

DENSITY-DEPENDENT SEARCHING TIME: IMPLICATIONS IN SURPLUS-PRODUCTION MODELS¹

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ABSTRACT

An initial theoretical consideration is presented to show how density-dependent searching time can be incorporated into surplus-production models of fisheries. A simple simulation is used to demonstrate the management implications associated with failure to account for this parameter in fisheries where handling time reduces the total time initially available for searching.

The failure to measure density-dependent searching time in assessing fishing effort can lead to erroneous conclusions concerning the collapse of a fishery. In this paper, I will develop my argument using two simple models: Graham's equilibrium yield model (Graham 1935; Ricker 1975) and Holling's (1959b) "disk" equation. I will conclude by drawing parallels between this simple theoretical treatment and patterns that have been observed in searching fisheries.

DEVELOPMENT OF THE MODEL

I begin with the normal definition of the instantaneous rate of fishing mortality, F , as

$$F = q \cdot f = C/N \quad (1)$$

where q is the instantaneous catchability coefficient and is the proportion of the stock (N) that is caught (C) by one unit of fishing effort (f); this fishing effort (f) is the total gear in use for a specific time (Ricker 1975). Following the example of Beddington (1979) and Fowler (1980), I depart from the normal treatment of f , by considering

$$f = f' \cdot t'_s \quad (2)$$

where f' is a physical measure of the total fishing gear in use and t'_s is the proportion of the total fishing time (t') which is available for and used in searching.

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If searching time is a constant, independent of stock abundance N , then a linear relationship is normally expected between C/f' (or C/f) and N up to some theoretical limit, as in a Holling (1959a) Type I curve (Fig. 1A) or in the Palohemio and Dickie (1964) model.

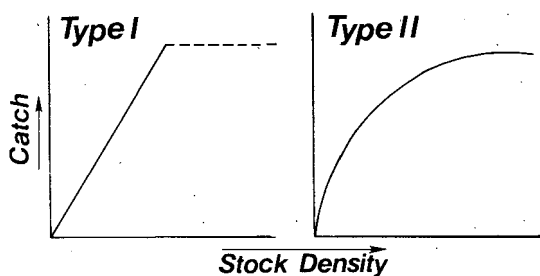


FIGURE 1.—Two types of functional responses of catch to stock density, after Holling (1959a).

If, however, fishermen must expend a substantial amount of time in harvesting the catch once it is sighted, this handling time (t'_h) will reduce the time initially available for searching (e.g., Guland 1956, 1964; Rothschild and Suda 1977). Holling (1959b) describes one such dependence of t'_s on N as

$$t'_s = t' - t'_h (C/f'). \quad (3)$$

Equation (3) describes a curvilinear decline in C/f' with increasing stock abundance (Fig. 1B). Substituting Equation (3) into Equation (2) into Equation (1), we obtain

$$F = q \cdot f' \cdot (t' - t'_h \cdot C/f'), \quad (4)$$

which can be arranged to

$$1 = \frac{q \cdot f' \cdot t'}{F} - \frac{q \cdot f' \cdot t'_h (C/f')}{C/N}$$

$$F = \frac{q \cdot f' \cdot t'}{1 + q \cdot t'_h \cdot N}$$

Inserting this definition of F as a substitute in Graham's equilibrium yield model, then

$$Y_e = B_e \cdot F_e = k \cdot B_e \cdot (B_x - B_e)/B_x$$

$$= B_e \cdot q \cdot t' \cdot f' / (1 + q \cdot t'_h \cdot B_e) \quad (5)$$

where B_x is the maximum stock biomass, k is the instantaneous rate of increase of the stock as density approaches zero, B_e is the stock mass at an equilibrium position, Y_e is the equilibrium yield, and F_e is the fishing mortality rate which maintains the stock at B_e (Ricker 1975).

As expected a plot of Y_e against B_e or F_e will yield a symmetrical hyperbola, Figure 2A; a plot of q against B_e will denote that q is a constant regardless of the relative magnitude of t'_h to t' . This is not the case, however, if we ignore the effect that stock density has on searching time. For example, a plot of Y_e against $f' \cdot t'$ results in an asymmetrical hyperbola skewed to the right, Figure 2B. The distortion increases as the ratio t'_h/t' approaches 1 and is a result of the increased time the fleet must spend searching for fish as population biomass approaches zero, Figure 2C. Additionally, if searching time is assumed to be independent of stock abundance, q will be incorrectly measured as $q/(1 + q \cdot t'_h \cdot B_e)$ and will appear to be inversely related to population density, Figure 2D.

Note that when $t'_h > 0$, $f' \cdot t'$ will not peak at $B_e = 0$ (for the situation described in Equation (5)). Instead, it will peak at some intermediate level of B_e and will then decline, Figure 2E. Thus, even for the hypothetical equilibrium fishery, $f' \cdot t'$ would have to "voluntarily" decline from a maximum level as B_e approaches zero.

DISCUSSION

The assumptions inherent in Equation (5) limit its direct application as a qualitative model of existing fisheries. However, the general behavior described in Figure 2B, D has been noted in several recent papers (Fox 1974; Pope and Garrod 1975; Schaaf 1975b; MacCall 1976; Ultang 1976; Garrod 1977; Peterman 1980; Peterman and Steer 1981; Bannerot and Austin 1983). Two important

examples occur with the Pacific sardine and Atlantic menhaden fisheries.

In their analysis of the available catch and effort data on the California based fishery on Pacific sardine, Fox (1974) and MacCall (1976) were forced to relax the usual restriction of a constant catchability coefficient which is independent of population size. Rather, they applied a density-dependent catchability coefficient of the form

$$q = \alpha N^\beta \quad (6)$$

where α and β are constants, assuming a constant catch per unit effort. The general patterns predicted by these analyses are similar to those in Figure 2B, D, with MacCall noting an inverse relationship between the apparent q and population abundance, and Fox noting a collapse of the fishery in plots of catch versus vessel-months, Figure 3. Both of these patterns may be the result of an inability to describe mathematically how the time available for searching increased as the population of sardines declined.

It is generally assumed that Atlantic menhaden have been overfished since the early sixties. Support for this conclusion was derived from the surplus-production work of Schaaf and Huntsman (1972), later updated by Schaaf (1975a). In both studies the available effort index (vessel-weeks) was modified in an attempt to correct for changes in fishing efficiency with time. Under the assumption of a constant q and lacking detailed information on vessel characteristics and catch, the authors adjusted effort by "multiplying the effort observed in each year by the relative change in q ", using either 1965 (Schaaf and Huntsman) or 1971 (Schaaf 1975a) as a base year. The resulting pattern (Fig. 4A) strongly suggests that the fishery was operating on the descending arm of the catch-effort curve.

In another paper, Schaaf (1975b) observed an inverse relationship between his estimates of catchability coefficient and the population density, generating a pattern, like MacCall's (1976), similar to Figure 2D and at least partially explained by the lack of information on density-dependent searching time. However, Schaaf's apparent density-dependent estimate of q violates his early assumption of a constant q for use in standardizing the available effort data. The point is not trivial. Without this adjustment, the available effort data suggest that the Atlantic menhaden fishery is operating on the ascending arm of the catch-effort curve, Figure 4B.

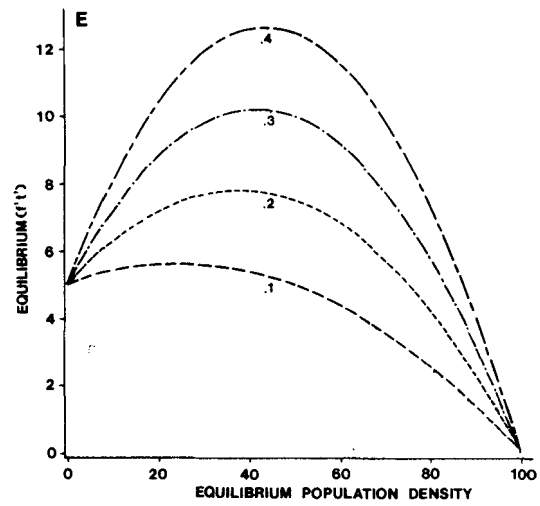
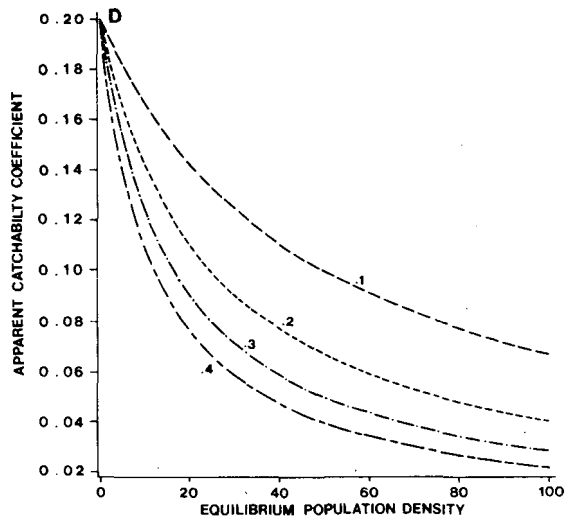
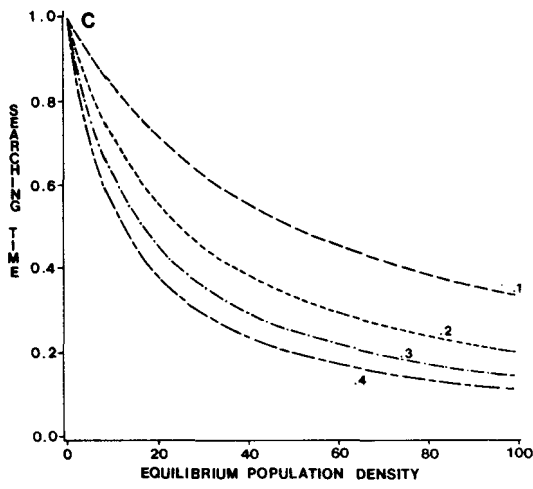
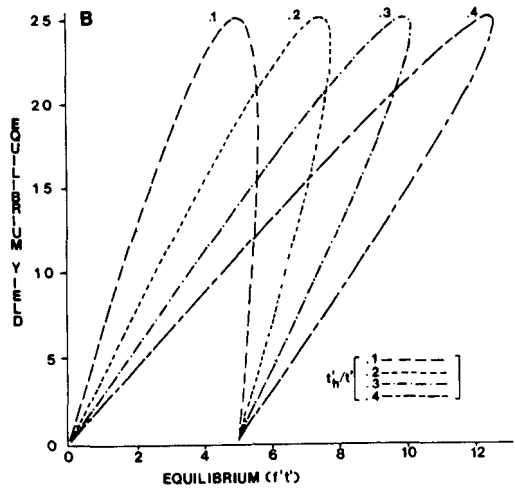
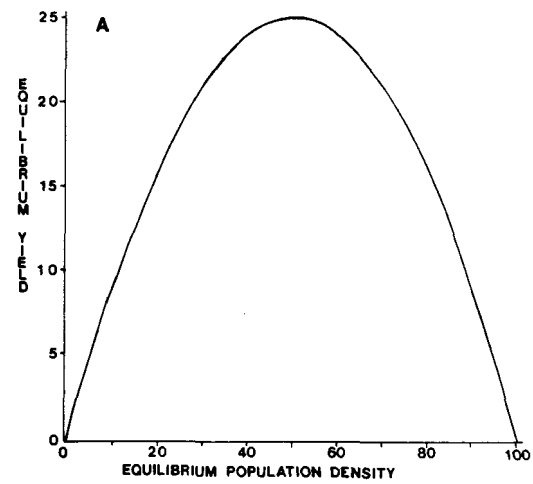


FIGURE 2.—Effect of variation in the ratio of handling time (t'_h) to total fishing time (t') on the relationship between (A) equilibrium yield, Y_e , and the equilibrium biomass of the stock, B_e ; (B) Y_e and the product of t' and equilibrium fishing gear; (C) searching time and B_e ; (D) catchability incorrectly estimated as $q/(1 + q \cdot t' \cdot B_e)$ and B_e ; and (E) equilibrium $f' \cdot t'$ and B_e . The model used is Equation (5) where $B_\infty = 100$, $k = 1$, and $q = .2$.

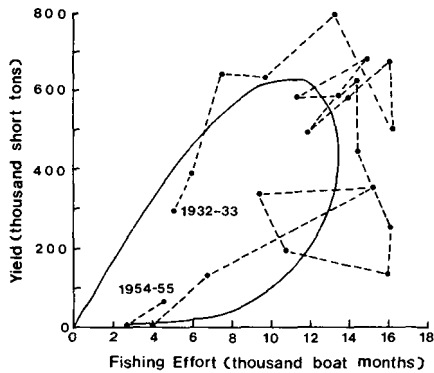


FIGURE 3.—Catch versus a nominal effort index for the California Pacific sardine fishery (after Fox 1974).

IMPLICATIONS

In this simple treatment, I have shown how some available estimates of fishing effort are inadequate to describe a fishery where searching time is stock-density dependent. More realistic models can be based upon an examination of detailed log-book data for inferences as to the relationships between searching time, stock abundance, prey and fleet distribution, and cooperation among the fleet. Hassel (1978) offers a comprehensive review of current approaches.

Even with better estimates of fishing effort a catastrophic collapse may be unavoidable because of parameters that cannot be measured or controlled (e.g., Clark and Manguel 1979). These estimates are important, however, in order to use surplus-production models for estimating the causes of such catastrophic collapses as that of the Pacific sardine fishery. Such estimates may also be necessary to suggest whether existing fisheries such as the Atlantic menhaden are actually being overfished.

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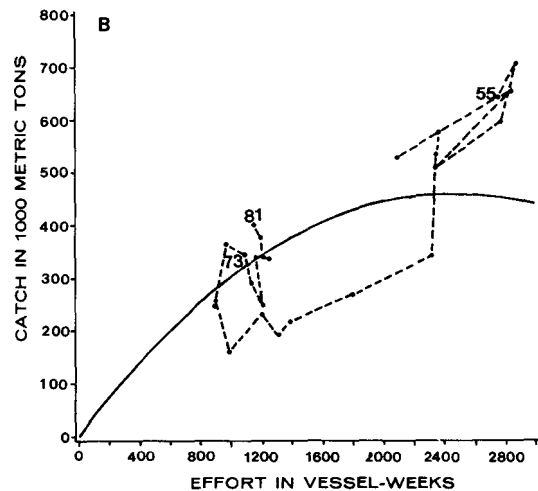
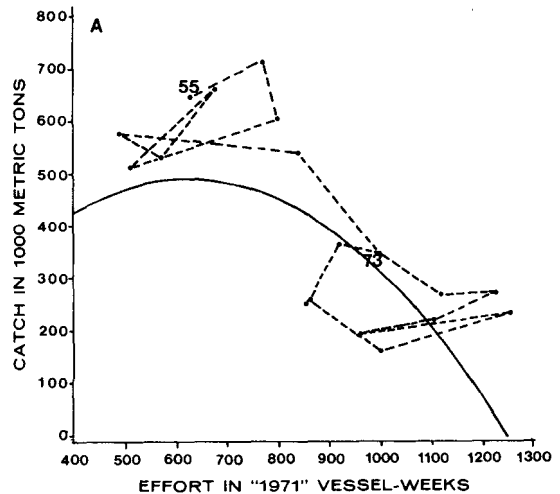


FIGURE 4.—Comparing the difference between fitting catch data for Atlantic menhaden when the effort is measured as (A) Schaa's (1975a) 1971-vessel weeks and (B) vessel weeks. Curves were fit after the technique of Marchesseault et al. (1976).

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