International Council for the
Exploration of the Sea

C.M. 1963

Symposium on the Measurement
of Abundance of Fish Stocks

No. 15

Catch per Unit Effort as a Measure of Abundance

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It is often taken as a basic assumption of much fish population work that the catch per unit effort is proportional to abundance. This relationship is exactly equivalent to the fishing mortality being proportional to fishing effort. As this latter is a way by which fishing effort may be defined, or calibrated, the basic assumption usually made is more strictly that the statistics of nominal fishing effort available (e.g. number of fishermen, or hours fishing x average horse power of ships) are in fact valid and reliable measures of true fishing effort. This review is therefore concerned with ways in which the relation between nominal effort and real effort (or fishing mortality) may break down; particular attention will be paid to failures correlated with changes in total effort or with abundance, rather than with seasonal, or apparently random, variations. The fishing effort of a fleet, as generally available in published statistics, is the sum of the efforts of the individual units, each computed as the product of the fishing power of that unit (often taken as 1 when there are notgreat differences between units) and the time spent fishing, or the number of operations.

Consider a fishery operating on a certain stock. From the fishery a certain unit effort (a trawl haul, a setting of a lobster pot) can be chosen at random; from the stock an individual fish can be chosen at random. There is a certain probability, q, that the selected individual fish will appear in the catch of the selected unit of effort. This formulation does not imply that the chances of being caught by a certain unit of effort are the same for all fish; some will be a long way from the gear, others near, but not behaving suitably, e.g. swimming too high to be caught in a bottom trawl. In fact only a small number of individual fish can possibly be caught, and most of these may be caught. The coefficient, q, is the probability of one of these individuals being the one chosen at random, e.g. if loo fish out of a population of loo,ooo are taken by a unit of gear, then q = o.ool. Clearly if q were constant at all times, and at all levels of total effort and stock abundance, then, in the given effort units, catch per unit effort would always be proportional to stock abundance. So far as the study of catch per unit effort as an index of abundance is concerned, the absolute value of q is unimportant, so long as the c.p.e. is always proportional to the abundance. It is a matter of further, often rather complex, analysis and research to express q in absolute terms, i.e. to determine how many fish per square mile are equivalent to a catch per hour of loo fish. The present problem is essentially one of studying variations in q.

Variations in q may be classified in two ways. Firstly, according to the direct causes of the variation; these may include:-

(a) changes in the proportion of the total area inhabited by the stock which is covered by the unit of nominal effort, i.e. the 'swept' by the gears. This is equivalent to changes in <u>fishing power</u>. (For some gears, e.g. trawls, the 'swept area' is literally the area covered by the trawl while being towed; for the searching type of gear, e.g. purse-seines, the area covered actual operation of the gear is less important than the area searched by the ship before shooting the gear).

(b) changes in the proportion of fish within the area 'swept' by the gear which are in fact caught by the gear, i.e. changes in the vulnerability to the gear.

(c) changes in the probability that the selected fish lies within the area swept by the gear. If the fish or fishing effort were randomly distributed this probability would be equal to the ratio of swept area to total area inhabited by the stock, but in practice, of course, fishing is concentrated in the more densely inhabited areas. A distinction may be made between this effect in a small area (e.g. on a particular fishing ground) - the aggregation of Gulland (1955) - and that in the area inhabited by the whole stock - the concentration.

The distinction between (a) and (b) may be clear enough for some gears, e.g. a trawl, where the area swept can be taken as the area between the tracks of the two other boards. For others, e.g. traps, there may be a very large area surrounding the gear in which a fish might get caught, though the probability of this happening decreases to a very low level at large distances from the gear.

The variations in q may also be classified according to the relation to other factors; such changes include:-

(i) changes with the amount of fishing

(ii) changes with the stock abundance

(iii) long-term changes, or trends, in time

(iv) cyclical changes (seasonal or diurnal changes)

(v) random or irregular changes.

The last is of least importance, especially when dealing with statistics of commercial fishing, where the catch per unit effort may be derived by thousands of separate fishing operations, so that even big random variations in individual catches have little effect on the mean value. Large random variations are however a greater disadvantage in analysing data from research vessel surveys, which may have to be based on only a few operations.

Cyclical changes

In nearly every fishery the catch per unit effort has regular fluctuations over the year. Some of these fluctuations reflect real changes in abundance; the seasonal patterns of losses due to fishing and natural mortality are not likely to be exactly the same as the patterns of gains due to growth and recruitment. For example, the abundance (in terms of weight) is likely to be a maximum in the autumn, i.e. towards the end of the period of maximum growth, and a minimum in the spring. Other, and often more important causes of annual fluctuation in c.p.e. are various changes in q, due to changes in distribution or behaviour of the fish. In the extreme there are seasonal fisheries (e.g. many herring fisheries) where the catch per unit effort is nearly zero outside the fishing season. For most studies of abundance, and its long-term changes, these seasonal fluctuations, whatever their cause, are irrelevant, and the need is for some single figure giving an index of abundance for the year. This could be obtained as the c.p.e. at the height of the fishing season, i.e. at a time when q is a maximum, in effect using the relation

$$\text{Abundance} = {}^{1}/q \text{ max. x (c.p.e.)max.}$$

This index only uses data from one part of the year, and therefore is likely to be more variable than one using all available data of catch and effort. The simple annual c.p.e., i.e. the total catch divided by the total recorded effort is not suitable, because its relation to the mean annual abundance varies with the seasonal distribution of fishing - if relatively more fishing is done at the best times of the year the catch, and c.p.e. will increase. The ratio of annual c.p.e. and abundance is in fact equal to a weighted mean value of q_t, the value of q at any time t during the year, the weighting factors being the amount of fishing during the particular period.

Mathematically if during the period t

$$C_t / f_t = q_t A$$

where A is the mean abundance during the year

$$\sum C_t = q_t f_t A$$

and

$$\frac{\sum C_t}{\sum f_t} = \frac{\sum f_t q_t}{\sum f_t} \cdot A = \bar{q} A$$

Any mean of the q_t's which uses constant weighting factors, in particular the simple mean, (i.e. equal weight) can be used to provide a satisfactory index of abundance. The unweighted mean is equivalent to using as an index of abundance the mean of the c.p.e.'s in each season of the year. These considerations may be demonstrated by data for the English motor trawlers fishing for cod at Faroes. The table below gives the relevant statistics of catch (in tons), effort (in hours fishing) and catch per unit effort for each month in 1960 and 1961.

	1960			1961		
Month	Catch	Effort	c.p.e.	Catch	Effort	C.p.e.
January	312	3,139	9.9	116	1,960	5.9
February	339	3,605	9.4	101	2,354	4.3
March	804	4,811	16.7	452	4,754	9.5
April	957	7,131	13.4	330	3,295	10.0
May	725	6.362	11.4	148	2,733	5.4
June	726	7,078	10.3	409	5,946	6.9
July	596	7,047	8.5	244	4.071	6.0
August	667	8,118	8.2	340	5,163	6.6
September	696	7,413	9.4	205	4,622	4.4
October	600	7,132	8.4	179	3,364	5.3
November	507	6,856	7.4	153	2,263	6.8
December	128	2,468	5.2	73	1,675	4.4
Total Year	7,057	71,160	9.9	2,750	42,200	6.52
Mean c.p.e. for year			9.85			6.29

Two indices have been derived for the abundance in 1960; total catch divided by total effort (= 9.9), and the mean of the monthly c.p.e.'s (= 9.85). Similar indices have been derived for 1961. Whichever index is used the estimated decline in stock abundance from 1960 to 1961 is similar (to 65% and 63% of the 1960 estimated abundance respectively) so that the choice of index is obviously not critical in this particular example. This is because the seasonal distribution of fishing effort was much the same in the two years. Clearly, though, the ratio of total catch to total effort could be greatly distorted if the seasonal pattern of fishing changed; in the extreme, if all the fishing in 1960 had been done in December, and all the 1961 fishing in April, the 1961 c.p.e. would have been nearly double that of 1960. The index of abundance derived as the mean of the monthly c.p.e.'s is free of such distortion, though of course it does require some data in each month.

Sometimes estimates of abundance are required at more frequent intervals than annually. Then the monthly c.p.e. will have to be used, but should be adjusted to the seasonal average, i.e. if over a period the March and December c.p.e.'s are on the average 1.5 and 0.5 times the annual average c.p.e., then the observed c.p.e.'s should be adjusted by factors of $^1/1.5$ and $^1/0.5$ respectively, i.e. the 1960 figures become 10.8 and 10.4. It may then be convenient to take monthly averages of these indices over say three or six months.

Similar considerations apply to other cyclial changes, e.g. diurnal variations. In themselves they are not important in the study of stock abundance, but may be a considerable nuisance if there are changes in the distribution of fishing during the day. Such changes may not be likely in a commercial fishery, but may occur with research vessel fishing. For instance on one occasion fishing may be done only during the day, and on another throughout the twenty-four hours, which may result in a drop in catch per unit effort if q is low at night.

Long-term trends

Long-term trends in q will be most frequently caused by improvements in the fishing operation. These may be direct improvements in the actual gear, increasing its fishing power, e.g. the Vigneron-Dahl improvement of the otter trawl, or improvements in the aggregation or concentration of fishing onto the fish stock, that is the fishing being more precisely concentrating on the highest density of fish, either directly by detection of the fish - e.g. asdic, echo-sounding or spotting from aircraft - or indirectly by better navigational facilities (Decca, radar, etc.) or better communication between ships. Fishing power, and changes in fishing power may be fairly readily measured by direct comparisons of catches on the same ground, either by fishing with a standard vessel (e.g. research vessel), or by analysis of detailed records of ordinary commercial operations. (Beverton & Holt, 1957; Gulland 1956). Such analysis is particularly useful when the improvements (e.g. increased size or power of ships) have taken place over a period, and old and new units are fishing at the same time.

Such comparisons cannot be so easily made for technical improvements leading to better aggregation or concentration, for by definition this results not in better catches at a given position, but a slightly different fishing position, where the catches are in fact better. A comparison could be made from commercial records, comparing catches from the same stock. However, many of the technical improvements considered may take place very quickly, so that not many comparisons of old and new gears fishing together are possible. Also (and this applies, though possibly not so acutely, to fishing power comparisons) the more skilful fishermen are likely to use the new gear first, so that the observed differences is likely to include the difference between progressive and conservative fishermen, as well as the difference due to the improved equipment.

Once measured, the increased efficiency has to be incorporated in some way into the statistics of total fishing effort. In the extreme the efficiency of each unit in terms of fishing power and possibly also concentration could be measured in some standard units, and this measure included in the recorded effort statistics of that fishing unit, i.e. one fishing boat is 1.08 times as efficient as the standard, so that each say one hour fishing by that boat would be recorded as 1.08 standard hours. However, this introduces more detail than is necessary; the requirement so far as eliminating the trend in q is concerned, is to make the average q the same from year to year, independent of increases in mean efficiency of the fishing units. Thus instead of estimating the efficiency of each unit separately, a figure may be estimated from the characteristics of the vessel and gear (tonnage or horsepower of the ship, or length of net). The procedure is most simple if fishing power is directly proportional to the characteristic, e.g. if it is proportional to the engine horsepower. Then the fishing effort of each unit can be expressed at once in such standard terms as horsepower hours, i.e. the time spent fishing times the horsepower of the engine.

Even more simply the correction for increased efficiency may be applied to the complete statistics of all ships for the year. The correction factor equal to the efficiency of the fleet as a whole may be derived from the characteristics of the ships in the fleet. It may be a simple function, e.g. proportional to average horsepower, but could be fairly complex, taking into account the ancillary gears - echo-sounders, asdic, etc., being used. This factor can then be applied to the simple recorded statistics of nominal fishing effort, e.g. hours' fishing. A danger of this method is that the mean fishing power of the fleet as given, say, in the registration lists, in which each ship is given equal weight, may not be the same as the mean fishing power of the fleet as operated, in which each ship should have a weighting factor equal to the time it spends fishing. (i.e. effectively collecting effort statistics as in the previous paragraph). However, the fishing time of the various ships may be known to be approximately equal, or weighting factors close to the real fishing time could be used, e.g. number of voyages.

Fishing time, or rather the relationship between true fishing time (or number of operations) and the recorded statistics of fishing time, may show trends in time, particularly when the statistics are not well developed. In the extreme, only statistics of number of fishermen, or ships, may be available, the implicit unit of fishing time being a year's operations. This may sometimes be satisfactory; the time spent fishing per year by the average Lowestoft steam or motor trawler can have altered little over the past fifty years - time in port and time lost at sea steaming to the grounds, time between hauls, and time lost due to bad weather and damage to the nets have not changed greatly. For this fleet therefore the catch per hours fishing or catch per ship will give (apart from a difference in scale) almost identical indices of abundance. For other fleets the relation between true fishing time and other approximate measures of fishing time (total available time - e.g. the whole year, number of voyages, days at sea, days on the fishing grounds and days fishing) can all change over a period. Some factors affecting the proportion of time "lost" (which will affect some at least of the measures of fishing time)are:-

Time in port.	Reduced by better maintenance of ships and gear. Increased to give better conditions for fishermen.
Steaming time.	Reduced by faster ships. Increased (as a proportion of total time) by need to make shorter voyages (and to bring back fresher fish). Increased by the need to go further from port to find fish.
Time between hauls.	Reduced by more efficient handling of gear. Reduced (as a proportion of total) by having longer hauls (for trawlers in particular). Increased by greater efficiency in catching leading to delay in handling the catch on deck.
Time lost due to weather.	Reduced by having more sea-worthy ships. Increased by having to go where weather is worse (e.g. whaling in the Antarctic).

For trawls and other more or less continously operating gears, there is clearly a 'correct' or 'best' measure of fishing time - the time for which the gear is actually on the bottom fishing, against which other possible measures of fishing time can be judged. For other types of gears - traps, gill nets, long lines, etc.- catches do not increase steadily with the length of time the gear is operating - a lobster pot left down on the bottom for two days will probably catch more, but less than twice as much as one left down for one day. If, therefore, there has been an increase in the average duration of one operation (e.g. the length of time the lobster pots are left on the bottom) then statistics of the number of operations will underestimate the later effort, while statistics of total duration (i.e. number of operations times average duration) will overestimate the later effort. (Clearly if the average duration of operation does not alter, then either number of operations or total duration would be valid measures of effort). The effective fishing time is best estimated by obtaining statistics of either number of operations or total duration, whichever is most convenient, and applying a correction factor determined by the average duration. This factor will have itself to be estimated either by special research fishing, or detailed analysis of commercial records. There are also gears, e.g. purse-seines, whale catchers, for which the critical time, i.e. that for which the catch per unit time is most nearly related to stock abundance, is not the time spent in the actual catching operation, but the time spent searching. Again the problem of determining the precise measure of fishing time to use only becomes important when there are changes in the proportions of the total operating time spent in steaming to the grounds, searching for fish on the grounds or actually working the gear. If definition of what constitute searching time is difficult, particularly as a matter of routine collection of statistical data, statistics of some simpler if less accurate measure of fishing time - e.g. time away from the port - may be collected to form the basic statistical data. Correction factors to adjust this nominal fishing time to more precise fishing time can then be obtained from more specialized information, e.g. log books kept by the more co-operative fishermen in which the proportion of the total time away from port which actually spent on the fishing grounds is recorded in detail.

Variations with amount of fishing

Changes in q due to changes in the total amount of fishing, while serious if they occur, are fortunately not very common. The effective fishing power of a fishing unit will not usually be changed much by the number of other units that are fishing at the same time. The presence of these other units may, however, affect the positions, and hence the concentration on the fish. There may be only a limited number of favourable positions for fishing, and once these are occupied any additional fishermen will have to fish elsewhere, and hence experience a lower c.p.e. If there is sufficiently detailed information on fishing position this effect may be detected, and could be eliminated by using as an index of abundance the catch per unit effort of only those fishermen fishing in the most favoured positions.

Additional fishing may also reduce the c.p.e. at a given level of abundance by changing the behaviour of the fish, for instance by breaking up the shoals of schooling fish, though it is doubtful if this occurs as often as is claimed by fishermen objecting to the incursions of visiting fishermen. This effect is clearly difficult to measure quantitatively, but some measure of the extent to which it is occurring may be obtained by detailed analysis of commercial catches, particularly of the frequency distribution of different sizes of catch (to see whether the 'patchiness' of fish has changed), or by echo-surveys of the area by research vessels.

Where searching is important more fishing may actually increase the catch per unit effort of individual vessels because the increased number of ships increases the probability of the biggest shoals being located by the fishing fleet as a whole.

Changes with abundance of fish

These types of change are perhaps the most important, as they will change the whole shape of the relation between stock abundance and c.p.e. from a proportional one to some type of curve. If the change is such as to reduce the fishing power of the gear at high levels of stock abundance and hence of catch per operation it is often described as gear saturation. The most obvious example is a gear like a hook where there is only room for e.g. one fish per hook and when this one fish has been caught the chance of catching another (i.e. the effective fishing power) falls to zero. Clearly this first capture will happen earlier or more frequently when the stock abundance is high. Similar if less precise examples of gear saturation occur in many other types of gear - e.g. gill nets, where the presence of fish in the net may frighten off later arrivals or many types of trap (e.g. whelk pots, Hancock, in press). However, in some fish traps the presence of fish may in fact attract further fish, resulting in what might be termed negative saturation - the fishing power of the gear increasing with stock density.

The extent of loss of fishing power may be estimated, and hence a correction factor obtained to give the effective fishing effort and catch per unit effort, if certain assumptions can be made about the form of the saturation. For a long line, and possibly for other gears, the fishing power at any time may be taken as proportional to the difference between the catch taken at that time and some maximum catch (i.e. for a long line the fishing power is proportional to the number of unoccupied hooks). Then the average fishing power of the gear during one operation, during which the fish are assumed to be encountering the gear at a constant rate, will be given by

$$f = \frac{-\ np}{\log\ (1-p)}\ fo \quad \text{(cf. equation 2.12 of Gulland, 1955).}$$

when fo is the initial, unsaturated, fishing power

and p is the ratio of the actual catch to the maximum catch (i.e. for a long-line the proportion of hooks unoccupied at the end of operation).

For long lines the maximum catch is clearly the total number of hooks, but for other gears this maximum is less obvious, and may have to be estimated by special research - e.g. by measuring catches taken during different fishing times.

Olsen (   ) has described a particularly striking example of saturation in a fishery for scallops (Pecten meridionalis). Following the introduction of more efficient techniques, the dredges used filled up with scallops within a few minutes, though in accordance with previous custom the dredges continued to be towed for a total of half an hour. The catch per haul was therefore constant and equal to the capacity of the dredge. The effect could be considered as reducing effective fishing power for the whole tow, but more easily as a reduction in the fishing time, which really includes only the first few minutes of the whole tow. The presence of this type of saturation could be detected from detailed knowledge of the fishing, but purely from commercial records it would not be possible to know when, during the tow the dredge filled up, and hence estimate the effective fishing time. (In the above example this was discovered from direct underwater observation of the gear in action).

Similar 'saturation' of fishing time can often occur, especially when the actual operation of catching the fish takes up only a proportion, possibly small, of the total time at sea, the rest being taken up with steaming to and from the fishing grounds, searching for fish, etc. Thus small boats fishing for shoaling fish may catch in one successful haul, as many fish as they can conveniently carry. The catch per haul, or per voyage, is likely to be constant over a fair range of stock abundance, which latter would be better measured by the catch divided by the time on the grounds looking for fish. Such reduction in true fishing time can also occur in a trawl fishery, for example, in the English fishery in the Arctic the hours spent fishing (i.e. with the trawl on the bottom) per day at sea was reduced at high levels of stock abundance (Gulland, 1956). These effects will not be serious provided a good measure of fishing time has been obtained (e.g. hours fishing rather than days at sea for the trawlers, hours spent searching rather than number of voyages for the small boats, etc.).

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