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SOME CONSIDERATIONS UNDERLYING DEFINITIONS OF CATCHABILITY AND FISHING EFFORT IN SHELLFISH FISHERIES, AND THEIR RELEVANCE FOR STOCK ASSESSMENT PURPOSES

by

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ABSTRACT

The problems of catchability and effort definition in invertebrate fisheries have been reviewed from available literature on four broad categories of fisheries; hand gathering, dredging, trawling, and trap fisheries. Units of nominal effort have been proposed, and factors affecting fishing power and catchability coefficient tentatively identified. These include a variety of physiological, environmental, and behavioural considerations for the species concerned, in addition to the more obvious mechanical considerations which determine the area of influence and efficiency of the gear. Spatial distribution of fishing effort (fishing strategy) in relation to the distribution pattern of the species can determine the effectiveness of a given unit of effort, and together with problems of gear saturation (especially in trap and dredge fisheries), may introduce a density-dependent bias into the definition of fishing effort. Definitions of effort (e.g. "days on the ground"), which inadequately partition the fishing process into its components of "search time" and "handling time", may incorrectly estimate the true fishing pressure on the stock, over a range of population densities. These sorts of bias are particularly misleading when effort data is used in models predicting optimal sustained yield.

Whenever it is possible to quantify factors affecting fishing power and catchability, it is suggested that they be used to obtain an estimate of corrected fishing effort which is additive over fishing units, and proportional to fishing intensity and fishing mortality rate.

RESUME

On a revisé les problèmes de définition du potentiel de capture et de l'effort de pêche des invertébrés dans la documentation disponible sur quatre grand types de pêche. Les unités d'effort nominal ont été proposés, et les facteurs influençant le pouvoir de pêche et le coefficient de capture ont été provisoirement identifiés. Ceux-ci incluent un éventail de considérations physiologiques, environnementales et éthologiques s'appliquant aux espèces concernées, en plus des considérations mécaniques plus évidentes, qui déterminent la superficie de pêche et l'efficacité de l'engin de pêche. La distribution spatiale de l'effort de pêche (stratégie de la pêche) en regard du type de distribution de l'espèce peut déterminer la validité de l'unité d'effort choisi, et avec les problèmes de saturation d'engin de pêche (particulièrement pour les trappes et les dragues), peut introduire une erreur influencée par la densité dans l'estimation de l'effort de pêche. Les définitions de l'effort (par exemple "jours sur le terrain"), qui négligent de subdiviser le processus de pêche en "période de recherche" et "période de manoeuvre", peuvent fausser l'estimation de la vraie pression de pêche sur le stock, en fonction des diverses densités de population. Ces genres d'erreur sont particulièrement trompeurs quand les données d'effort sont employées en modèles prédisant le rendement optimal soutenu.

Chaque fois qu'il est possible de quantifier les facteurs influençant le pouvoir de pêche et le potentiel de capture, il est suggéré qu'ils soient utilisés pour corriger l'estimation de l'effort de pêche, lequel peut alors s'additionner d'une unité de pêche à l'autre, et devient proportionnel à l'intensité de pêche ainsi qu'au taux de mortalité de pêche.

INTRODUCTION

A special meeting on population assessments of shellfish stocks held in Copenhagen in 1976 preceding the 64th annual reunion, highlighted the need for further research initiatives to improve our knowledge of the dynamics of shellfish stocks, and the definition of relevant parameters. At that meeting it became evident that studies on standardization of fishing effort and gear performance in relation to fishing mortality exerted by the gear have not kept pace with similar studies on gear used for harvesting marine finfish, despite the growing acceptance of effort limitation as a method of management in shellfish fisheries (Hancock 1976).

The Shellfish and Benthos Committee, at the 64th Statutory meeting, considered the findings of the special meeting on population assessments of shellfish stocks, and adopted the following resolutions:

C.Res.1976/3:5 Attention should be given to the definition of fishing effort for gears particular to shellfish fisheries and that standard measures should be adopted.

C.Res.1976/5:6 The effects of fishing practises on the habitat of shellfish should be given attention.

This paper attempts a preliminary description and definition of factors relevant to gear performance and fishing effort, while noting that the wide diversity of gears used for shellfish harvesting requires a series of definitions, each appropriate to a particular type of gear or harvesting technique.

Published data on fishing effort and gear performance in invertebrate fisheries is not readily available in a compiled form since, unlike the situation with respect to finfish where major emphasis was placed on these subject areas in the 1950's and 60's (e.g. ICES/ICNAF/FAO joint meetings on fishing effort and selectivity of fishing gear in 1957, 1963 ICES Symposium on the measurement of abundance of fish stocks, and the 1970 ICES meeting on measurement of fishing effort), a systematic examination of these problem areas has been lacking for invertebrate fisheries. The emphasis in these fisheries to date has been largely on empirical development of new gear designs suited to particular fisheries and local conditions. The resulting lack of standardization plays a large part in the difficulty of generalizing on gear performance.

Definitions of catchability, fishing effort, and fishing power

Historically, two approaches have developed to the description of fishing gear characteristics (Paloheimo and Dickie 1964; Gulland 1964b):

1) What may be termed the elemental approach necessary for first description of the mechanics of gear design and experimental studies of fish behaviour in relation to gear. Following Baranov (1918), a catchability coefficient is defined as $q' = ca/A$, which defines the proportion of individuals in stock area $\underline{A}$ removed by the gear sweeping unit area $\underline{a}$ with efficiency $\underline{c}$. This approach lends itself readily to measurement of physical characteristics of the gear (Treschev 1975), but since effective gear performance also depends on fish behaviour, and fishing strategy in relation to stock distribution patterns (which are not easily quantifiable), this also means that effort units must be an exact fraction of F to satisfy the equality $F = q'f$. This poses major practical problems in the definition of fishing effort, or more exactly in this case, fishing intensity.

2) The empirical approach usually adopted in population dynamics is to choose a convenient, easily measurable unit of nominal fishing effort (g) (from log records, port interviews), adjust this for fishing power of individual fleet units to arrive at a corrected fishing effort unit (f). The performance characteristics of the gear or fishing units can then be described in terms of the slope of the regression (q) between corrected effort and resultant fishing mortality rate (F) (determined independently from catch curves, cohort analysis, or tagging experiments).

A full understanding of the factors underlying performance of fishing units requires comparison between these two approaches. Evidently however, the definition of fishing effort unit chosen should ideally be closely correlated with the effective fishing intensity exerted in order to minimize spatial and temporal variations in q. At the same time, variations in q may result from changes in fishing power, effort distribution in relation to population density gradients (Rothschild and Robson 1972), as well as changes in availability by sex, size, and age. Corrections for these factors whenever possible should therefore be an integral part of fishing effort definition. The approach adopted here is to summarize for each type of gear what effort units seem most appropriate and the considerations that may lead to variations in q.

Evidently, in order to sum the individual units of nominal effort exerted by members of the fleet, some account must be taken of their relative fishing power. Thus, the definition of Gulland (1964b) states that "The fishing effort of a fleet, from commercial statistics, is the sum of efforts of individual units, each computed as a product of the fishing power of that unit, and the time spent fishing, or number of operations". We may note after Saunders and Morgan (1976) that if gear efficiency (p) = c/n, where c = catch per unit operation from n individuals within the area of gear influence, the absolute fishing power of the gear (r) $= \frac{a\,c}{n} = a\,p$, so that the fishing intensity exerted by g units of nominal effort by a given vessel is $f = g\,r$. In practise, because of problems in measuring absolute fishing power, it is usual to compare effective catches by different fishing units to a given standard vessel or vessel type within the same time-area stratum to obtain relative fishing power r' (Robson 1966) before summing up corrected nominal effort units to obtain total fishing effort of the fleet as $f = \sum_{i=1}^{n} g_i r'_i$ where the summation is over the i individual vessels in a fleet of n units. In general, for all gear types, the conversion from nominal to effective effort should eliminate where possible those factors which lead to variations in q, whether due to variations in fishing power, gear configuration, or any factors that affect the additivity of the effort unit.

Application of definitions of fishing effort and catchability in population assessments of shellfish stocks

A necessary simplification has been imposed on the subject by considering the problem of effort definition in terms of four principal types of gear or methods of fishing, namely:

1. hand gathering
2. dredges (including hydraulic harvesters)
3. trawls
4. pots and set gear

The main characteristics relevant to the question of effort definition for each of the above type of gear are reviewed under separate headings in the following sections.

The principal uses to which improved estimates of fishing effort and mortality can be applied are briefly reviewed here. The first, which is most directly relevant to the question of effort definition *per se*, may be considered under the heading of logistic models (e.g. Schaefer (1957); Pella and Tomlinson (1969); Fox (1975), and other subsequent developments) which attempt to define the status of the stock in terms of the empirical relationship between amount of fishing effort and weight of catch. The different approaches are all encompassed within the Generalized Production model, expressing the change in population size over time by: $dP/dt = \pm HP_t^m \mp KP_t - qfP_t$ where P_t is the population size, and H, K, and m are parameters that allow fitting of a wide range of curves to the plots of overall catch on fishing effort. The general similarity is that catch rises with effort to some point (MSY) before declining with further increases. This approach treats the population as a "black box" to which fishing effort is the main input, and an estimate of equilibrium yield at that level of effort the main output. Evidently, this approach, although it requires relatively limited data, is sensitive to errors or biasses in the units of fishing effort stemming both from changes in fishing power and gear selectivity, as well as changes in biological parameters of the stock.

The other principal approach relies on population sampling to estimate mortality rates and population sizes from size frequency and age composition of the catch (catch curves) or by virtual population or cohort analysis (Gulland 1965; Pope 1972; Jones 1974). If an estimate of natural mortality rate is available, these techniques allow estimation of fishing mortality rates, and by comparison of mortality rates with trends in fishing effort, changes in the catchability coefficient q can be detected with age and time.

Noting that q may be defined as the probability of one individual in the population being chosen at random by one unit of effort, variations in q may be due to one or more of the following factors:

1) changes in fishing power
2) changes in vulnerability, fishing strategy, or stock aggregation.

In general, long-term trends in fishing power are caused by improved gear: either by being better able to locate and stay on high concentrations, or, once there, to exploit them more efficiently. In the case of gears whose catch capacity may be exceeded (gear saturation), or where catch rate depends on local stock abundance (e.g. dredges, traps), q may be expected to be density dependent if some correction is not applied to the effort unit. Another type of apparent density dependence which may result from changes in fishing strategy with stock depletion is particularly applicable to non-motile organisms; namely fleet movement to new, less productive areas of the stock, which will effectively change the stock area (A) exploited (and hence the fishing intensity) and/or change the index of concentration of effort onto the stock (Rothschild and Robson 1972; Caddy 1975).

Any attempt at definition of fishing effort must evidently bear in mind the distinction between search time (time spent locating fishable concentrations of stock) and handling time, namely the time during which the gear is actually in operation (Beinssen 1976b). Although it may be impossible in some fisheries to distinguish these two components within the units of fishing effort available from commercial statistics, in many shellfish fisheries the index $\left[\frac{\text{search time}}{\text{handling time}}\right]$ may be expected to increase as stock depletion proceeds.

HAND GATHERING

Under this heading may be considered a wide variety of largely coastal fisheries, namely oyster tonging (Medcof 1961), cockle and mussel raking (Hancock and Urquart 1966), clam digging (MacPhail and Medcof 1963), together with various fisheries operated with the aid of aqualungs or other devices permitting manual collection of subtidal shellfish (e.g. Beinssen 1976a, 1976b).

Catchability and gear selectivity

The diversity of types of fishing under this heading do not at first sight permit much generalization particularly concerning gear selectivity, which may be a function of conscious judgement (hand culling), or by means of tine spacing (rakes or clam hacks), or be dependent on sieve mesh size (as in some intertidal cockle fisheries). These types of fisheries present in an elemental form certain problems which may be conveniently presented here since they apply to a greater or lesser extent to more elaborate fisheries.

Effort definition

While definition of fishing effort units may best be in terms of man-days on the grounds, hours underwater by divers, or directly in terms of the area of terrain searched, a definition of the relationship between effort and fishing mortality must take into account several additional factors, namely:

1) Spatial heterogeneity of the population (Pielou 1965) may confound the dynamic pool assumption, namely that a unit of effort exerted at any point in the population will produce a corresponding mortality. Many sedentary invertebrates (commercial or otherwise) share with benthic organisms in general a tendency towards contagious distribution (Elliott 1971), and the negative

binomial type of distribution also seen in many fish populations (Anon. 1974) seems widely prevalent. The recommended approach to assessment of this type of population (Gulland 1955) is stratification of the catch and effort statistics by subunit areas. For sedentary species, it may then be necessary to assess each unit area separately before summing over the whole fishing ground (Gales and Caddy 1975).

2) The strategy for hand gathering being to maximize yield/unit time spent collecting; for sedentary species it would seem likely that the resultant effort distribution will also be non-random. In addition, there may be a distinct cut-off point in terms of the minimum CPUE that may precede searching for another more densely populated part of the stock.

3) The definition of a unit stock posed one of the major problems for participants in the 1976 shellfish symposium; for populations which are at least partly subtidal, only a fraction of the stock may be available to exploitation. The locally highly efficient nature of hand gathering for gastropods such as Abalone (*Haliotis* spp.) and large decapods may result in the extension of the geographical range of a fishery into progressively distant or relatively inaccessible waters (reefs, etc.) with the result that on stock depletion, fishing effort units measured in days or hours at sea may largely come to consist of search time as opposed to time spent handling the catch. Conversely, indirect indices of time spent underwater, such as volume of breathing gases used per trip, may overestimate actual time spent collecting since depth and inaccessibility of harvestable densities may increase as stock depletion proceeds.

4) In terms of applicability of estimates of fishing effort to the measurement of population mortality, two types of fishing pressure may be distinguished within this group of techniques:

1. highly destructive types of fishing such as clam digging (Medcof and MacPhail 1964), "ploughing out" of cockles (Franklin 1972), and some types of dredge fisheries (e.g. Dare 1974; Caddy 1973) where indirect fishing mortalities are sufficiently high to make population analysis based on numbers of individuals landed (by virtual population analysis) likely to lead to underestimates of mortality at age. Catch and effort analysis may present the most tractable approach to the estimation of the relationship between fishing effort and sustained yield for these fisheries;

2. other (often highly efficient) types of hand gathering where good catch statistics may permit an alternative to effort analysis by such methods as virtual population analysis.

DREDGES AND MECHANICAL HARVESTERS

Under this heading may conveniently be considered dredges, which in terms of increasing complexity, range from towed rakes with attached bags used for handling harvesting oysters and irish moss *(Chondrus crispus)*, bucket dredges with chain or mesh linking (as for bar clams and ocean clams), and scallop dredges which may be either rigid-framed, with (Baird 1959), or without (MacPhail 1954) teeth, or essentially modified beam trawls with upper and lateral rigid supports and a lower sweep chain (Bourne 1964). As a special category here may be included hydraulic dredges of the continuous delivery type (MacPhail 1961).

Selectivity and catchability coefficient

Dredges are relatively unquantitative harvesting or sampling devices for benthic or epibenthic organisms (Holme 1964; McIntyre 1956), and although odometers have been used to measure distance travelled by dredges on bottom, the same studies (Bourne 1965) have indicated that mesh selection is relatively poor if the dredges are towed to fullness, or if other debris blocks the rings in the dredge (Baird and Gibson 1956). Under these circumstances the same correlation between selection factor and volume of dredge contents may occur as noted by McCracken (1963) for otter trawls, but to a more exaggerated extent. As a result, the range of sizes partially retained by the dredge may extend over a wide proportion of the available size range (Caddy 1972), necessitating culling out of undersized individuals on deck. Selectivity may also be exerted by the spacing of dredge teeth (Baird and Gibson 1956), which may also act to reduce the amount of debris entering the dredge. Preliminary evidence from cover experiments (pers. obs), using the Canadian offshore scallop dredge, suggest that a large fraction of dredge selectivity occurs through the bottom of the dredge. This must be particularly damaging to escaping individuals, especially if the terminal lifting bar at the end of the dredge is in contact with the bottom.

Factors affecting dredge selectivity and efficiency

Variations in bottom type may be expected to play a large part in gear selectivity and efficiency, depending on the amount of debris entering and plugging the dredge (Bourne 1965). More important, perhaps, is the effect of fishing strategy and spatial inhomogeneity of the stock referred to earlier, which means that the definition of fishing effort in terms of area swept by the dredge (Baranov 1918) may have to be modified in the light of the distribution pattern of the species (Caddy 1975; Allen 1976).

Temporal. Seasonal factors such as weather may affect catchability significantly through increased "jumping" of the dredge, even despite the addition of pressure plates to maintain contact with the bottom (Baird 1959). Gear efficiency may also vary on repeated towing over the same ground, particularly due to recessing of scallops, and the effects of the dredge in modifying and smoothing the bottom terrain.

Behavioural. More active species such as the queen scallop *(Chlamys opercularis)* and offshore scallop *(Placopecten magellanicus)* may show active swimming behaviour which can affect catchability so that efficiency will depend to some extent on towing speed (e.g. Caddy 1968).

Incidental mortality due to fishing. Rigid towed gear, which makes close contact with the bottom, may exert indirect mortalities greater than indicated by the number of individuals being landed in the catch. Non-selective damage at size may be caused by contact with the dredge frame or over-running by the gear. Evidently, for some gears at least, incidental damage has a large size selective component, and for scallop dredges, the highest probability of breakage seems to occur when an individual attains the size at which it is just prevented from passing through the dredge ring. Another component of incidental mortality is that caused by discarding of undersized individuals from deck, either due to rough handling during dumping of the catch and in subsequent culling, or physiological stress (Dare 1974). Both factors may contribute to death directly or by increasing availability to predation once returned to the grounds. Selectivity of hydraulic dredges used for many infaunal bivalves may be mediated either through a mesh screen in the delivery chute (Franklin 1972) or by manual culling. The general impression given is that this type of gear is relatively less destructive to discarded undersized individuals (MacPhail and Medcof 1963) than manual digging, although the danger of modification to the nature of the fishing ground by heavy repeated harvesting is a question that requires further consideration (e.g. deGroot and Apeldoorn 1971). Another major problem that occurs in fisheries using this type of gear is the incidental damage question. Possible incidental damage by dredges or moss rakes to other species (e.g. lobsters, Scarratt 1975) may be an important consideration.

Fishing power. Engine horsepower may have an influence on effective effort and can be used to stratify fishing units in fishing power calculations and effort summation. Crew size may influence the ratio of effective fishing time over handling time where processing of the catch is carried out at sea.

Definition of effort in dredge fisheries

Effort units expressed as days at sea or even days on the ground can be misleading in that they may introduce a density-dependent bias to the estimate of effective fishing effort. This is because the ratio of both search time to dragging time, and time spent dragging to time spent culling and processing the catch, will both vary with abundance. More appropriate effort units may be either defined in terms of the time spent on bottom by the gear, which may then be converted into area swept (where area swept = gear time on bottom x towing speed x effective dredge width). If the gear is unselective and quickly becomes saturated, the number of tows by the gear or by gear of a known capacity may be a more appropriate measure of fishing pressure. In this case (Allen 1976), the effective area of influence of the dredge will be a function of dredge volume and the proportion of shellfish in the material retained by the dredge (Table I).

TRAWL FISHERIES

Trawls are used for capture of reptant and natant decapod crustaceans, squids, and pectinids. Considerations underlying effort definition in trawl fisheries for finfish have been well documented elsewhere (Anon. 1957, 1960, 1974, 1976; Gulland 1964), and with several qualifications discussed here, probably apply equally to invertebrates fished with the same gear.

Fishing power

Two groups of species may pose slightly different problems in effort definition:

1) Species (particularly reptant crustacea) where effective trawl width and area swept may be the significant factor in determining fishing power, and

2) Species which may be dispersed throughout the water column (e.g. squids) or where at least some movement off bottom occurs (e.g. many commercial shrimp species), so that headline height and cross-sectional area of the trawl mouth are important in determining swept volume.

There are indications that effective trawl width not include the trawl wings if "herding" is not an important consideration for burrowing species such as *Nephrops* (Warren 1974). The use of the "area swept" approach may lead to errors in determining effective effort (Hoydal 1976; Carlsson 1976), not only because of loss of shrimp over the headline (which can vary diurnally), but also because of the "learning factor" by which fishermen locate high density patches. In practise, fishing power is usually calibrated relative to some standard; however, brake horsepower or other vessel/gear characteristics may be used as measures of fishing power if they can be shown to be correlated with catching rate.

Factors affecting catchability and gear selection

Catchability of *Nephrops* varies seasonally, depending on bottom temperature (Jensen 1965), oxygen content (Bagge and Munch-Petersen 1976), and may also vary diurnally. Behaviour of males and females may be differentially affected. Selection properties of shrimp trawls may be less clear cut than for groundfish species due to meshing, and in many cases there is a significant by-catch of small groundfish which has prompted several attempts to design gear that minimizes fish by-catch.

Effort definition. The problems here are similar to those well defined for groundfish trawl fisheries. Units of effort may be either in days spent on the ground, number of tows, or distance swept by gear of a known type, width, or cross-sectional area or volume.

Corrections to the effort unit

The problem of effort definition in multi-species fisheries has been addressed elsewhere (e.g. Anon. 1960; Ketchen 1964). This may be particularly important for those species showing contagious distribution and marked substrate preferences. This may make it necessary to apportion effort by subareas of known substrate or habitat type (Penn and Hall 1976) in order to arrive at an effort measure that is related to the fishing mortality exerted by the gear.

TRAP FISHERIES

The problems in defining practical measures for fishing power and fishing effort for "passive" gears such as trap fisheries have been reviewed by Hancock and Simpson (1962), Simpson (1975), and Bennett and Brown (1976). In addition to mechanical considerations such as trap size and design, size and shape of entrances, and escape holes, and the presence or absence of one-way valves (all of which may vary on a regional basis), fishing power of traps depends to a larger extent than for "active" gears on physiological and behavioural considerations; some of them poorly understood, and few of them adequately quantified.

The sequence of events outlined in Bennett and Brown (1976) summarize the main factors affecting the trap capture process. This is (with some modifications):

Process	Contributing factors
bait/trap attraction:	- type size, freshness bait - appetite (food availability, moult) condition) - sheltering response ? - diurnal, tidal feeding rhythms reproductive condition
locating trap:	- response time - random, directed walk (gear conflict ?) - effects of temperature on locomotory speed - soak time
entry to trap:	- inter-, intraspecific attraction, avoidance, competition (predation, cannibalism) - dimension of entry port (upper size limit ?) + trap size - number of individuals in trap (gear saturation)

escape from trap:
(- size of mesh, lath spacing, presence
(of escape ports
(- self-destruct panels to prevent
(ghost fishing of lost traps ?

Fishing power

Theoretically, fishing power could be determined from gear efficiency (the number of individuals captured as a fraction of those detecting the gear) and the unit area of gear influence (number detecting bait/population density). In practise, however, because of difficulties in measuring absolute fishing power, fishing power of a trap should probably be calibrated against some standard trap design and bait before summing effort over the whole fleet. In doing so, it should be borne in mind that trap interactions and contagious distribution patterns (Paloheimo 1963; Sinoda 1970) may seriously bias results, depending on trap location and proximity. In situations where gear saturation is likely to occur, the average fishing power during a fishing operation may be density dependent if ingress rate is a function of available space in the trap as well as population density (Munro 1974).

Unit area of gear influence. Miller (1975) quantified this parameter by calibrating trap catch of spider crabs *(Chionoecetes opilio)* against underwater photography. An experimental estimate of effective area fished was then obtained from $a = \frac{\text{catch/trap}}{\text{crab density}}$ of approximately 4100 m^2. While noting that this type of estimate may be affected by a number of factors such as soak time, response time, and proportion of population responding to bait (which latter may be expected to decline with distance approximately according to the inverse square law), it is interesting to note that the olfactory response threshold for *Homarus americanus* to freeze-dried cod extract (McLeese 1973) of 1×10^{-5} to 1×10^{-4} g/ℓ leads to a similar prediction for the order of magnitude of a. Assuming that 1 lb (453 g) bait of fresh fish may yield approximately 60% of its weight as "attractant", it will on dilution to 1×10^{-4} g/ℓ provide 1.824×10^3 m^3 of attractant. If we postulate a roughly laminar tidal flow and confinement of attractant dispersal to within 0.5 m of bottom, a similar order of magnitude for a is yielded as with Miller's calculations.

Nominal units of effort

Number of trap hauls and trap-days fished have both been advanced as units of effort in trap fisheries. Both measures may contain significant errors or biases as mortality indices, and this applies equally to less precise measures such as days on ground and number of trips.

Corrected effort units

Soak time. It is widely recognized (Sinoda 1970; Rothschild et al. 1970; Bennett and Brown 1976; Skud 1976) that trap catch does not increase linearly with time in the water, but increases towards an asymptote which may be expressed by the equation:

$$C_S = C_\infty\ (1-e^{-RS})$$ (Gulland 1955; Munro 1974)

where C_S is catch after S soak days reaching an asymptotic catch C_∞ at a rate determined by coefficient of capture R. Evidently, simple addition of trap hauls will underestimate total effective effort (f_{TOT}), if a significant proportion of traps are left longer than the standard soak time. For similar reasons, trap-days in the water will overestimate effective mortality if allowance is not made for declining fishing power with time over longer soak times. This type of bias is particularly serious, since longer soak times are likely to occur with higher effort and low biomass as fishermen use more gear, and also at high density and low effort when traps are more liable to be saturated even with short soak times. An adjustment for soak time can be made if parameters of the above equation are known by converting nominal effort to a common soak time T using:

$$f_{TOT} = \sum_{s} f_s \left[\frac{1-e^{-RS}}{1-e^{-RT}}\right]$$

<u>Corrections for environmental factors and behaviour</u>

It may be questioned whether corrections for these factors should be properly applied to the effort unit or to the catchability coefficient. In general, if the latter is to retain its usefulness as a parameter of the regression equation between effective effort and fishing mortality (ideally restricting variance in q to pure error), any good quantitative information available on the influence and magnitude of any factor on the effectiveness of the gear should be used to correct the effort unit. For example, if fishing power r_T is a linear function of temperature T (McLeese and Wilder 1958) in relation to some minimum temperature T_O at which fishing power is effectively zero:

$$r_T = r\ (T-T_O) \quad \text{where } r = \text{standard fishing power.}$$

Total fishing effort may then be given by:

$$f_{TOT} = r \sum_{T=T_O}^{T'} f_T (T-T_O)$$

where T' is the temperature at which the catchability ceases to be a linear function of temperature. If catchability is not linearly related to temperature, following Paloheimo (1963), effort may be adjusted for temperature-specific activity level by:

$$f_{TOT} = r \cdot \sum_{T} f_T \, (a_T - a_o)$$

if experimental data is available on the effect of temperature on feeding activity.

Corrections for catchability and gear selection

Variations in catchability have been traced by several authors to environmental and physiological conditions: e.g. temperature (T), salinity (S), and proportion in late moult stage (P) were demonstrated by Morgan (1974) from an experimental study to influence q by: $q = a + bT + cS - dP$ where a-d are linear regression parameters. Similarly, Paloheimo (1963) used results of McLeese and Wilder (1958) to relate catchability to temperature by: $q_T = q(T-T_0) = q'(a_T-a_o)$ (see previous section).

Trap selectivity evidently operates at both ends of the size spectrum: on small individuals (escapement through meshes or lathes), and on entry of large individuals (entrance hole diameter). Shape of entrance holes may determine species composition captured (Stasko 1975), as may special exit holes (Krouse and Thomas 1974; High 1976), both in actively fishing or 'lost' traps.

Physiological and behavioural considerations

Differential seasonal variations in q by sex have been observed for many crustacea (e.g. Hancock 1962), and in general, vulnerability to traps is seasonally highest in summer shortly following moulting, declining as the next moult is approached (Chittleborough 1975). Catchability may also show diurnal and tidal rhythms (Bennett 1974; Morgan 1974) and be influenced by mating (Hancock 1962), abundance of natural prey (Simpson 1975), intraspecific attractants (McLeese 1970), and avoidance (Hancock 1974). While it may be difficult to correct for some or all of these factors, they are likely to have the most serious impact on Delury estimates based on changes of catch per unit effort within a season (Hancock 1965); annual fishing effort may be relatively unaffected as long as the fishing seasons are relatively long in duration in relation to short-term effects.

SUMMARY

A review of existing literature relevant to fishing effort definition in invertebrate fisheries suggests that measurable units of fishing power and nominal fishing effort are available for most types of gear used in shellfish harvesting (e.g. FAO 1976). However, the main problem is in converting these into indices of fishing intensity which are additive for all fishing units and linear, density-independent measures of the fishing mortaltiy exerted by the gear. A number of factors

(behavioural, physiological, and distributional, as well as those relating to gear design and fishing strategy) have been identified as influencing effective fishing power and catchability, although in most cases their quantitative impact has not been elucidated.

The following general problem areas seem to call for further attention:

1) What is the nature and extent of density-dependent factors in existing measures of fishing effort, particularly for dredge and trap fisheries, and how can these be corrected for before applying the units in yield models to determine optimal levels of harvesting?

2) What is the relative significance of search time and handling time as components of fishing effort, and what should be the relative contribution of the two components as input to yield models?

3) What is the extent of indirect components of fishing mortality in those shellfish fisheries where discard mortality and gear damage are significant?

In relation to particular gear types:

4) An improved understanding and quantification of factors affecting fishing power in trap fisheries seems called for.

5) For those gear types where fishing has a significant impact on the habitat of shellfish (e.g. dredges, trawls), the effect of sustained level of fishing effort on the long-term production of the fishing grounds should be investigated.

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Table 1. Factors affecting fishing power, effort definition and catchability in invertebrate fisheries.

Gear fishing method	fishing power (r) = p x a Fishing efficiency (p)	Unit area of gear influence (a)	Nominal units of fishing effort (g)	Adjustments to obtain overall corrected effort (f)	Factors affecting catchability (q) and selectivity
hand gathering	[No. caught / No. in search area]	Area dug, raked or searched (per effort unit or time)	1) Number hrs, days searching, digging 2) No.dives/volume of breathing gases used (scuba) 3) No.divers, diggers	Individual fishing power	1) Type terrain, soil consistency, underwater visibility, amount of cover 2) Depth 3) Tine spacing, sieve size visual call point
dredge	unsaturated gear [No. caught / No. in path of gear] saturated gear [No. caught / Area of saturation x density]	Area swept = dredge width x towing distance (per unit operation or per time) [Dredge capacity / Volume material entering per unit area x fraction retained]	1) Hours dredges on bottom 2) No. tows 3) Days fished 4) Days on ground 5) Days out of port 6) No. trips 7) Fleet size, No dredges in fleet	1) Vessel fishing power 2) Density dependent corrections (e.g. sorting, handling time, dredge saturation)	1) Dredge width x No. dredges 2) Mesh size, tooth spacing, manual call point 3) Burrowing/swimming behaviour 4) Bottom type 5) Weather conditions
trawl	[No. caught / No. in path of gear]	Area (or volume) swept = effective trawl width x towing distance (per unit operation, or per time)	1) Hours trawl in water 2) No. tows or hauls 3) Days fished 4) Days on ground 5) Days from port 6) No. trips 7) Fleet size	1) Vessel fishing power 2) Multi-species effort correction	1) Effective trawl width 2) Mesh size, cull size 3) Availability changes (migration, trawl avoidance)
traps	[No. caught / No. detecting bait or trap]	[No. detecting bait or trap / population density] (during a standard soak time)	1) No. trap hauls 2) No. trap days fished 3) Days fished 4) Days from port 5) No. trips 6) Fleet size/No. traps in fleet (1 and 2 corrected for soak time)	1) Trap/vessel fishing power 2) Soak time, gear saturation 3) Environmental factors	1) Trap design, size 2) Mesh size, entrance diameter, escape holes, cull size 3 Bait 4. Physiological state (moult condition, activity) 5) Inter-intra-specific competition 6) Gear interreaction 7) Migration, seasonal availability changes