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INTERPRETATION OF LONGLINE HOOK RATES

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SUMMARY

The meaning of longline hook rate and the concepts of competition for hooks, hook saturation, and fish clumping are examined for systematic effects that might bias nominal hook rate. It is concluded that fish clumping is a likely effect that could reduce the catchability of the gear as population declines, biasing CPUE downward with respect to population size.

RESUME

La signification du taux d'hameçon de la palangre et les concepts de compétition des hameçons, la saturation d'hameçons et les aggrégations de poissons sont examinés pour étudier les effets systématiques qui peuvent biaiser le taux de capture par hameçon nominal. On en conclut que les aggrégations de poissons ont un effet probable qui puisse réduite la capturabilité de l'engin au fur et à mesure que la population diminue, biaisant la CPUE vers le bas par rapport à la taille de la population.

RESUMEN

Se examina el significado de la tasa de anzuelos de palangre, y los conceptos de competición por anzuelos, saturación de anzuelos y agregaciones de peces, para buscar los efectos sistemáticos que podrían sesgar la tasa de anzuelos nominal. Se concluye en que las agregaciones de peces causan un efecto que probablemente reduzca la capturabilidad del arte según disminuye la población, sesgando la CPUE en sentido descendente con respecto al tamaño de la población.

Introduction

Time series of longline catch rates often show a characteristic pattern. There is frequently an initial, short period of relatively rapid decline succeeded by a long period of slow decline. Can these features be due to systematic effects peculiar to the longline gear, recognizing that the gear fishes passively and that a hook becomes saturated upon catching a fish? Can loss of baited hooks during the increasingly longer intervals between encounters of targeted (target) fish, whose population is being reduced, produce a bias in the hook rates with respect to actual decrease in the exploited population?

In seeking to answer the above questions, the concepts describing random encounters of fish with hooks, as well as how schooling and other behavior might effect catch rates of longline sets, were reviewed. The interpretation of the longline hook rate and the concept of competition for hooks is described in some detail because of their conceptual importance. No particular data set or fishery is considered in this paper. Its purpose is to evaluate the likelihood that longline catch per unit effort may not be linearly related to population size.

Longline Hook Rates

The hook rate for a target species by tuna longline gear is traditionally expressed as catch per 100 or 1000 hooks. If the entire longline set consisting of a standard number of hooks, actual or prorated, is considered the unit of effort, the hook rate measures the CPUE that is a function of average population size and amount of sets deployed, as in the standard catch equation. As such, the standard longline set is a fishing gear with low catchability. It fishes for about 12 hours catching 40-50 target fish using about 2000 hooks (Au 1985). While longline fishing effort can be considered as a set, it is more natural to consider the individual hook as the unit of effort, because the number of hooks deployed is a variable readily altered in fishing tactics. Futhermore, if each hook acts independently, i.e., if fish schools encounter one hook at a time, the hook rate can be analytically dissected, based on the theory of random encounters. However, treating each hook as the unit of effort brings forth the difficulty that the fishing gear is imminently saturable, i.e., each hook can catch only one fish . Since the hooks are at least quasi-independent, the hook rate therefore tends to measure the fraction (f) of the hooks set that encountered schools (and caught fish), rather than measuring the local density (N) of fish, as catch/effort of non-saturable gear is considered to do. This fraction can be written:

$$f = 1 - e^{-\bar{N}}$$

where the exponential term is the probablity of not encountering fish whose local density $\bar{N}$ is low and which therefore encounter the hooks as a random, Poisson process. Eq. (1) shows that fish density $\bar{N}$ is logarithmically not linearly related to hook rate f.

The Catch Equation based Random Encounters With Hooks During a Set

The basic idea here is that the time rate of increase of target fish caught is proportional to the baited hooks remaining, plus a correction term to account for fish escaping after being caught. This is expressed by the differential equation (Murphy 1960):

$$dC/dt = bX - cC$$

where C = total fish caught up to soaking time t
X = baited hooks remaining
b,c = constants

whose solution is

$$C/H = \frac{b}{c-a-b}\left[e^{-(a+b)t} - e^{-ct}\right] \qquad (2)$$

where H = total hooks
a = instantaneous loss rate of baited hooks due to catching non-target spp., bait falling off, etc.
b = instantaneous hook rate of target sp. at a particular population density.
c = instantaneous rate of loss or escape of target fish already caught.
t = soak time of hooks.

Equation (2) is a function of time with a distribution skewed to the right. It is instructional to notice that such an expression is approximated by the lognormal function, fits a wide range of ecological frequency distributions, and can be considered to result from two processes simulataneously generating and modifying a distribution (Preston 1981). This equation has a maximum at some intermediate value of soaking time. The lower the instantaneous rate b and the higher the escape rate c, the lower will be the realized hook rate C/H and the more will the maximum be shifted to the right. Equation (2) may be rewritten, by multiplying the numerator and denominator by exp(ct):

$$C/H = \left[e^{-ct}\right]\left[\frac{b}{z-c}\left(1-e^{-(z-c)t}\right)\right]$$

where z = a+b

and it becomes apparent that

C/H = P(catching target sp.) x P(already caught fish not escaping).

It can be shown that when there are few competing "risks" to baited hooks, i.e. when a and c are relatively low, catches can be substantially increased by extending the soak time, as is to be expected. However, in longline operations, the maximum soak time is limited by the daily activity cycle of fishing and vessel operations, or perhaps by bait deterioration with time and behavior of fish. The soak time therefore is probably not a major variable and the hook rate can be treated as pertaining to a fixed time period.

The Parameter b and Population Density

The parameter b is the instantaneous hook rate for target fish, and it varies with population density $\bar{N}$. If a=c=0, Eq. (2) becomes for a unit soak time (cf. Gulland 1955 and Eq. (1))

$$C/H = 1 - e^{-b} \tag{3}$$

which is the probability of catching target fish given there are no other risks. Now b is the total risk coefficient affecting the H hooks due to the action of N target fish. Therefore

$$C/H = 1 - e^{-q_L N} \tag{4}$$

(see Beverton and Holt 1957; Cooke 1985) where q_L is the coefficient determining the degree to which N fish interact with H baited hooks, producing C and mean surviving hooks $\bar{H}$, just as q, the catchability coefficient in the classic catch equation determines the degree to which fishing effort produces catch and a resulting average population size. The two q's are similar but not the same: both have dimensions 1/(time x effort), where effort is due to hooks, etc., in the classic equation and to N fish in the longline equation. Both are proportional to area swept by the hunting fish or hook and the efficiency factor of the fish or hook. The difference is that q_L relates a given constant N (during the relatively short time of the set, N does not change) to the average remaining baited hooks $\bar{H}$, instead of a given constant fishing effort to average N (during the fishing year N does decrease in the classic equation), and that catch per hook, C/H, cannot be greater than one, i.e.

$$0 \leq C/H \leq 1.0$$

In search theory (Koopman 1979) q_L in Eq. (4) would be the instantaneous detection coefficient for N hunters searching randomly for H targets.

One way to see why b is proportional to density N is to note that

$$g(w) = \lambda e^{-\lambda w} ,$$

where w = waiting time for a fish encounter
λ= mean encounter rate,

is the probability density for waiting times between separate encounters that occur as a Poisson process (e.g., Hogg and Craig 1965, Hillier and Liebermann 1969). Then the probability of encountering fish during a soak time T is

$$\int_0^T \lambda e^{-\lambda w} dw = 1 - e^{-\lambda T}$$

as in Eq. (3), where now b = λ. Therefore, b is the mean number of encounters per unit time, which is proportional to fish density N. Finally, notice that the mean time interval between encounters is inversely related to density:

$$\bar{W} = \int_0^\infty w \lambda e^{-\lambda w} dw = 1/\lambda .$$

Effect of Parameter Values

The effects of changing the parameters of Eq. (2) on target fish hook rates can be shown as a response surface representing hook rates as a function of different levels of bt, the instantaneous hook rate for target fish, and of exp [-(a+b)t], the first term within the parentheses of Eq. (2) (see Fig. 1). This term is labeled Q_0, and is the probability of a hook not catching any fish.

Figure 1 shows the response surface of target fish hook rate, C/H, described by Eq. (2), for exp(-c) = 0.50, i.e., with 50% loss rate of target fish as an example, and for a unit soak time (t = 1). The isopleths shown are in percentage units, i.e., target fish caught per 100 hooks set. The range of b is restricted by the level of Q_0, which is a function of a+b, hence the triangular boundary of the overall response surface. Response surfaces for other levels of the loss parameter c are similar in shape but higher in values as c decreases. They are not shown.

Notice that as b decreases (target population decreases), the isopleths of C/H decrease and rapidly become vertically oriented within the graph, especially at high levels of Q_0. The trajectory followed by a longline fishery on the response surface should incline toward the lower left, because as b decreases with declining population size, Q_0, the percent of empty hooks, should increase (Q_0 increase top to bottom on graph). Longline sets in established fisheries typically have target fish hook rates of less than 5% and Q_0 of more than 90%, so the lower left corner area of Fig. 1 is pertinent. There the isopleths are virtually vertical. The characteristic slow rates of decrease in hook rate seen in longline fisheries therefore suggests that the trajectory of a fishery on the response surface tends to follow the isopleths, which means there must be a rapid increase in Q_0. Such an increase can occur if the hook rate of competing, non-target fish also decreases with that of target fish, i.e., if longline fishing significantly affects the non-target population too. Then the hook rate of target fish described by Eq. (2) must also be affected by changing parameters other than that due to the decreasing target population. However, c, the target fish loss rate is likely constant as it should not be affected by population size.

Adjusting for Competing Risks

While it was alluded above that competition for hooks was not likely important in longline fisheries, that may not always be so, especially in the initial stages of those fisheries. The theory for adjusting for these and other risks is therefore reviewed next, ultimately so that hook rate may be related to population size through Eq. (4). This theory follows that of Rothschild (1967), but differs in that the probability of fish escaping is also considered.

Baited hooks may be taken by non-target species, or the bait may deteriorate or come off. These other sources of loss, measured by the parameter a in Eq. (2), compete with the target fish for the baited hooks. Figure 1 shows three possible trajectories of fisheries on the response surface operating under different conditions of changes in parameter a. The initial point of the trajectories starts arbitrarily at b = 0.8, Q_0 = 0.20. If the initial point was located in the lower left corner, e.g., at b = 0.2, Q_0 = 0.80, the different trajectories would be similar, though more tightly clumped together. If parameter a were zero, the trajectories would follow the right margin of the response surface. The trajectory patterns illustrate the fact that the more parameter a decreases (competing risks decrease) with decrease in parameter b (target population decrease), the more is the trajectory increasingly inclined downward to the left, in the direction of the isopleth trends. Hook rates would then decrease slowly. Changing values of parameter a during the course of a fishery means that a series of target fish hook rates are not comparable unless the effects of parameter a are normalized or eliminated.

Removing competing risks can be done mathematically. The theory is clearly explained by Neyman (1950). He considered the case where at the end of M time stanzas (M=1,2,...,M) an individual (here, a hook) will be in one of four states (here, applied to the catching of fish):

$S_0(M)$ = hook untouched - no fish caught
$S_1(M)$ = hook has caught a non-target species or hook has become non-functional because of bait falling off, etc.
$S_2(M)$ = hook has caught a target species
$S_3(M)$ = hook had caught a target species which has since escaped or otherwise been lost.

The probabilities of transition from states S_0 to S_0 is q_{00}, from S_0 to S_1 is q_{01}, and from S_0 to S_2 is q_{02}, where $q_{00} + q_{01} + q_{02} = 1.0$. The transition probabilities from S_2 to S_2 = q_{22}, and from S_2 to S_3 is q_{23}, where $q_{22} + q_{23} = 1.0$. Also, once S_1 or S_3 is attained, the hook stays in that state, i.e., $q_{11} = q_{33} = 1.0$. This scheme of transfer between states S_i and the transition probabilities are shown in Fig. 2.

Thus the hooks can transfer from S_0 to S_1 or S_2, with transition probabilities q_{01} or q_{02}, but not to S_3. S_3 can only be transferred from S_2, with probability q_{23}. Once a hook transfers to S_1 or S_3, it remains in that state. The probability that at the end of M time instants the hook will have caught a target fish [state = $S_2(M)$] is:

$$\begin{aligned} P[S_2(M)] = {} & [S_2(1) \cap S_2(2) \cap \ldots \cap S_2(M)] \cup \\ & [S_0(1) \cap S_2(2) \cap \ldots \cap S_2(M)] \cup \ldots \cup \\ & [S_0(1) \cap S_0(2) \cap \ldots \cap S_0(M-1) \cap S_2(M)] \end{aligned} \qquad (5)$$

because once S_2 occurs, it must not subsequently succumb to S_3 in order that S_2 be the outcome. Now $P[S_2(M)] = Q_2$ = crude (unadjusted) rate of risk from target fish, which, in a set of hooks encountering fish and other risks as a Poisson process with each hook acting independently, is simply (catch of target fish)/(hooks fished). From (5)

$$Q_2 = q_{02}(1 - q_{23})^{M-1} + (1 - q_{01} - q_{02})q_{02}(1 - q_{23})^{M-2} + \ldots$$
$$+ (1 - q_{01} - q_{02})^{M-1} q_{02}$$

which, after algebraic manipulation, becomes

$$Q_2 = \frac{q_{02}}{q_{01} + q_{02} - q_{23}} (1 - q_{23})^M - (1 - q_{01} - q_{02})^M \qquad (6)$$

Other crude rates Q_i can be derived:

$$\begin{aligned} Q_0 = (1 - q_{01} - q_{o2}) &= \text{P(hooks remain untouched)} \\ &= \text{(untouched hooks)/(hooks fished)} \end{aligned} \qquad (7)$$

$$\begin{aligned} Q_1 = \frac{q_{01}}{q_{01} + q_{02}}(1 - Q_0) &= \text{P(hook is taken by a competing sp. or effect)} \\ &= \text{(hooks taken by other spp. etc.)/(hooks fished).} \end{aligned}$$

$$Q_3 = \text{(hooks with escaped or lost target fish)/(hooks fished).}$$

Neyman also defined the net (adjusted) rates of risk P_{ij}:

$$P_{01} = 1 - (1 - q_{01})^M = P(\text{hook will have caught a non target spp. or otherwise become non-functional} \mid \text{all other risks are eliminated})$$

$$P_{02} = 1 - (1 - q_{02})^M = P(\text{hook will have caught a target sp.} \mid \text{all other risks are eliminated}) \tag{8}$$

$$P_{23} = 1 - (1 - q_{23})^M = P(\text{caught target fish will have escaped or otherwise been lost} \mid \text{all other risks are eliminated}),$$

i.e., P_{ij} is the probability a hook initially in state S_i will be in state S_j at the end of M time intervals, under the artificial conditions where all other risks are eliminated. The "elimination" is accomplished because in the expression for P_{ij} the term $(1 - q_{ij})^M$ is always the probability of escaping the risk of transfer from state S_i to S_j, regardless of other risks present or not. Rothschild (1967) recognized that this elimination effectively adjusted for competition for hooks due to presence of other than target fish. Combining Eq. (6), (7), and (8), Q_2 may be written

$$Q_2 = \frac{q_{02}}{q_{01} + q_{02} - q_{23}} (1 - Q_0 - P_{23}). \tag{9}$$

If $q_{23} = 0$, $P_{23} = 0$, i.e., there is no risk that target fish caught might later escape or be lost. Then Eq. (9) becomes Eq. (7) of Rothschild (1967). Extending the above for the continuous case by letting M become large so that each time interval is very short, and putting $\lambda_i = q_{ij} M$

where the q_{ij}'s are now the instantaneous transition probabilities and λ_i's are constants (= total transition probabilities), Eq. (8) and (9) become

$$P_{02} = 1 - e^{-\lambda 2} \tag{8'}$$

$$Q_2 = \frac{\lambda_2}{\lambda_1 + \lambda_2 - \lambda_3} \left[e^{-(\lambda_1 + \lambda_2)} - e^{-\lambda_3} \right] \tag{9'}$$

where Eq. (9') is exactly equivalent to Murphy's (1960) Eq. (2). Neyman further showed that P_{ij} could be expressed in terms of Q_{ij}:

$$P_{02} = 1 - Q_0^{\frac{Q_2 + Q_3}{1 - Q_0}} \tag{10}$$

which is P(hook will have caught a target fish in the artificial case where all other risks are eliminated),

in terms of Q_0, Q_2, and Q_3 the crude rates of risk (= the relative frequency of empty hooks, of target species caught, and of target species escaped). Notice that if $Q_3 = 0$, Eq. (10) is the expression given by Rothschild (1967).

Calculating P_{02} from Q_i's adjusts for hook competition that is potentially biasing; this adjusted hook rate is always higher than the crude or nominal hook rate, becoming more so when Q_0, the fraction of unused hooks, is low, i.e., when hook competition is strong. However, as Rothschild noted, the correction for hook competition is always small when the overall hook rate is small, which is the typical case for oceanic longline fisheries. Moreover, when hook rates are small, say under 20%, the relationship of C/H to population size [Eq. (4)] is nearly linear, thus obviating the need to linearize that relationship by a transformation.

Behavioral Factors

The above considerations result from the theory of random encounters without regard to behavior. In view of the typically low hook rates of longline sets, sytematic biases would more likely be due to fish behavior that changes with population size.

Consider first the possibility of a reduced likelihood of fish biting a baited hook when the population is reduced, and the schools are fewer and smaller. In a reduced population, individual fish might be better fed and less likely attracted to unnatural bait. Pelagic fish schools are probably not socially organized; when food is encountered, individuals likely "scramble" for that food. Each fish would be compelled to take food quickly, when it first becomes available. In smaller, better fed schools, individuals might very well be more cautious.

Related to the above is the effect of schooling. Paloheimo and Dickie (1964) sketched an example showing the usual asymptotic relationship between catch per search time and prey population density with finite fishing or handling time per school; they concluded it may be impossible to distinguish between abundance and schooling changes, and that the latter may have the greater effect. The evidence is that fish form schools to better detect and intercommunicate the presence of food or predators (Partridge et al. 1980). School reforming is therefore likely, and for any level of food density, which may be affected by population density, there may be a minimum school size that is formed. As the exploited population declines, we would expect both fewer schools and an altered distribution of school sizes. Larger schools would decrease in size from attrition, and smaller schools that were reduced to below minimum size would reform into intermediate sized schools. If this also resulted in more clumped schools, hook rates would both be lowered and more variable. Hook rate would be lowered because clumping or schooling immediately lowers the average density of "targets" from N to N/S where S is the average school size. If school reforming caused average school size to increase, the probability of encountering a school, from Eq. (4), could drop rapidly with N; essentially q_1, the catchability, would reduce to q_1/S in Eq (4). If furthermore, the schools become more clumped in space as N decreases, the variability of hook rate would be expected to increase so that the variance would be much larger than the mean. If the large clumps, when encountered, saturate the few, widely separated hooks they intercept, the overall hook rate would remain low. In contrast Cooke (1985) discussed the possibility of catchability coefficients having a positively skewed probability distribution with variance constant with N. The result was catch rates that underestimated declines in density because of increasing catchability as N decreased. Greater clumping of the surviving schools and longline sets encountering fewer schools on average and thus taking a smaller fraction of the population would seem more likely.

Discussion

In the above review it was shown that competing risks to the baited hooks of a longline set, such as that due to the catching of non-target species, could alter the relationship of CPUE to target fish population size. In particular, if the population of competing species is also reduced by the fishing effort, the CPUE of the target species might then decrease only slowly with decline in target species population. However, when the hook rate is low, as it is in most longline fisheries, the correction for this effect must be small. Another competing risk is the effect of bait deteriorating or falling off. This risk, however, is likely to be constant, not changing with size of the exploited population. As long as fish are caught randomly, there should not be a systematic effect resulting from bait condition. Finally, while the non-linear relationship between CPUE and population size N expressed by Eq. (4) should be used, that relationship is nearly linear anyway, when hook rates are low (Fig. 3). It seems more likely that increased clumping of schools is a possible mechanism that could reduce the efficiency of longling gear. The reasoning presented is simply the inverse of the often offered argument that concentration of a declining population into fewer and fewer schools that fishermen are able to more easily locate increases the catchability of a unit of fishing effort. When populations can be estimated, along with CPUE rates, this increase in catchability does seem to occur (Peterman and Steer 1981, Bannerot and Austin 1983). However, if fishermen are not able to track the concentrated schools, and effort continues to be applied randomly, as is approximately the situation in most oceanic longline fisheries, average gear catchability should decrease by the same argument, because many gear sets will fish where schools are unlikely to occur and because a short section of a longline set can never catch more than a few fish from a clump. This of course is the logic behind schooling, clumping, or convoying by prey as a strategy against predators. The predator encounters less prey per unit search time; when it does encounter a large school, it is quickly saturated (Brock and Riffenburg 1960, Olson 1964). This can happen even if the probability of taking a prey from a clump increases as prey clumping increases (Taylor 1976). The benefit from schooling tends to be greatest when schools are large (e.g. when populations are large), because though the schools may be more easily detected, the fishing gear also takes a smaller proportion of the fish within the schools (Olson 1964). The catchability of longline sets chould therefore decrease with population density until the schools are too scattered for effective reforming; thereafter, the smaller schools would tend to behave like randomly encountered individuals with constant catchability.

There can be little doubt that pelagic fish schools do reform after being reduced by fishing, and that the schools do not simply become more thinly dispersed as their population decreases. Reforming and concentrating behavior should decrease the average catchability of randomly fishing longline sets, but whether the effect is strong or systematic enough to offset the tactics of not so random, actual longline fishing is the question. Conceptually this could be determined by comparing longline catch rates with a long time series of relative population size estimates obtained by random survey, using non-saturable fishing gear.

More realistically, estimates of relative population sizes will not be forthcoming except from CPUE data. If the latter are used to infer relative population size, the possibility of a non linear relationship should be acknowledged. The relationship may be empirical, of the form

$$\text{CPUE} = aN^{f(N)}$$

where both CPUE and N are normalized to vary between 0 and 1.0, and a is a constant. The exponent f(N) reflects the biasing of catchability upward or downward as a function of population size. If catchability increases with decreasing N, f(N) is less than 1.0. If catchability decreases with decreasing N, f(N) is greater than 1.0; the latter should hold for longline sets fishing randomly on a population continuously reforming and clumping. The hypothetical fishery trajectories drawn in Figure 3 illustrate a family of such relationships with f(N) increasing linearly with N: $f(N)=1+cN$, where the constant $c \geq 0$. This linear increase describes a population whose catchability tends to decrease continuously with population decrease because of reforming and clumping of schools. At the same time , however, this effect is being countered by an increasing tendancy of the school distribution to appear random in space as school density decreases, because catch rates of low density populations are inherently less variable and less affected by the non-Poisson components of variation (Cassie 1962). Therefore, the reduced catchability settles toward a constant value and the CPUE approaches the origin of the graph at a constant angle.

While it will probably be difficult to demonstrate any of the effects discussed above, the possibility that longline hook rates are biased with respect to poupulation size should be recognized. Returning to the questions posed in the Introduction, low hook rates would appear to mitigate against development of most systematic biases. The longer time intervals between fish encounters in reduced populations that allow more time for bait deterioration should not cause a bias provided the encounters continue to be random. Clumping of schools could reduce gear catchability, causing understimates of population relative size (CPUE), wrong inferences about population trends, and underestimates of population production.

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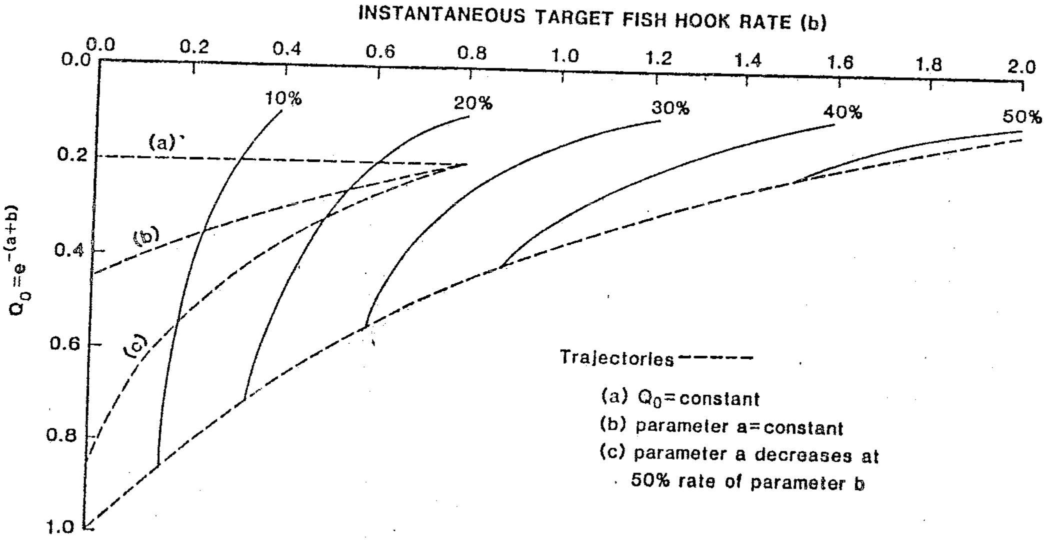
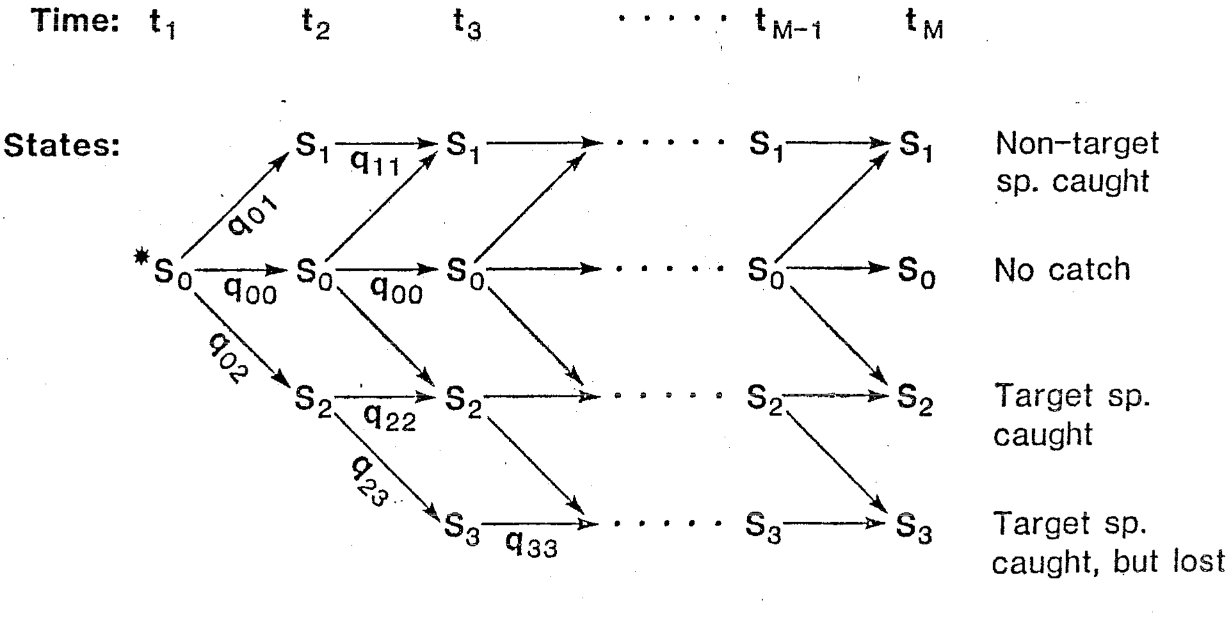


Figure 1.

Hook rate (C/H) from Eq. (2) as a function of b, the instantaneous hook rate of target fish, and of Q_0, the proportion of untouched hooks on the longline set. Isopleths are the C/H hook rates expressed as percents. Exp (-c) in Eq. (2) is set at 50%; the paths of three possible fisheries, responding differently with respect to changes in parameter a as parameter b, or target population, declines, is shown.



*Initial state is the untouched, baited hook

Figure 2

Scheme of competing risks, each of which has probability q_{ij}, which if met, results in the transfer from one state S to another. Each state represents a condition of the hook with respect to its catch.

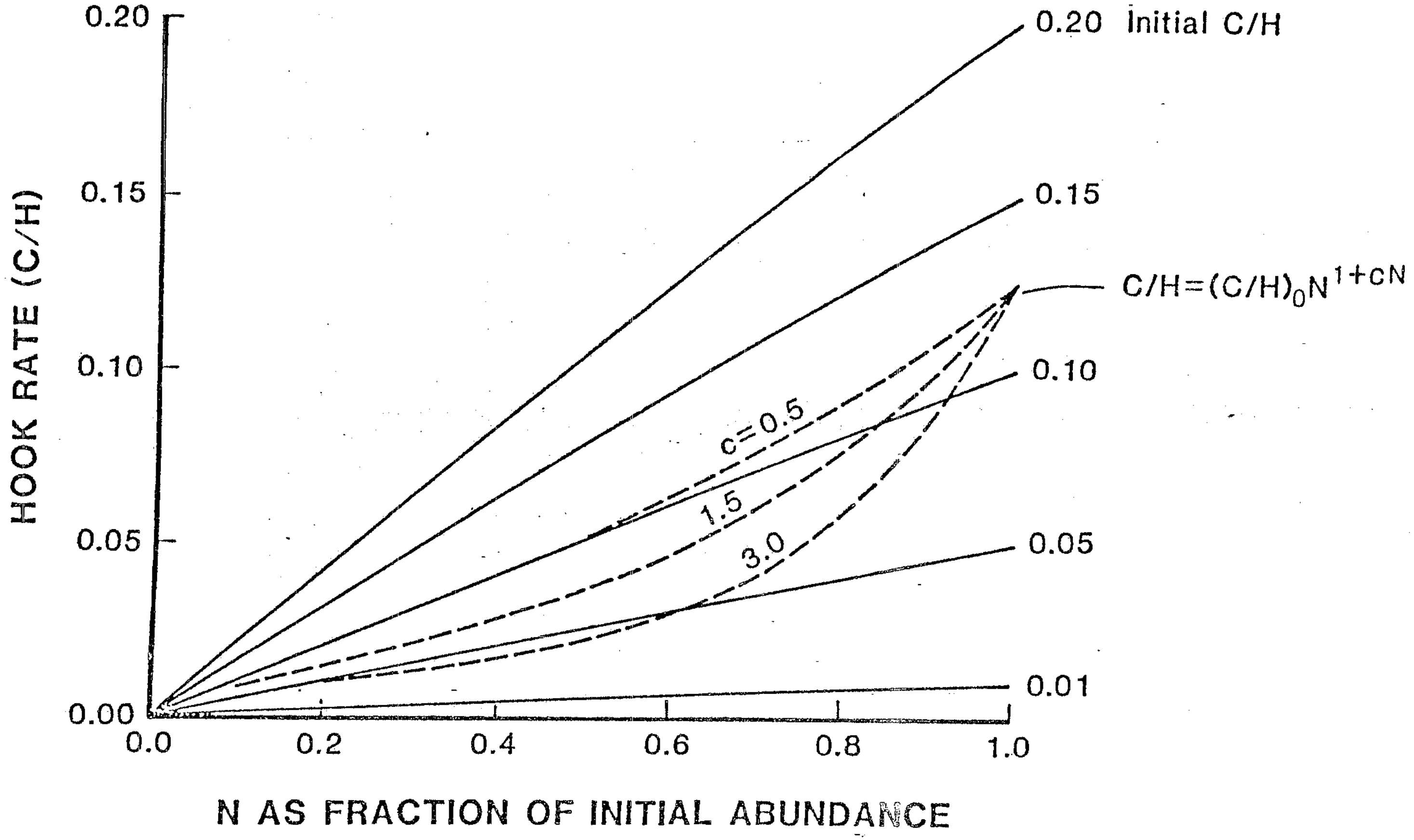


Figure 3

When catch rates (C/H) are low, the relationship of C/H with population density N is nearly linear (diagonal appearing lines). The curves represent a possible family of relationships when catchability decreases with decreasing N.