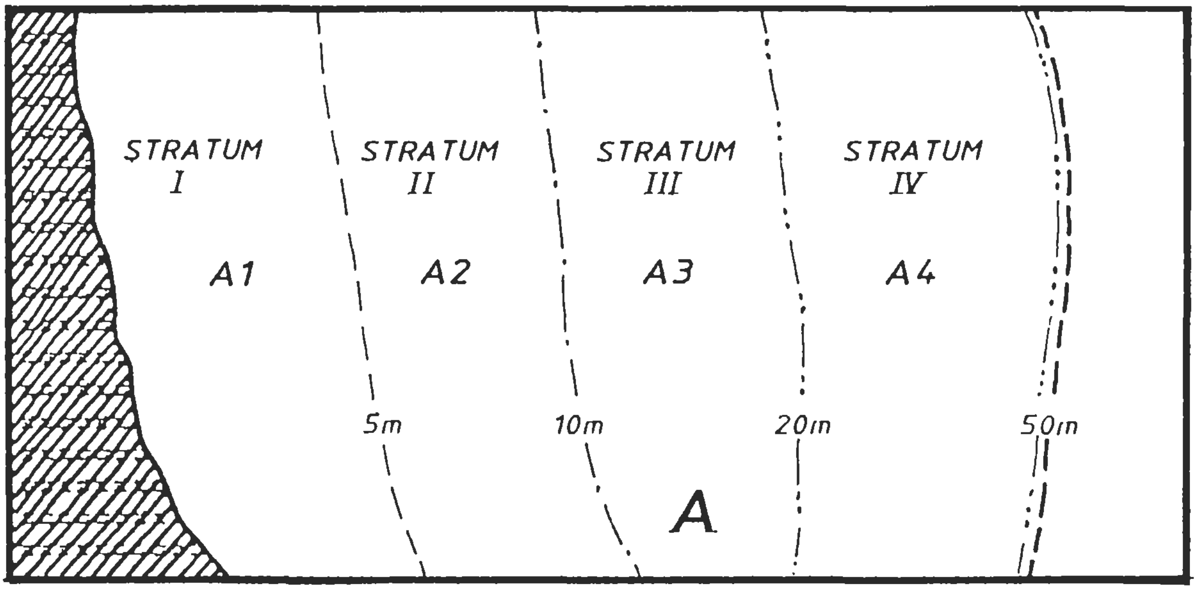

Fig. 13.7.1 Example of stratification

and the variance:

$$VAR(B) = VAR(B(1)) + VAR(B(2)) + VAR(B(3)) + VAR(B(4)) \qquad (13.7.4)$$

where VAR(B(i)) is calculated by Eq. 13.7.2. If we work with densities, in units of biomass per square nm. (cf. Eq. 13.6.2) the parallel to Eq. 13.7.3 becomes:

$$b = [b(1)*A1 + b(2)*A2 + b(3)*A3 + b(4)*A4]/A \qquad (13.7.5)$$

and the parallel to Eq. 13.7.4 is

$$VAR(b) = VAR(b(1))*(A1/A)^2 +\ldots+ VAR(b(4))*(A4/A)^2 \qquad (13.7.6)$$

where Ai is the size of stratum no. i and A is the total area of all strata. Eq. 13.7.6 is then seen to be analogous to Eq. 7.2.11 with A as N, Ai as N(j). Confidence limits of B and b can be calculated as described in Section 2.3.

Stratification may be based on the total catch of a mixture of species or on the catch of a single species. It is often desirable, however, to focus on several species, or groups of species, each with its own type of distribution. In such cases a stratification procedure must be decided on for each species, or for each group of species with similar distribution patterns within the area surveyed.

For a more detailed description of the statistical aspects of a trawl survey see Fogarty (1985) and Gavaris and Smith (1987). The latter discuss the effect of stratification by comparing the precision obtained from stratified sampling to that of simple random sampling, using the method of Sukhatme and Sukhatme (1970).

The above formulas all assume that the number caught per trawl hour is a normally distributed random variable. A better description of survey data is often obtained by assuming the so-called "delta-distribution" (Pennington, 1983). This distribution takes into account that survey data often contain a large proportion of zero observations and that the non-zero observations form a log-normal distribution rather than a normal distribution.

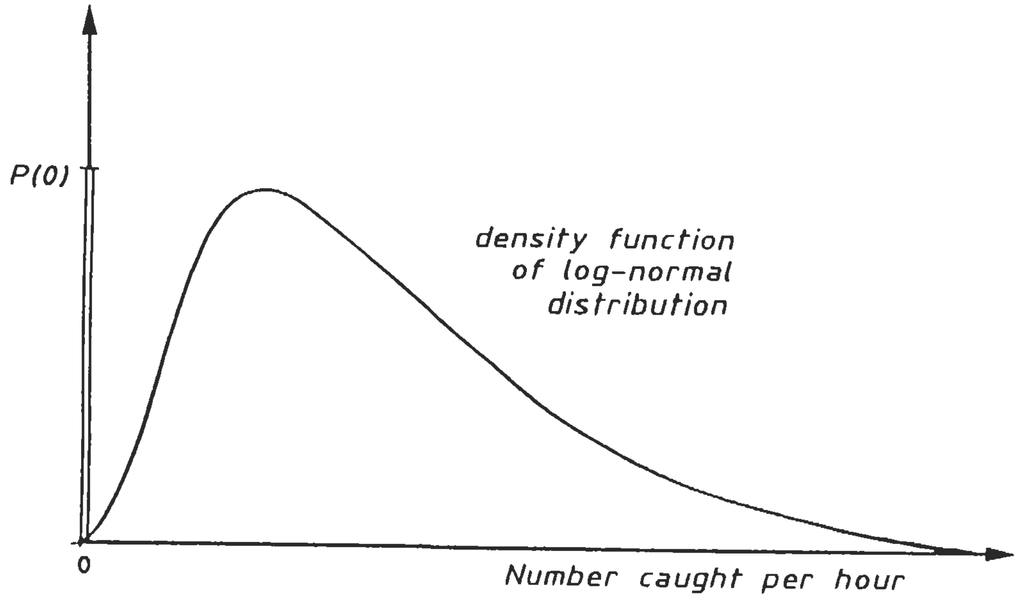

Fig. 13.7.2 Delta-function

A log-normal distribution is asymmetric and skewed to the right hand side. Fig. 13.7.2 shows a schematic delta-function. Note that the point zero has a positive probability. In his paper, Pennington gives the expression for the unbiased estimators of the parameters of the delta-function.

13.8 ESTIMATION OF MAXIMUM SUSTAINABLE YIELD

Gulland's formula for virgin stocks (Eq. 9.2.1):

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MSY = 0.5*M*Bv
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(M: coefficient of natural mortality; Bv: virgin stock) or Cadima's formulas for exploited stocks (Eqs. 9.3.1 and 9.3.2):

```
MSY = 0.5*Z*B   or   MSY = 0.5*(Y + M*B)
```

have often been applied when estimating the maximum sustainable yield (MSY) per year from the total biomass as estimated from exploratory surveys (see e.g. Saville, 1977, or Troadec, 1980). It may be better, however, to apply the modified Fox model (Garcia, Sparre and Csirke, 1987) described in Section 9.4 using Eq. 9.4.10 or Eq. 9.4.11.

Anyway, these are crude methods and should be relied upon to give only the order of magnitude (1,000 tonnes, 10,000 tonnes, etc.) of the fish stock. Yet, if nothing is known in advance, even such an estimate of the order of magnitude may be valuable.

One problem is that M is usually not known before the surveys are carried out. When the stock is virgin (unexploited) an estimate of M can be obtained by analyzing the catch curves obtained during the exploratory survey (cf. Section 4.4) because when the stock is unexploited, then F = 0 and thus Z = M. Pauly's empirical formula, Eq. 4.7.2.1 (Pauly, 1980b) can be applied when growth parameters are available.

(See **Exercise(s)** in Part 2.)