

FISHERIES BIOLOGY and MANAGEMENT for Pacific Island students

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1: Introduction

Although available statistics are poor, the annual production from fisheries in Pacific Islands is small - perhaps less than 0.5% of the world total of approximately 89 million tonnes (Fiu, 1987). Most important world fisheries are based on temperate-water species (Table 1) which are present in high abundance; a feature of tropical ecosystems is the high diversity (but often low abundance) of species.

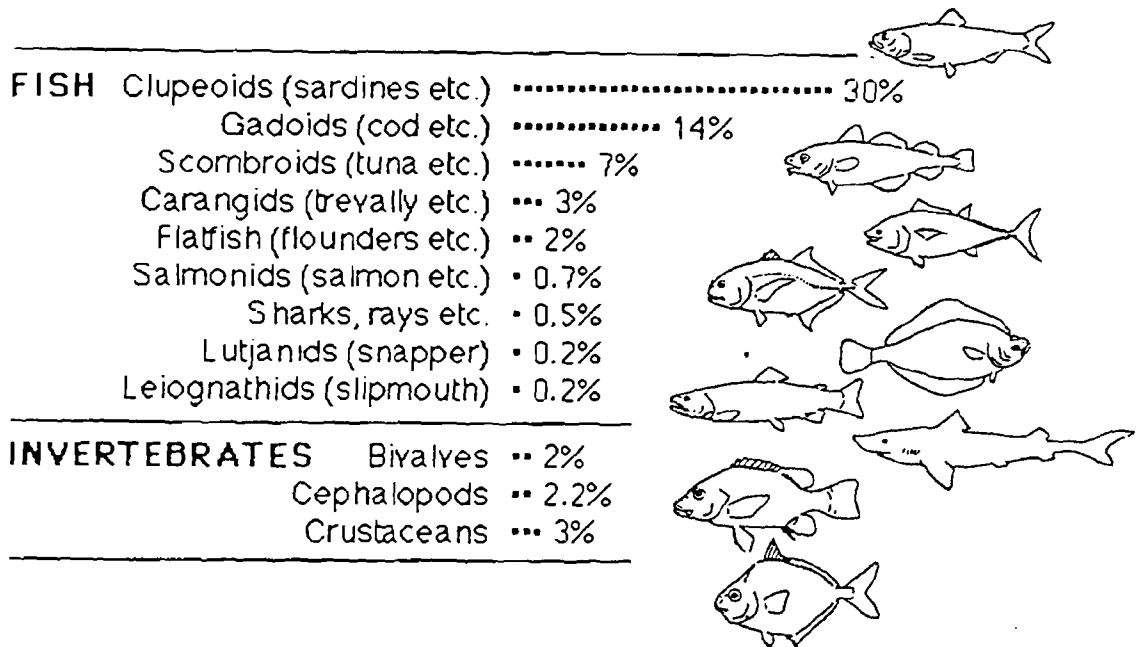


Table 1: Annual production of the major groups of fisheries resource species as a percentage of the total world catch.

Large fisheries occur in areas where upwellings result in high nutrient levels and, through the food chains, the rich production of suitable target species. The Pacific Ocean has upwellings off the coast of South America and, more importantly for island countries, around the equator in the western Pacific. The latter upwelling results in the important tuna fisheries in the

Extended Economic Zones (EEZ's) of Papua New Guinea, the Solomons, Kiribati and to a lesser extent Vanuatu, Fiji and Samoa. In these countries, tuna fisheries provide an important source of foreign exchange through exports. For example in the Solomon Islands and Vanuatu, fish is the most important single source of foreign exchange. (Doulman, 1987). Demand for fish and fishery products has been increasing rapidly, and, given trends in existing prices and population growth, global demand is projected to be 114 million tonnes by the year 2000 (Fiu, 1987).

The low commercial catch from Pacific Island countries masks the fact that many marine species provide important sources of protein to local communities. Seafood consumption is particularly high in low-lying Pacific Islands where soils are too poor to support agriculture. In tropical islands in general, fish consumption may be above 50 kg per person per year compared with about 15 kg in Australia (Lawson, 1985). In centres of high population, fishing to supply local markets also provides an source of employment. Participation in island based fisheries is especially high if subsistence fishing is considered.

A fishery consists of a complex set of interactions between the environment, the target species and the fishing industry. The study of fisheries is therefore equally complex, and includes the broad disciplines of oceanography, ecology, biology, gear technology, seafood science, economics, sociology and politics.

Although the emphasis of this manual is biological, it provides an overview of Pacific Island fisheries including fishing methods, species caught, fisheries biology, economics and fisheries management. With population growth rapidly fueling demand, particularly in many developing countries, managing fish stocks will be of paramount importance in the years to come.

2 Fisheries in Pacific Islands

Fishing Methods

Fishing gear and methods used depend on the target species. Methods vary from very simple techniques, such as the collection of lobsters by divers, to complex and expensive operations such as purse seining for tuna. A range of fishing gear is shown in Figures 1 to 5.

Figure 1: Baited traps or pots are used to catch crustaceans, such as crabs and shrimps as well as certain fish species such as snappers. The principle is that crustaceans or fish, attracted to the bait, enter the trap through conical entrances from which it is difficult to escape. In several Pacific Islands, unbaited maze traps have been built out from shore lines to catch migrating coastal fish such as mullet.

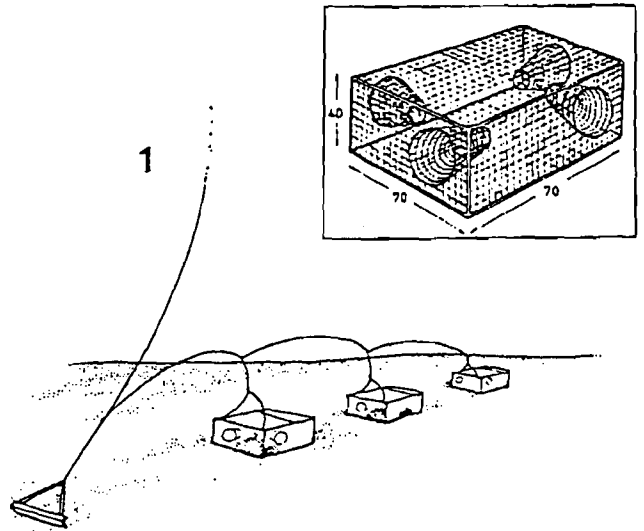


Figure 2: Gill nets are used in shallow water to catch species such as mullet. Such nets are usually made from almost invisible monofilament nylon, which locks behind the gill covers (opercula) of bony fish or the gill slits of sharks.

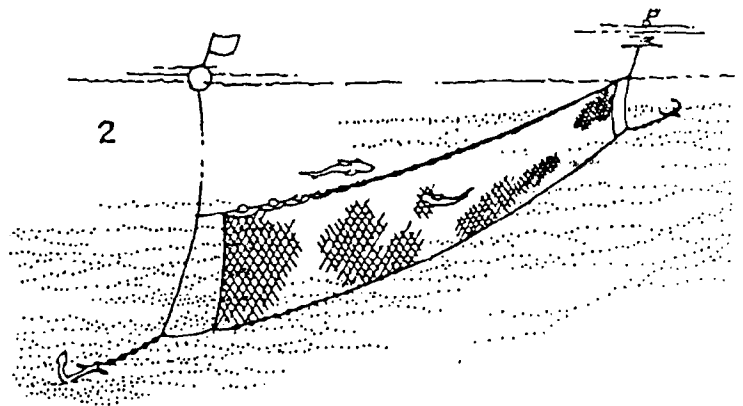
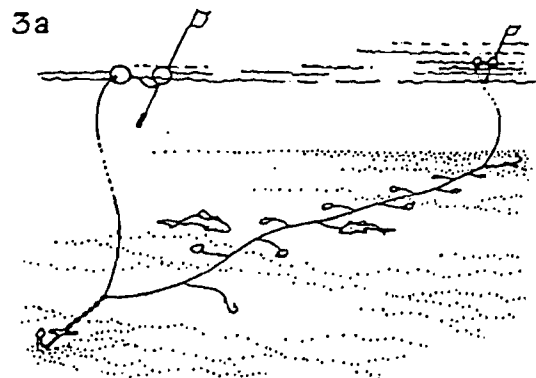


Figure 3: Hook and line gear is used in a wide range of configurations. A long line (Figure 3a) is a horizontal line with side hooks, and is set near the surface for pelagic fish such as tuna, or on the bottom for demersal species.

Drop-lining gear consists of a vertical line with baited hooks set on short side lines and is used to catch fish such as deep-water



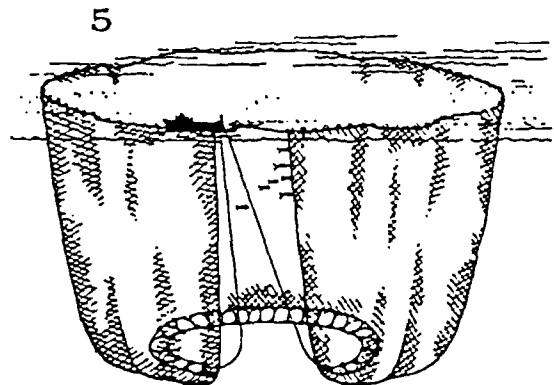
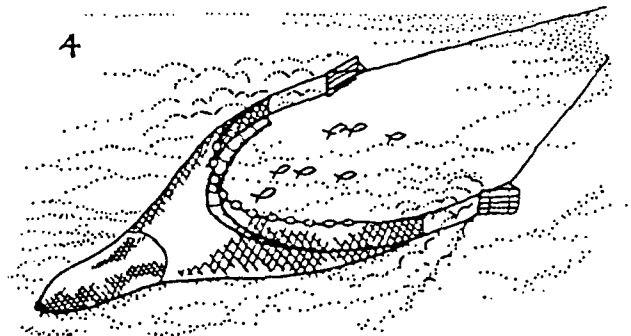
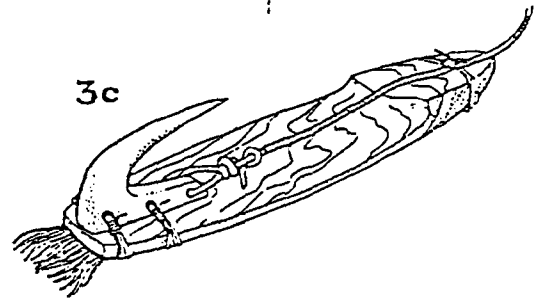
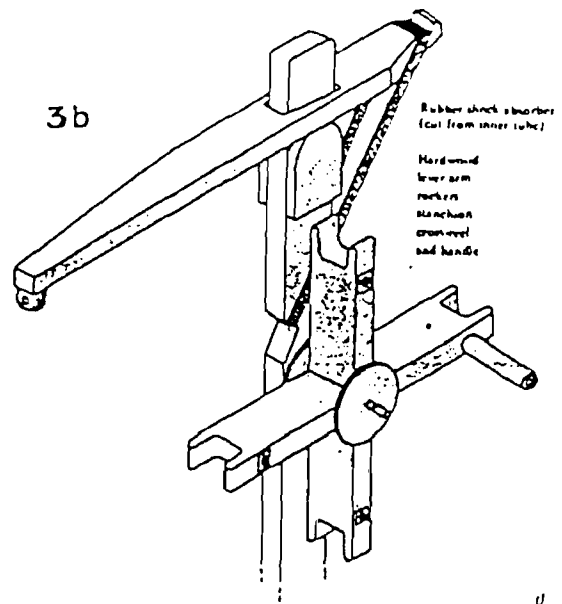
snapper. A wooden hand reel (Figure 3b), promoted by the South Pacific Commission, may be used to handle drop-lines in deep water.

Lines with lures are trolled for some species, such as mackerel, barracuda and tuna. A traditional tuna fishing lure is shown in Figure 3c.

Tuna may also be caught by using barbless hooks on short lines connected to poles; the tuna are encouraged to strike the hooks by "chumming" the water with live baitfish.

Figure 4: Otter trawls derive their name from the otterboards, or doors, which act as paravanes to hold open the mouth of a conical net. During towing, the doors create clouds of sand which may help to concentrate species in the mouth of the net. The catch is eventually retained in the cod-end. Penaeid prawns and a variety of demersal fish species are caught by otter trawling. In most tropical islands, the presence of coral limits the use of demersal trawling gear.

Figure 5: A purse seine is a net which is set in a circle around a school of pelagic fish such as tuna or mackerel. Floats are fastened to its upper edge and weights to its lower edge. A purse line runs around the lower weighted edge, and is hauled in to close off the bottom of the net.



Resource species

The most important fisheries resource species in Pacific Islands are summarised in Table 2 and Figure 1. Although the biology of these species is beyond the scope of this course, a general knowledge of their basic taxonomy and biology is assumed.

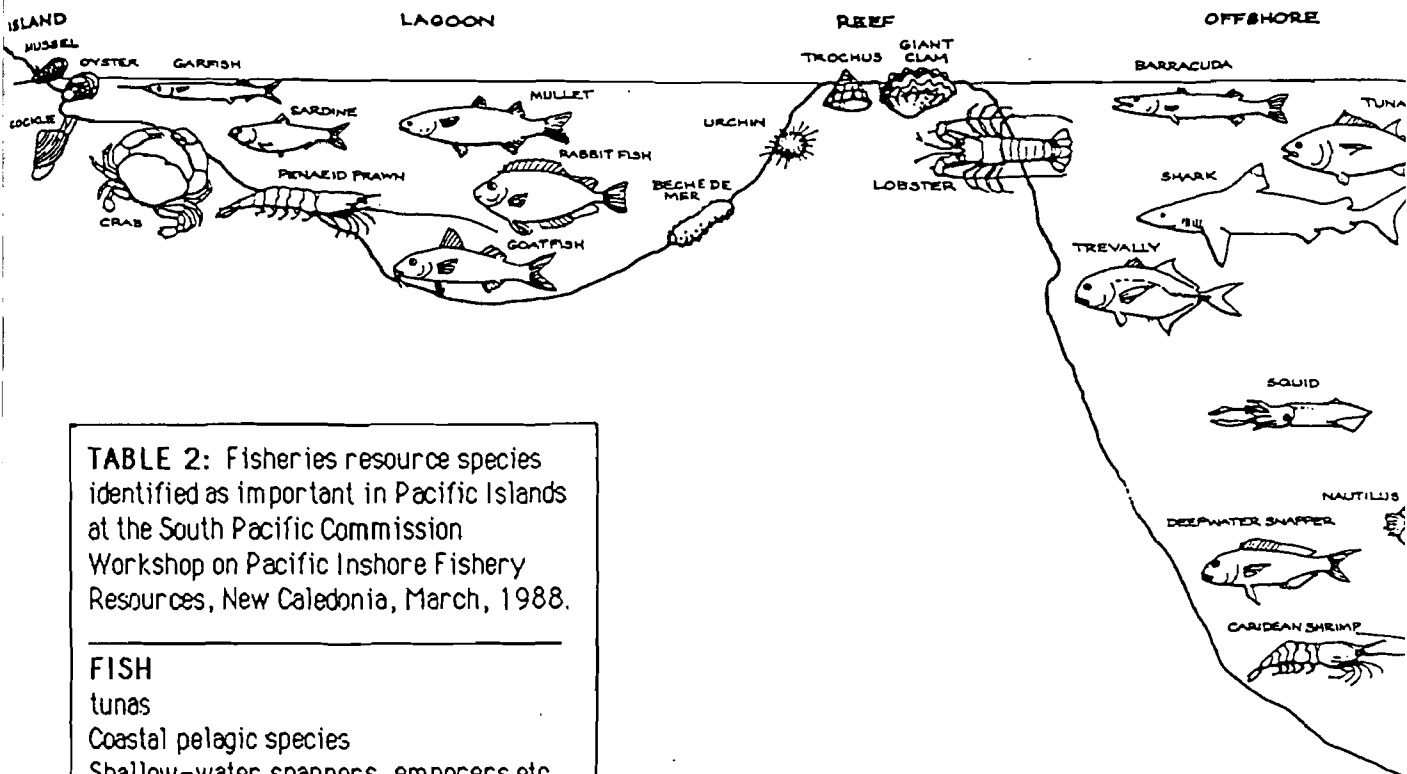


TABLE 2: Fisheries resource species identified as important in Pacific Islands at the South Pacific Commission Workshop on Pacific Inshore Fishery Resources, New Caledonia, March, 1988.

FISH

- tunas
- Coastal pelagic species
- Shallow-water snappers, emperors etc.
- Deep-water snappers, groupers etc.
- Sharks
- Baitfish

CRUSTACEANS

- Lobsters
- Penaeid prawns or shrimps
- Deep-water shrimps
- Crabs

MOLLUSCS

- Gastropods - Trochus and Green Snail
- Bivalves - Giant clams and pearl shell

ECHINODERMS

- Beche-de-mer

OTHERS

- commercial algae
- precious corals
- turtles

Figure 6: The distribution of Fisheries resource species on a profile of a typical tropical 'high' island.

3 Fisheries Biology

Fisheries biologists contribute to fisheries science in two main areas; first, by studying the basic biology and distribution of resource species (which leads to the elucidation of the species' life-cycle) and secondly, by studying the population dynamics of the species. In both cases, research is directed towards gaining information which can be used to manage the resource.

In order to discuss population dynamics, it is instructive to consider a fish stock as a simple biological system (Figure 7). In this system, the stock biomass is increased both by the growth of individuals and by recruitment (the addition of small individuals to the fishable stock). The stock also is being reduced by natural mortality (mostly by predation) and, in the case of exploited species, by fishing mortality as well.

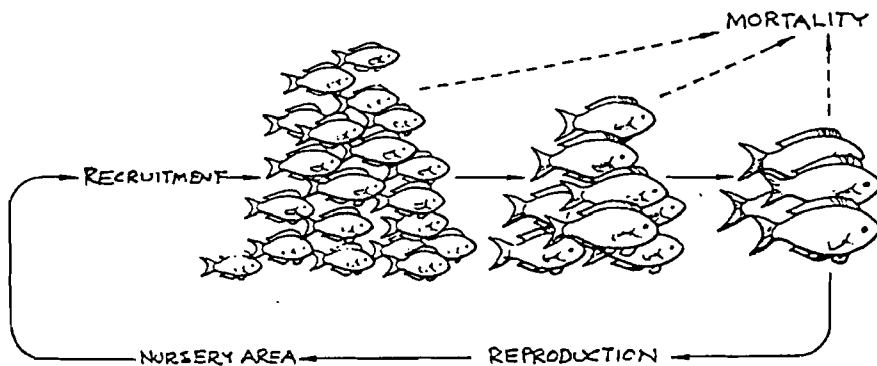


Figure 7: A fish stock viewed as a biological system. Three separate year classes are shown, all of which are being reduced by mortality. Losses due to mortality are balanced, on average, by the recruitment of sub-adults, in some cases, from a nursery area.

In species which are unexploited or exploited at a low level, losses due to mortality are balanced, on the average, by gains through recruitment. Stock abundance will, therefore, fluctuate around a mean level. If exploitation is high, however, the stock may be reduced to a level where reproduction and recruitment are affected.

A major task of biologists is to estimate the population parameters summarised or implied in Figure 7, namely stock abundance, growth, recruitment and mortality. It should be noted however, that the system is dynamic and values of the parameters may fluctuate widely, even in the absence of fishing. Several standard texts are devoted to methods of obtaining estimates of these parameters, including Ricker (1975), Pauly (1980), Pitcher and Hart (1982) and Gulland (1983), and a selection of these methods is given in the following sub-sections.

Stock Abundance

The estimation of stock abundance is often important in fisheries studies as a means of estimating other population parameters such as survival and yield. In some cases, estimates of absolute abundance (the total number of individuals) are required - see the exercise suggested in figure 8.

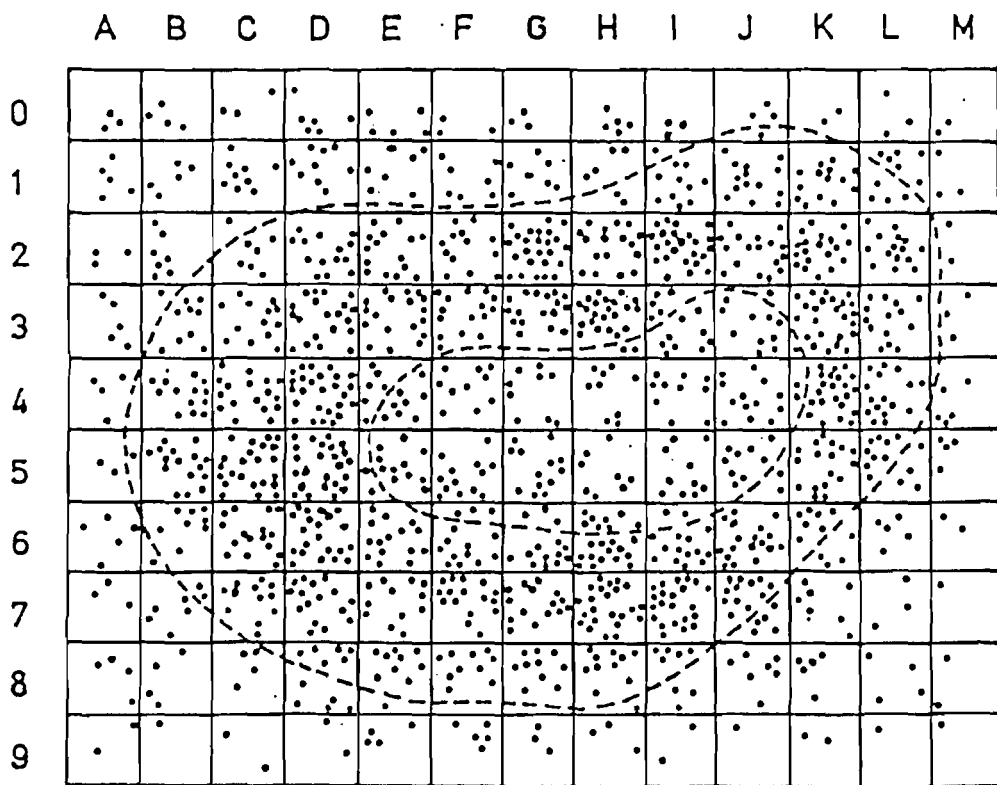


Figure 8: The distribution of beche-de-mer (black dots) around a sand-bank. Estimates of absolute abundance may be obtained by techniques such as quadrat and transect sampling.

In most situations, however, it is sufficient to obtain estimates of relative abundance (the number of individuals in one area in relation to the numbers present in another area or in the same area at another time).

Catch per unit effort is the most commonly used index of relative abundance in fisheries biology. Catch (C) and fishing effort (f) data are usually collected in all managed fisheries. Catch per unit effort (C/f) may be recorded in many ways; as the number of fish caught per hook per hour, the number of lobsters caught per hour diving or the weight of prawns caught per hour of trawling. Figure 9 shows a data sheet used to record catch per trap of deep-water shrimps and the relative abundance (C/f) of shrimps by depth.

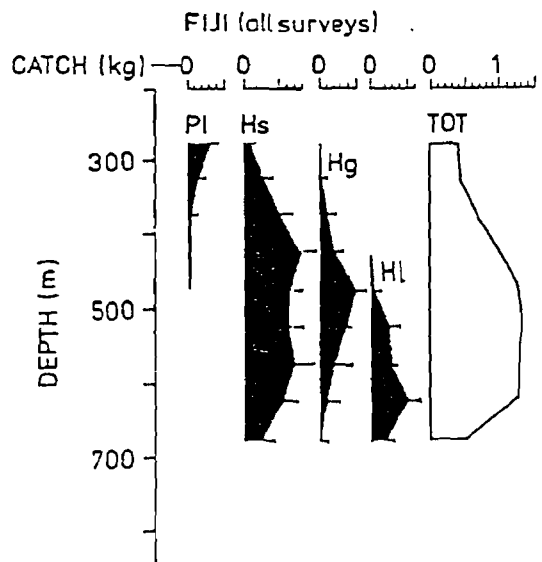
DEEP-WATER SHRIMP TRAPPING SURVEY							
LOCATION.....		OBSERVERS.....			DATE.....		
	SETTING	HAULING		Number of traps set in string.....			
TIME AT.....				Bait type.....			
DEPTH (m) AT..				Comments (trap damage, etc)			
CATCH DATA		* traps numbered from hauling line end					
SPECIES	sample measured? ✓	TRAP 1*		TRAP 2*		TRAP 3*	
		type.....	weight(g)	type.....	weight(g)	type.....	weight(g)
<i>P. longirostris</i>		number		number		number	
<i>H. ensifer</i>							
<i>H. laevigatus</i>							

Figure 9: (above) Part of a field data collection

sheet used in a trapping survey for deep-water shrimps (from King, 1988).

If traps are used over a range of depths, a figure showing the relative abundance of shrimps with depth can be constructed.

(right) The relative abundance (kg per trap per night) of deep-water shrimp caught off Laucala Bay, Fiji. (King, 1984).



It is unlikely that any fishing technique used will be totally efficient. All fishing gear is selective. Only a proportion of the fish present will come into contact with the gear and even less will be retained. In a trawl net, for example, very small fish are less likely to be retained than large ones, whereas in a gill net, both very small and very large fish are unlikely to be caught - the distinction between large and small being related to mesh size (Figure 10).

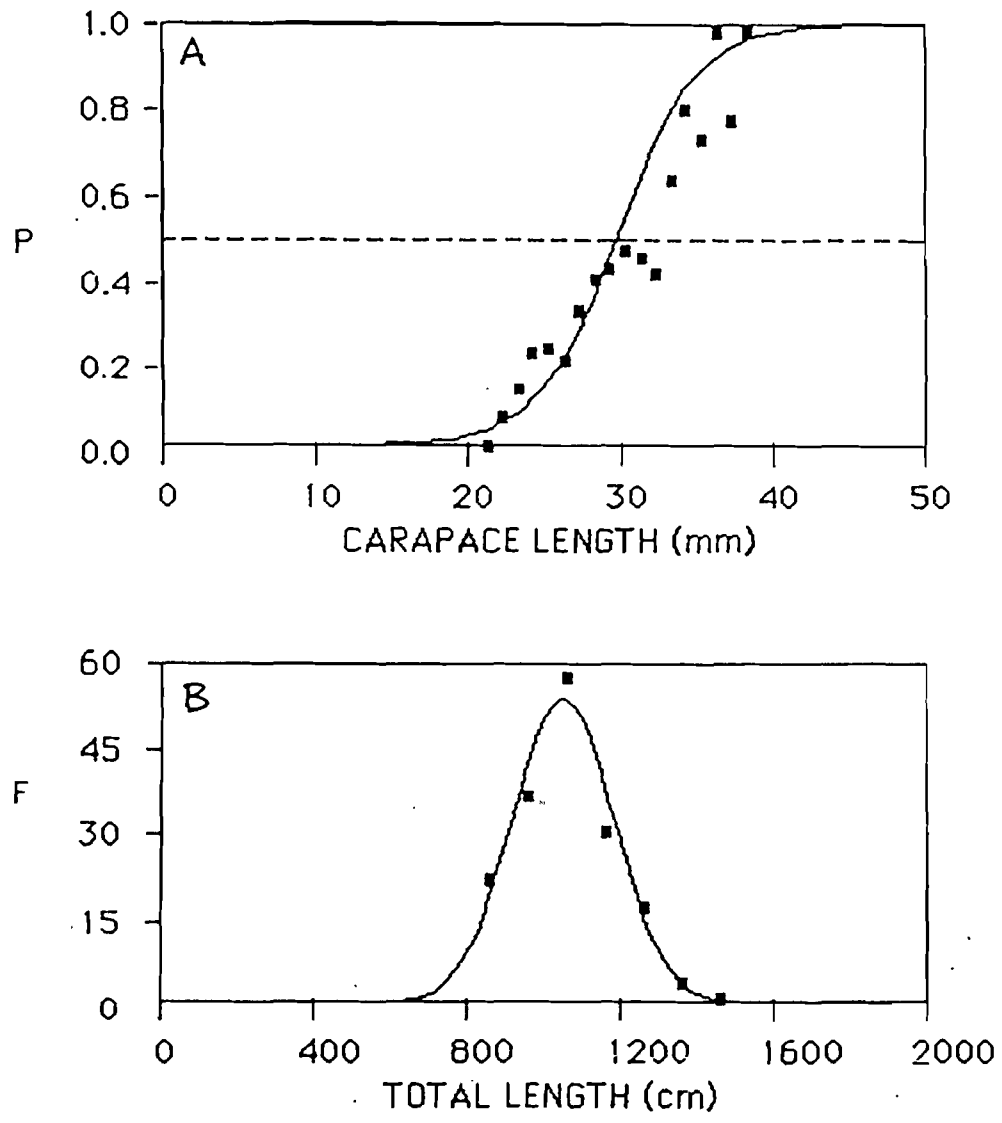


Figure 10: Mesh selectivity curves: A) Probability of capture versus carapace length for the western king prawn, *Penaeus latisulcatus*, for a trawl net with 41 mm mesh size. Data from King (1979). The broken line (at P=0.5) cuts the logistic curve at a mean length of first capture (Lc) of 29.8. B) Numbers caught versus total length for the gummy shark, *Mustelus antarcticus*, for a gill net with 15.2 cm mesh size. Data from Kirkwood and Walker (1986) with a normal curve superimposed.

Catch per unit effort will therefore be related to, but less than, the absolute abundance of fish in the gear's area of influence. The best that can be hoped for is that the relationship of catch per unit effort (C/f) to the true abundance is approximately linear; that is:

$$\text{Abundance} = q (C/f) \dots\dots\dots 1$$

where q is the catchability coefficient (and the slope of the relationship).

In most cases the value of q is not known and therefore absolute abundance cannot be estimated from the index. This defect is unimportant if information on abundance is required in relative terms. That is, if the questions to be answered are - Is the relative abundance of fish on ground A different from that on ground B? - or, Is the relative abundance of prawns in one year different from that of the previous year?

It should be noted, however, that in many cases the catchability of a species is not constant. The catchability of some species, such as penaeid prawns, may change in response to behavioural changes with the time of day, the lunar cycle and season.

Growth

Of the food taken by a particular species, much of the dietary energy is used for body maintenance, activity and reproduction. Only a small part, often less than one third, is available for growth in size. A complex array of selective forces determines whether a greater or lesser quantity of energy is diverted to growth at the expense of other important requirements such as reproduction. Advantages of a fast growth rate may include, for example, reaching a size early in life which gives the species some immunity from its predators. Attaining a large body size may allow a large number of eggs to be carried, or the production of large eggs with correspondingly higher chances of larval survival. From a fisheries point of view, growth is important as it is this parameter, as well as recruitment, which influences the catch that can be

taken from a stock (Figure 7).

Growth may be described in terms of changes in length, width or any other linear dimension as well as weight. Length is often easier to measure, particularly when out at sea, where the vessel's vertical motion affects weighing instruments, but weight measurements are often required for fisheries work (in calculating yield for example). Thus, it is useful to determine the relationship between measurements of length and weight over a wide size range of individuals.

When animals are growing at the same rate in all linear dimensions, that is, increases in length, width and height are proportional to each other, growth is said to be isometric. In this case there is a simple linear relationship between the standard length and other dimensions. That is:

$$Y = I + SX \dots\dots\dots 2$$

where Y and X are the two variables, I is the intercept on the Y axis and S is the slope. The coefficient of determination (r^2) is usually calculated to express the degree of association between the two variables and takes values between zero (no correlation) and one (perfect correlation). Statistical tables can be consulted to determine if the value of r^2 is significant; i.e., to find the probability of the correlation arising by chance alone.

If an animal is growing isometrically and doubles in length, its weight will increase in relation to the increase in volume (by 2^3 times). Thus there is a cubic or power curve relationship between length (L) and weight (W):

$$W = aL^b \dots\dots\dots 3$$

where b has a value close to three for isometric growth and a is a constant determined empirically. Power curves are best fitted to length and weight data by transforming equation 3 to a linear form using natural logarithms as $\ln W = \ln a + b (\ln L)$. The data may be treated as a linear regression (as in equation 2) by plotting $\ln W$ against $\ln L$ to estimate a (as the antilogarithm of the intercept) and b (as the slope). A length-weight

relationship for a species which is of irregular shape, such as an oyster, may show a large amount of scatter (Figure 11).

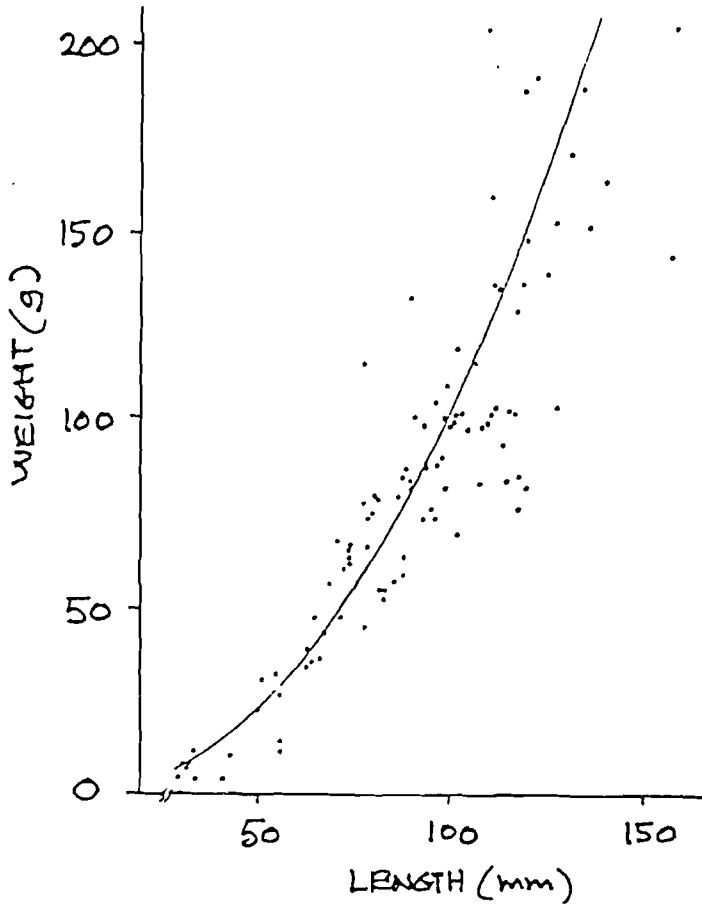


Figure 11: The relationship between length (mm) and total wet weight (g) in the Pacific oyster, *Crassostrea gigas* (King, 1977). In the length-weight relationship (equation 3), $a = 0.005$ and $b = 2.15$.

Growth models

Several models have been used to express growth using simple mathematical equations (Allen, 1971). The von Bertalanffy growth equation, possibly because of its incorporation into fisheries yield equations by Beverton and Holt (1957), has been most commonly used in studies on marine species. This model, based on physiological concepts, has been found to fit data from a wide range of species, although the use of any single model is unlikely to represent growth over the entire lifespan. The von Bertalanffy equations, in terms of length and weight respectively, are:

$$L_t = L_\infty (1 - \text{EXP}[-K(t - t_0)]) \dots\dots\dots 4$$

$$W_t = W_\infty (1 - \text{EXP}[-K(t - t_0)])^3 \dots\dots\dots 5$$

where L_t and W_t are the length and weight at age t , L_∞ and W_∞ are the theoretical maximum (or asymptotic) length and weight that the species would reach if they were allowed to grow indefinitely, and K is a growth coefficient which is a measure of the rate at which maximum size is reached. As an animal is unlikely to grow according to the above equations throughout its whole lifespan (particularly in the pre-adult stage) the curve often cuts the x-axis at a value less than zero - hence t_0 (the theoretical age at zero length) usually has a small negative value.

Growth curves of some representative commercial species are shown in Figure 12. In fisheries research, growth curves are usually estimated from either length-frequency distributions, mark-recapture experiments, or growth checks formed in hard parts such as scales, otoliths and vertebrae.

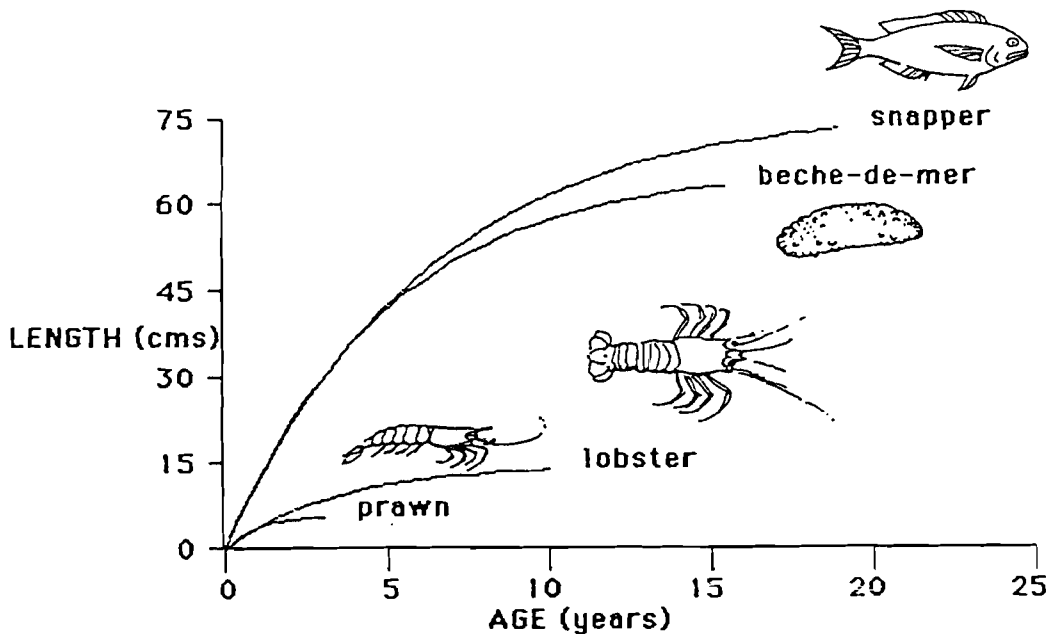


Figure 12: Growth curves for selected commercial species including the penaeid prawn, *Penaeus latisulcatus* (King, 1979), the lobster *Panulirus penicillatus* (Prescott, 1988), the beche-de-mer, *Thekenota ananas* (Conand, 1988), and the deep-water snapper, *Pristipomoides filimentosus* (Langi & Langi, 1988). Each curve has been terminated at ninety-five percent of L_∞ .

Length-frequency analysis

When a large unbiased sample is taken from a fish or invertebrate stock, lengths of individuals may be measured and graphed as a length-frequency diagram as shown in Figure 13. If the population spawns once per year over a relatively short time period it is possible to attribute approximate ages to the various "peaks" or modes in the length-frequency distribution.

The largest mode (of the group N_1 in Figure 13) is formed by a group of small individuals less than one year old (designated the 0+ group). The second mode, N_{12} , is formed from a spawning one year before the 0+ group and is therefore 1+ years old; each successive group is one year older than the one before it. In other words, each annual spawning has produced a normally distributed group within the polymodal distribution of the total population. Using this method, often called the "Petersen method", a growth curve can be estimated from the position of the modes in a single length-frequency sample.

A second method of using length-frequency data relies on obtaining multiple samples collected at separate times from the same stock. In this method, sometimes called modal class progression analysis, a series of length-frequency distributions is arranged sequentially in time and the major modes (N_1 , N_2 and N_3 in Figure 13) are traced as they progress along the length axis.

The single sample method presents several difficulties. For example, if the sample is collected by commercial nets the smaller size-classes may not be well represented due to escapement through the meshes of the net. The spawning period may be extended, especially in tropical species, making individual modes hard to distinguish. If spawning occurs more than once a year, the modes will not be from groups twelve months apart.

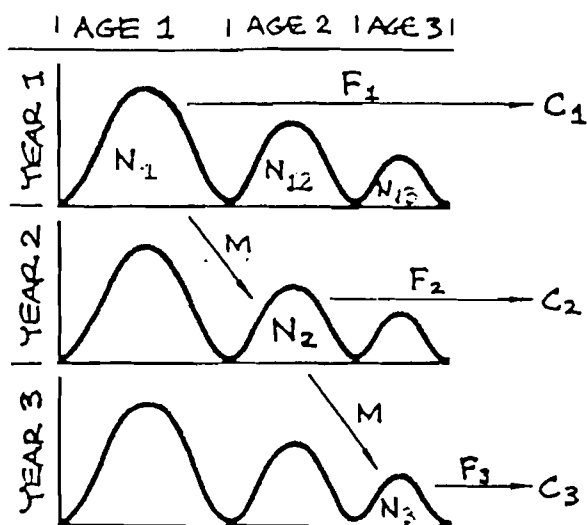


Figure 13: Length-frequency distributions with three different age groups shown for three consecutive years. Growth may be estimated from either, A) a single sample, where the distances between the modal values of N_1 , N_{12} and N_{13} are assumed to represent growth between year classes, or, B) multiple samples, obtained at three consecutive times, where the progression of the modal values of N_1 , N_2 and N_3 may be followed along the length axis.

Mortality can also be estimated by the reduction in numbers (from N_1 to N_2 to N_3) during which the age group is reduced by natural mortality (M) and fishing mortality (F); the latter is related to the catch (C) - see Cohort Analysis.

There are several procedures available for estimating the growth parameters of the von Bertalanffy equation (equation 4). The following example is based on length-frequency data from a small sample of a fish known as blue grenadier, *Macrurus novaezelandiae*. In practice a much larger sample would be used and the example is given to show the methodology involved rather than to accurately describe the growth of blue grenadier.

The numbers of individuals (the frequency) associated with each one centimetre size class are presented as a length-frequency diagram in Figure 14a. It is assumed that each of the modes arrowed represent successive year classes. Note that there is some subjectivity involved in selecting the important modes but sometimes the application of a running mean to "smooth" the curve and get rid of (presumably random) irregularities will accentuate the modes which represent distinct size-classes.

After substituting L_{t+1} for L_t in equation 4 (and supposing t_0 equals zero) the difference between this new equation and equation 4 is given by:

$$L_{t+1} - L_t = L_{\infty}(1 - \text{EXP}[-K(t+1)]) - L_{\infty}(1 - \text{EXP}[-Kt])$$

By manipulation, this equation can be made to assume a linear form:

$$L_{t+1} = L_{\infty}(1 - \text{EXP}[-Kt]) + L_t \text{EXP}[-Kt]$$

This suggests that length (L_t) at age t can be plotted against length (L_{t+1}) at age one year later ($t+1$) in a graph known as a Ford-Walford plot (Figure 14b). The regression line through the data will have a slope of $\text{EXP}(-K)$ and an intercept of $L_{\infty}(1 - \text{EXP}[-Kt])$. These may be manipulated to estimate K as $-\text{Ln}$ (slope), and L_{∞} as intercept/(1 - slope). Alternatively, L_{∞} can be read from Figure 14b as the point where the regression line crosses the diagonal line of equality between L_t and L_{t+1} (where there is no growth between age t and $t+1$).

The remaining parameter in the von Bertalanffy growth equation, t_0 , can only be estimated if length at a particular age is known; this is not the case in the blue grenadier example. Equation 4 can be altered to give:

$$t_0 = t + (1/K) (\text{Ln} [(L_{\infty} - L_t) / L_{\infty}]) \dots \dots \dots 6$$

In a fast-growing species with a brief annual spawning period, several year classes may be clearly evident in length-frequency distributions. If the spawning period is long or growth is slow, the older size-classes in particular may "bunch" together in the length-frequency distribution, making separation difficult. In these cases, graphical or computer-based analyses may assist in "breaking up" the distributions into the component groups which represent separate age classes. Cassie's graphical method (1954) has now been superseded by computer programs such as ELEFAN 11 (Pauly et al., 1981) and MIX (Macdonald and Green, 1985). ELEFAN is claimed to separate the distribution into groups in a more objective manner than visual techniques

although some subjectivity may still be involved in interpreting the results from difficult data. The program MIX, which requires the assumed number of age groups in the sample, is applied to the blue grenadier data in Figure 14c.

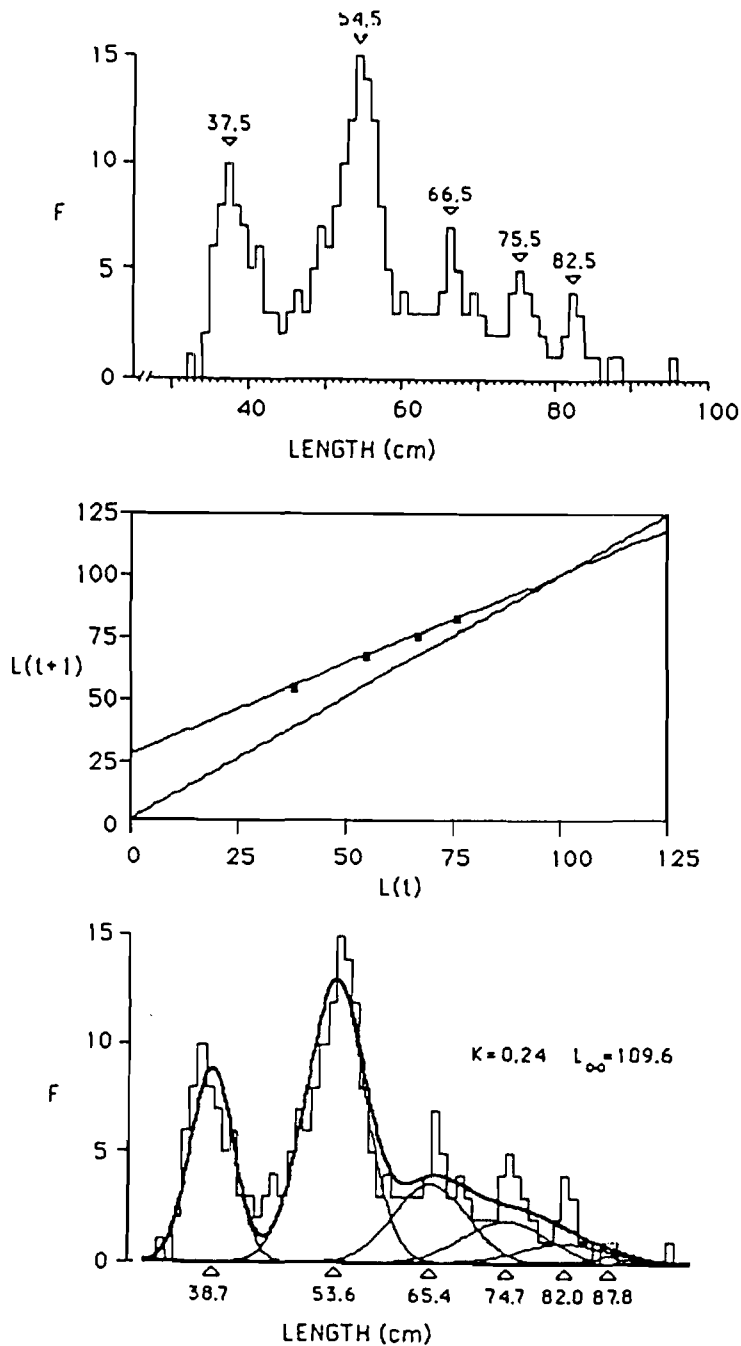


Figure 14: Length-frequency data from a small sample of blue grenadier (in practice, a much larger sample would be used - see text). A) the data presented as a histogram; arrows and values indicate the modes used in B) a Ford-Walford plot which estimates the growth parameters as $K=0.31$ and $L_{\infty}=101$ cm, and C) an output from the computer program MIX with six normal curves and a continuous heavy curve showing the summed distribution. Estimated means are shown by arrows.

Length-frequency data collected at small time intervals (e.g. on a monthly basis) allow the possibility of detecting fluctuations in growth rates with season. In temperate waters, growth rates are often depressed during the cold winter months and, in tropical waters, the growth of estuarine species may vary between wet and dry seasons. In these cases, growth may be modelled by adapting the von Bertalanffy equation to include a sine wave function (Figure 15).

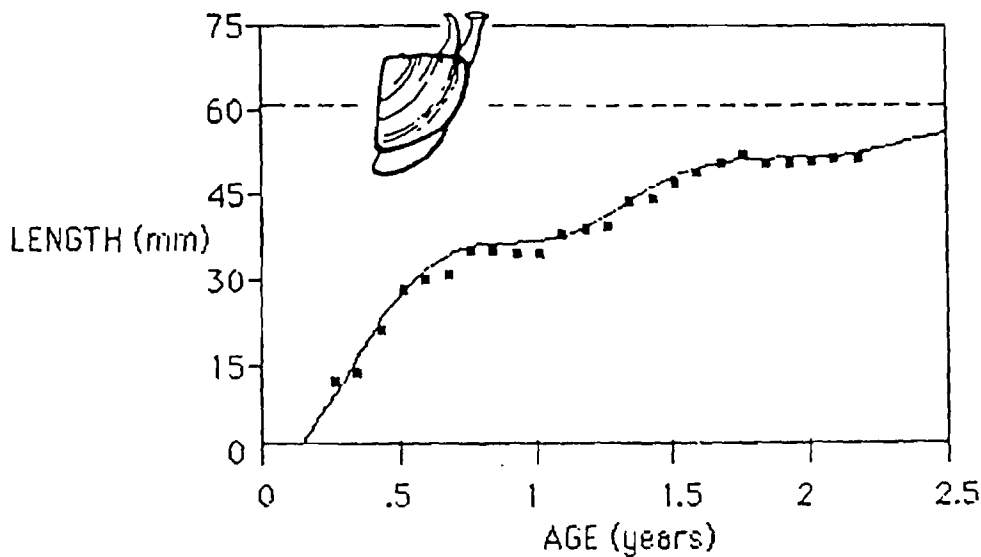


Figure 15: A "seasonalised" growth curve for the surf clam or pipi, *Donax deltoides*, (a bivalve). A computer program (King, 1986) was used to fit the curve to the modal values from length-frequency data collected over two years. The "flat" areas of the curve indicate reduced growth rates during winter months. The broken line represents an L_{∞} of 62 mm.

Mark-recapture data

Tagging or marking fish or invertebrates is an expensive method of gaining biological information. The method usually involves spending considerable time at sea and the payment of rewards for the return of recaptured tagged animals. In spite of the time and expense involved, tagging experiments are widely used in fisheries biology because of the usefulness of the data collected. In certain circumstances tagging data can be used to estimate

population size, mortality rates, and migration, as well as growth rates.

In most tagging experiments used to estimate growth it is necessary to be able to recognise individual fish - that is, each tag used will have a unique number or code. The main assumption in such experiments is that growth of the individual is not affected by either the tagging process or the presence of the tag. Tagged animals are recaptured after being at liberty for varying lengths of time. In a heavily exploited fishery tagged individuals may be recaptured in a very short time. In some species the time between release and recapture may be long; internal tags used in school sharks (Galeorhinus australis) have been recovered after more than 33 years (Olsen, 1984).

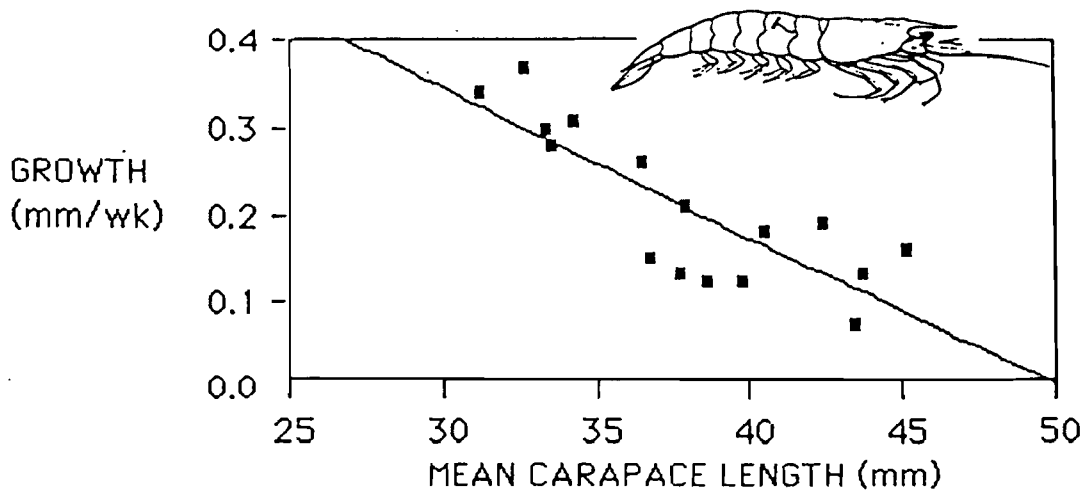
If a tagged fish of length L_1 is released at time T_1 and recovered at time T_2 when its length is L_2 , the growth rate per unit time is $(L_2 - L_1)/(T_2 - T_1)$. This growth rate can be plotted (Gulland and Holt, 1959) against the average size of the animal between release and capture, $(L_1 + L_2)/2$.

Table 4 is in the form of a work-sheet and is based on selected mark-recapture data for a penaeid prawn. The figure below the table shows a regression line of growth rate against mean length while at liberty; the intercept on the x-axis (where the growth rate is zero) is therefore an estimate of L_∞ , and the slope (with sign changed) an estimate of K .

Table 4: Selected mark-recapture data for the penaeid prawn, *Penaeus latisulcatus*. (King, 1979). The prawn shown has a plastic tag inserted between the first and second abdominal segment.

The relationship between mean length (mm) and growth rate (mm per week) is shown in the graph below. Growth parameters are estimated from the numerical value of the slope and the x-axis intercept respectively as $K=0.02$ and $L_{\infty}=49.8$.

carapace length (mm) at release	carapace length (mm) at recapture	time free (weeks)	growth rate (mm/wk)	mean length (mm)
28.2	34.0	17.0	0.34	31.1
29.7	35.2	14.7	0.37	32.5
30.6	35.7	16.9	0.30	33.2
32.1	34.7	9.3	0.28	33.4
32.2	36.0	12.1	0.31	34.1
34.1	41.4	35.6	0.21	37.8
35.0	38.2	21.0	0.15	36.6
35.1	37.5	9.3	0.26	36.3
36.5	38.6	16.3	0.13	37.6
37.6	41.5	33.9	0.12	39.6
37.7	39.3	13.9	0.12	38.5
38.7	42.0	18.6	0.18	40.4
39.9	44.5	24.0	0.19	42.2
40.7	46.5	44.6	0.13	43.6
42.1	44.5	36.0	0.07	43.3
45.0	45.8	5.0	0.16	45.4



Hard part analysis

In temperate and cold water species, reduced winter growth rates result in the formation of annual growth checks on hard parts such as the scales, opercular bones, vertebrae, spines and otoliths of fish and the shells of molluscs. In tropical species seasonal growth checks may be associated with biological factors such as spawning or environmental factors other than temperature, such as decreases in the salinity of lagoons or bays during rainy seasons. Although major checks in growth may occur annually, minor checks may form at smaller time intervals. In the last 10 years there has been some interest in the assessment of daily growth rings in the otoliths of tropical fish (Gjosaeter et al., 1984). Traditionally all the daily growth increments in the otolith have been counted, but recently the less tedious method of using the density of increments in several different segments of the otolith has been used (Ralston, 1985; Baillon, 1988).

The age of a fish may be determined simply by counting the number of checks, as long as the periodicity of their formation is known. The fish scale shown in Figure 16 has three clear checks corresponding to three winter periods. More information can be obtained by estimating, through a process called 'back-calculation', the previous sizes of the fish at the time of each individual check formation.

The simplest case is where there is a direct relationship between scale and body length over the lifespan of the fish. In this case, the length of fish (L_x) at any previous check formation (x) can be back-calculated using the formula:

$$L_x = L_p (S_x/S_p) \dots\dots\dots 7$$

where L_p equals the fish length at present (at the time of capture), S_p equals the present scale length, and S_x equals the scale length at check x . If the scale in Figure 16 was taken from a whiting of 38 cm length, the

back-calculated fish lengths using equation 7 would be 16.7 cm, 29.9 cm and 35.7 cm for the first, second and third winter respectively. In practice, a large sample of fish is examined and the average length at each age is estimated. As the data are from equal time intervals (one year apart) a Ford-Walford plot can be used to estimate K and L_{∞} .

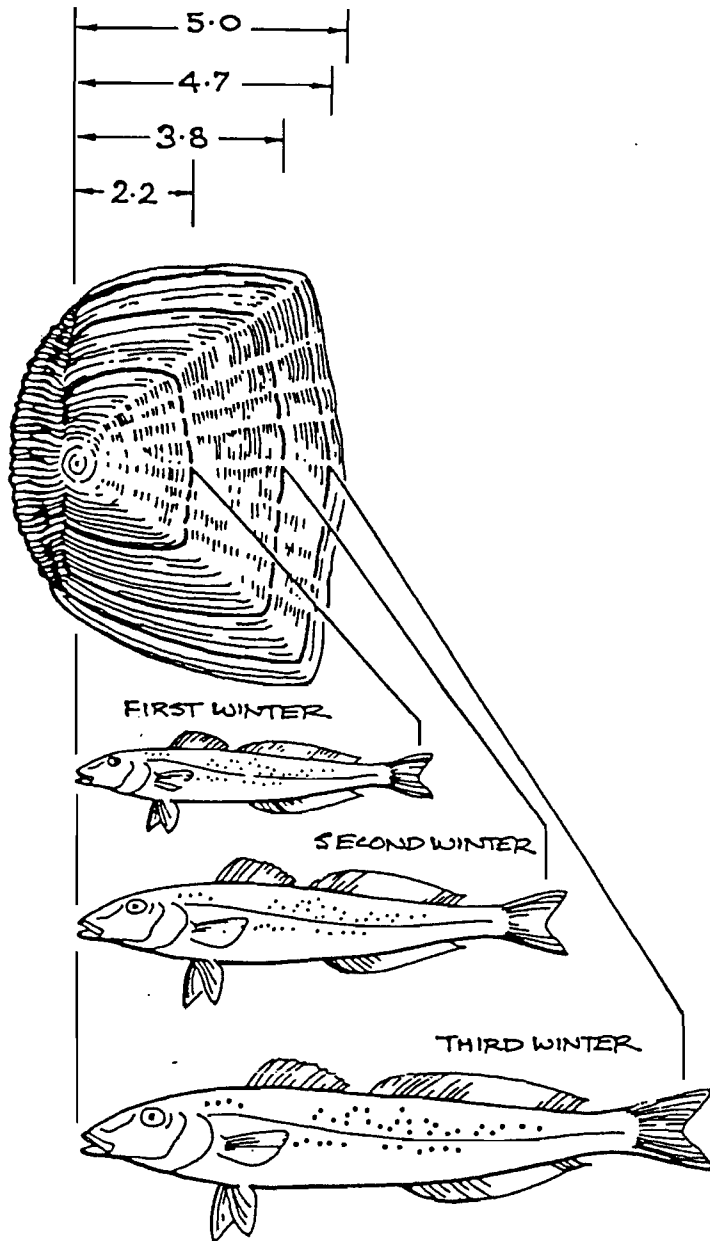


Figure 16: The relationship of winter checks in a scale to age of King George whiting, *Sillaginoides punctatus* (scale redrawn from Anon., 1987c). Distance from the focus (or scale centre) to the three winter checks and the posterior edge of the scale are in arbitrary units.

Often the analysis of hard parts is more complex than the outline given above. If the relationship between fish length and hard part length is non-linear (or linear without passing through the origin) correction factors must be used. The identification of true annuli or checks should always be validated either indirectly with independent estimates of age, or directly by the examination of hard parts from an animal of known age (Beamish and McFarlane, 1983). A general review of methods and principles involved is given in Bagenal (1974).

Recruitment

When juveniles reach a certain age or size, they are recruited into the adult stock. This recruitment may take the form of a migration from established nursery areas (Figure 7). Recruitment usually occurs over a particular time period of the year, and over a certain size range of individuals. The mean length at recruitment (L_r) may be estimated by using a similar graph to that presented for trawl mesh selectivity (with L_r replacing L_c in Figure 10a) and converted to mean age at recruitment (t_r) by using a growth equation (e.g. equation 4)

The relationship of the number of new recruits to the size of the spawning stock is of interest because it provides insight into what happens to recruitment when a fish stock is reduced by fishing. Two models have traditionally been used to describe stock-recruitment relationships.

The Beverton and Holt (1957) equation suggests that recruitment approaches an asymptote at high stock densities:

$$R = S/(a+bS) \dots\dots\dots 8$$

where R is the number of recruits, S is the number of individuals in the spawning stock and a and b are the parameters of the curve. Figure 17a shows a series of Beverton and Holt curves for different values of a. Species with a

short life-cycle and high fecundity (prawns, for example) are likely to have stock-recruitment relationships with low values of a , and show no reduction in recruitment even when stocks are reduced heavily by fishing. Recruitment in such fisheries, however, is likely to suddenly 'crash' at low levels of stock abundance.

The Ricker (1975) equation describes the situation where recruitment reaches a maximum before decreasing at higher levels of stock abundance:

$$R = a S \text{ EXP}(-bS) \dots\dots\dots 9$$

where R is the number of recruits, S is the number in the spawning stock and a and b are the parameters of the curve. Figure 17b shows a series of Ricker curves for different values of b . This model suggests the presence of density dependent mechanisms; perhaps adults compete more successfully for the same resources as juveniles, or adults prey on young of the same species.

The parameters in both of the above relationships can be found by converting the relevant equation to a linear form. Ricker's equation, for example, can be altered by using natural logarithms to:

$$\text{Ln}(R/S) = \text{Ln}(a) - bS$$

A regression line will, therefore, have an intercept of $\text{Ln}(a)$ and a slope of $-b$ which allows a and b to be estimated and substituted in equation 21.9 to draw the curve. Alternatively, a computer can be used to fit the curves by iterative least squares, which would also provide estimates of confidence limits; this last factor is important taking into account the usually large amount of scatter in plots of recruitment against stock size (Figure 17c).

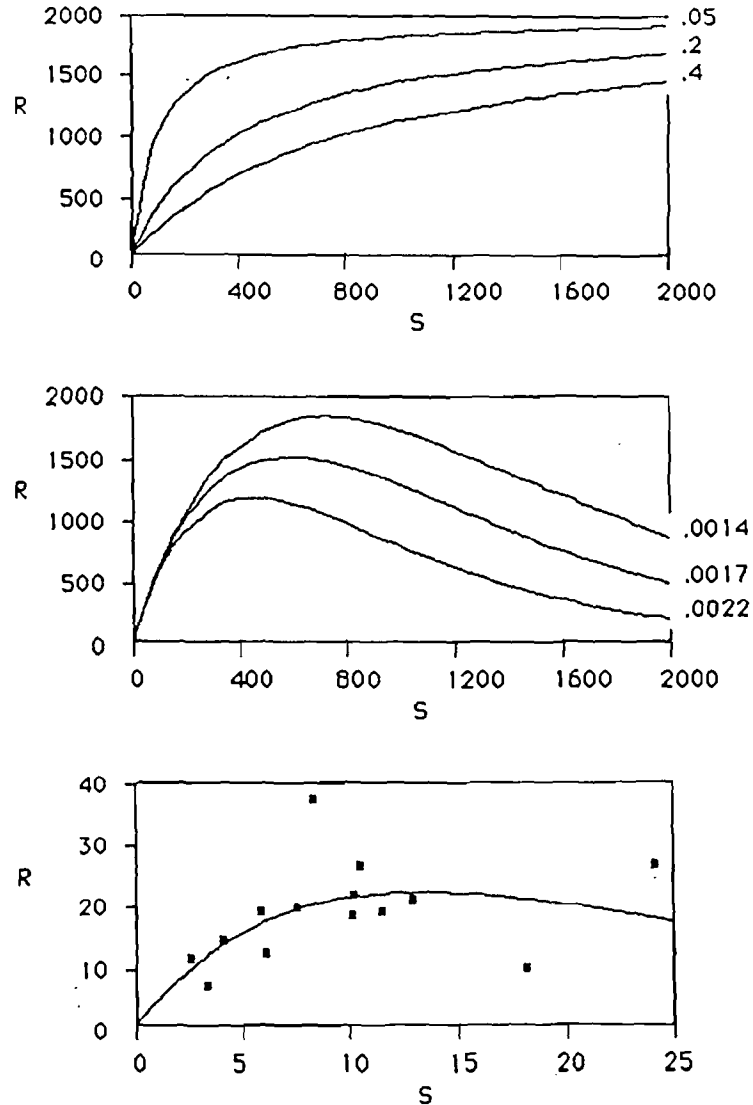


Figure 17: Stock-recruitment relationships: A) Beverton and Holt curves for values of $a = 0.02, 0.2$ and 0.4 with $b = 0.0005$, B) Ricker curves for values of $b = 0.0012, 0.0015$ and 0.0022 , and C) A Ricker curve through data for the tiger prawn, *Penaeus esculentus* (unadjusted data from Penn and Caputi, 1986).

Mortality

Many factors in the marine environment act to reduce the chances of survival of individuals in a population. These include adverse conditions, lack of food, competition and, most important of all in marine species, predation.

Mortality caused by these factors may be concentrated either earlier or later in the life-cycle of a species. Rarely, if at all, will the rate of mortality be constant over the entire lifespan. Most marine species, including ninety-six percent of all fish, are oviparous and produce large numbers of small eggs; mortality rates in the early larval stages are extremely high. One of the assumptions often made is that, after recruitment, adult mortality rates are constant over the remainder of the life-cycle.

The loss of individuals in a population through death can be discussed in terms of the proportion of individuals that survive (S) over a particular time interval, or the proportion that die (A). Annual mortality (A) is therefore the complementary value of survival (S), so that:

$$A = 1 - S \dots\dots\dots 10$$

Mortalities given as proportions (or converted to percentages) are inconvenient when considering several different causes of mortality which are not independent. It is more usual to consider the mortality rate Z which applies over a very short time interval, dt, in which causes of death are independent of each other (Gulland, 1983). The instantaneous rate of change in a population of size N is:

$$dN/dt = -ZN \dots\dots\dots 11$$

where Z is the instantaneous mortality coefficient. Equation 11 can be rearranged and integrated to give:

$$N_t/N_0 = \text{EXP}(-Zt) \dots\dots\dots 12$$

where N_0 is the initial number of individuals at time $t=0$ and N_t is the number remaining at time t. Thus, the number of individuals surviving over time is of the form of a negative exponential as shown in Figure 18c.

Instantaneous mortality rates can be related to proportional or percentage rates using equations 10 and 12 so that:

$$\text{Survival rate (S)} = N_t/N_0 = \text{EXP}(-Z)$$

$$\text{Annual Mortality (A)} = 1 - S = 1 - \text{EXP}(-Z) \dots\dots\dots 13$$

As instantaneous rates are independent, mortalities from different causes can be added. Therefore the total mortality rate (Z) is the sum of fishing mortality (F), which is caused by the fishing operation, and natural mortality (M), which is caused by all other factors:

$$Z = F + M \dots\dots\dots 14$$

In an unexploited stock $F = 0$ and, therefore, $Z = M$.

Catch curves

Under the assumption of a constant rate of mortality, population numbers surviving will tend to decline exponentially with time as shown in equation 12. This equation can be rearranged to give the linear equation:

$$\text{Ln}N_t = \text{Ln}(N_0) - Zt$$

Graphing the natural logarithms of numbers surviving over successive years will therefore produce a straight line relationship referred to as a "catch curve" (Beverton and Holt, 1957; Ricker, 1975). A line of best fit through these data will have a slope numerically equal to the instantaneous mortality rate Z.

An example of using catch curves is given in a study of the jackass morwong, Nemadactylus macropterus, a fish trawled off southeastern Australia (Smith, 1983). Figure 18a shows a length-frequency distribution for females caught during 1978/79. As the age structure of the population had been determined from otolith studies (Smith, 1982) it is possible to calculate the relative abundance of each age-group. The natural logarithms of these values are plotted as a catch curve in Figure 18b in which the initial ascending data points represent groups of individuals which are either not fully recruited or are too small to be totally vulnerable to the fishing gear used. A regression line (with slope -0.55) is fitted through the descending portion of the catch curve. The instantaneous mortality rate of $Z=0.55$ (42.1 percent per year) was used to construct the survival curve in Figure 21c. This method assumes that

