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Dynamic Models of Technological Interaction:
Man as a Prudent Predator

by

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Abstract

The regulation of complex, multifishery systems will increasingly require that we make accurate predictions of where and when fishing effort will be allocated. Effort allocation decisions by fishermen are the result of a complex set of rules governed by economic considerations, the regulations in force, and to a certain degree, the habitual patterns of fishing. Depending on the relative strength of these factors, fishing effort allocation may either be proportional to resource abundance or disproportional. Classical predator/prey theory is used to describe situations wherein effort (1) increases disproportionately with increased resource abundance, (2) decreases disproportionately with abundance, or (3) remains proportional. The weighting of landings by value (=revenue) offers a clear analogy to optimal foraging theory. Existing models of fishery effort allocation are reviewed, and alternative models are proposed. The ideal outcome of dynamic effort allocation modeling would be a probability distribution of the numbers of vessels, by métier, likely to be engaged in various alternative fisheries. Data necessary to validate candidate models can only come from time series observations of individual vessels or fleets of vessels with very similar characteristics.

Introduction

The assessment and prediction of multispecies/multifleet fishery effects has evolved from a static approach, based on fixed effort distribution patterns by métier, to dynamic models based on feedback control (McGlade and Allen 1984; Allen and McGlade 1986a; b; Laurec et al. 1991; Laloë and Samba 1991). The increasing sophistication of techniques for predicting where and how effort will be allocated is necessary given the increasing flexibility exhibited by multi-purpose fleets, and the large increases in harvesting capacity in many areas of the world. In open access fisheries, such as those off the east coast of the United States, increases in total effort have occurred despite significant declines in resource abundance and yields (Figure 1). Traditional fisheries theory would predict an exit of effort from fisheries such as those off the eastern United States. That the severe declines in CPUE and total landings have not stimulated effort to exit the fishery is attributed in part to lack of attractive alternatives, and to the fact that the profitability of the fisheries has not declined as fast as resource abundance. Lack of landings (supply) have been compensated for by steep increases in the prices paid for traditional species such as groundfish, and particularly for flounders (Murawski et al. 1991).

A scenario of increasing (depensatory) fishing mortality with declining resource abundance is potentially destabilizing to the population, and may ultimately exacerbate a fishery collapse. Much literature and some recent empirical evidence is available from the ecological literature on the nature of the relationship between prey abundance and predation mortality (Holling 1959; Murdoch 1969; Chesson 1984; Anonymous 1992). This paper explores the functional response of fishing fleets to changes in resource abundance, profitability, and the allocation of fishing effort to alternative métiers. Parallels to predator/prey models are drawn, and the use of optimal foraging theory as a context in which to view effort allocation is proposed. Data sets and analyses necessary to validate candidate functional responses of effort to resource conditions are considered.

Functional Responses in Predator/Prey Systems

The 'functional' responses of predators to prey abundance have been developed to measure the per capita consumption (or predation mortality) as a function of the size of both the predator and prey populations (Holling 1959; 1965; 1973; Hildén 1988). For a given population size of predators, the predation mortality can be characterized as an increasing, decreasing or constant function of prey population size. A type II functional response implies a declining predation mortality rate with increased prey density (and vice-versa), while in a type III response predation mortality is a dome-shaped function of prey population size. All types of models and their variants have significant implications for the population dynamics of both predators and prey (Hildén 1988). A type II response can be attributed to a fixed number of predators continuing to extract most of their diet from a single prey species. Thus, predation mortality rates rise while population density declines. At some point

the predation mortality becomes extremely destabilizing to the prey population, and it collapses. The predator population must then seek alternative prey. Type III models can exhibit dependant mortalities similar to, or greater than those exhibited for type II functional forms, depending on the steepness of the right-hand tail of the curve (Hildén 1988).

It is unusual, however, for a predator to have but one prey species. Rather, a 'prudent' predator exhibits some degree of switching among prey items, as a function of the relative availability of various diet items. Numerous authors have explored the implications of switching among prey items by a predator, on the dynamics of the prey resources (Murdoch 1969; Oaten and Murdoch 1975; Chesson 1978; 1983, Chesson 1984; Anonymous 1992). Switching is technically defined as follows: for an individual predator, the mean rates of consumption of two prey items are X_1 and X_2 , and the densities of the prey are H_1 and H_2 (Chesson 1984). Murdoch and Oaten (1975) define ('positive') switching by the relationships between the ratios of consumption to abundance:

$$c = (X_1/X_2)/(H_1/H_2).$$

If c is an increasing function of the ratio of densities of H_1/H_2 , then positive switching to species 1 is said to occur. Conversely, then, negative switching from species 1 is said to occur when c is a decreasing function of H_1/H_2 . It should be emphasized that switching does not occur just because the ratios of the two prey change in the diet. It is the change in diet relative to the change in density that determines the magnitude and direction of switching.

Negative switching is thus characterized as prey under-representation in the diet at high stock levels, while positive switching in prey over-representation at high prey stock sizes.

The implications of both positive and negative switching on the stability of prey populations have been considered (Oaten and Murdoch 1975; Chesson 1984). It is believed that positive switching acts to stabilize populations (by removing proportionally more from the prey stock when super-abundant, and conversely less when at low levels). Negative switching (as with type II and some type III functional response models) is potentially destabilizing to the populations, since predators are swamped at high prey stock size, and predation mortality increases greatly at low prey stock abundance (Chesson 1984). Chesson (1984) argued that if prey preferences vary between individual predators but the preference of an individual does not change with prey density then aggregate preference of a population of predators can change with prey density. Recent analyses of fish population predation in the North Sea suggest that a weak negative switching model fit empirical stomach content data better than a neutral or positive switching option (Anonymous 1992, work conducted by H. Gislason and J.-R. Larsen). It is not known if these results actually imply negative switching or are an artefact of the aggregation of the stomach content data for MSVPA predators. Clearly, however, the prey selection patterns by individual predators optimize on energetic content of the total prey field, as growth rates of North Sea fishes are rapid, and relatively stable over time, despite large fluctuations in the densities of individual prey items. This energetic optimization in prey selection is described by a rich ecological literature in optimal foraging theory (see Oaten 1977 for but one example of the application of the theory). Briefly, optimal foraging theory sees the predator as an entity that will maximize energy intake, subject to risks of non-successful encounters with prey, and potential caloric pay-offs. This may be a very useful context from which to view a fishing firm, fleet, or métier.

Modeling the Predator/Prey Dynamics of Fishermen

Modeling the predator/prey dynamics of fishermen is relatively new. Clark (1985) considered simple models of investment decisions, with the basis of decision making being maximization of net revenue flow. McGlade and Allen (1984) and Allen and McGlade (1986a; b) developed Lotka-Volterra-type predation models to explain the dynamics of discovery and exploitation in a mixed-species fishery environment, with considerable patchiness in the distributions of animals, and temporal variability in recruitment. Likewise, Hilborn and Walters (1987) proposed a simple dynamic model stock harvesting that incorporated simple rules for allocating the proportion of total effort to be allocated to each of several spatial areas, for test fishing. Final fishing rules incorporated sequential harvesting in proportion to relative catch rates. An elaboration of this simple model was to assume that fishermen maximize on the landed value of the catch (in this case a mixed-species aggregate).

The most elaborate dynamic models of mixed species, multileet interactions yet produced are those of Laurec et al. (1991) and Laloë and Samba (1991). Laurec et al. (1991) propose a 2-stage process in which the allocation of effort by each fleet (gear type/size category) is allocated to each métier (spatial unit of relatively homogeneous species composition and yield potential). They argue that allocation of effort by a fleet to the various feasible métiers is in part governed by economic optimization ('optimal foraging' in the economic sense), and in part by a habitual component. The 'habitual' component of the allocation decision is a proxy for a very complex behavioral model that integrates the perceived risks associated with moving fishing grounds, information that may be available from others that may have fished the alternative grounds, and a number of 'quality of life' factors that may determine where and how fishermen choose to fish. The Laurec et al. (1991) model is solved in two parts. First, a tentative allocation of effort among the métiers is made on the basis of the relative profit per unit of fishing effort expected prior to the beginning of the fishing season:

$$b_{i,m}^1 = (S_{i,m}^+)^{\beta} + \sum_m (S_{i,m}^+)^{\beta}$$

where: $b_{i,m}^1$ = the proportion of effort allocated to métier m , considering only relative profitabilities, $S_{i,m}^+$

= the potential profits per day at sea fishing in métier m (or 0, which is greater, e.g. no negative profits), and ∂ = the 'preference coefficient' (positive, ranging from 0 to ∞ , with all 0 values giving equal effort allocation among all métiers). The effects of differing levels of ∂ are simulated in Figure 2. In this example 10 métiers were each assigned relative profitabilities ranging from 1 to 30. Five of the métiers are plotted, along with 11 values of ∂ , ranging from 0 to 10. Clearly, values in excess of 3 result in virtually all the effort accruing to the most profitable fisheries, with very little remaining to be allocated to the others.

The second stage of the Laurec et al. (1991) allocation model accounts for the relative 'inertia' in allocations between years due to behavioral factors. The initial ($b^1_{i,m}$) effort allocations are subjected to a second model in which the relative 'adherence' of the fleet to a particular métier is determined:

$$b_{i,m} = \mu b^0_{i,m} + (1-\mu)b^1_{i,m}$$

where: $b_{i,m}$ = the final effort distribution (proportion) by fleet and métier, b^0 = the effort proportion in year $t-1$, and μ is the adherence parameter, ranging from 0 to 1 (a value of 1 indicating absolute adherence to the previous year's effort pattern). The effect of varying μ from 0.01 to 1.0 for three of the métiers described in Figure 3 are given in Figure 4. The Figure presents the absolute difference between $b^1_{i,m}$ and $b_{i,m}$ for a high, medium and low profit case. As the adherence coefficient increases to 1, the effort allocated to each fishery approaches .1, and thus the difference between b^1 (predicted on the basis of relative profit) and b is maximized. The medium profit case shows the smallest change between b^1 and b , since it was allocated about 10% of the effort in any case. The low profit case increases to 10% of the total effort at $\mu=1.0$.

These models were used to simulate the distribution of effort among fleets fishing in the Celtic Sea (Laurec et al. 1991) under varying parameter assumptions. The identification of separate economic and behavioral aspects of the allocation process is clearly warranted, however, as a practical matter the estimation of μ and ∂ require rather elaborate information, which have not been heretofore collected. The estimation of the proportion of effort accruing to each métier as an exponential function of potential profitability is also somewhat problematic. Projecting 'year-ahead' profitability as the initial basis for effort allocation implies the ability to forecast supply (and through a demand curve, revenues), as well as costs. Given uncertainty in these projections, we must conclude that some effort trials will be conducted in all potential métiers, even those in which negative profitability is forecasted for the upcoming year.

The model proposed by Laloë and Samba (1991) incorporated seasonal fluctuations in the availability of resources, and hence a longer time-series of 'habitual' effort patterning. However, it may be that effort decisions are not made in a 'year-ahead' mode, but are rather conditioned by fishing experiences at a variety of time scales. A probabilistic model of tow location decisions (Hassager and Lassen 1993, this Symposium) indicated that effort allocation decisions to change fishing grounds are dependent on the results of the most recent trawl tow. Thus, it is critical to consider the appropriate time scale at which effort allocation decision making takes place. It is indeed a fact that alternative métiers can be fished within the same trip, and thus classification based on trip summaries of catch may give a false impression of the degree of directivity actually taking place.

Models of the Future

The application of models from predator/prey theory to predicting effort allocation decision making is attractive since there is considerable theoretical and experimental evidence validating model performance. The use of optimal foraging theory to explain the energetic implications of various functional feeding responses offers a framework in which to view the trophic consequences of interacting populations. Similarly, fisheries decision making must be judged against fundamental economic criteria related to the profitability of alternative outcomes. What is apparently unique about fishery systems is the range of individual response given the same basic facts of relative profitabilities of alternative fishing activities. Thus, models such as those proposed by Laurec et al. (1991) have modeled the economic factors associated with effort allocation, then filtered the results for the substantial inertia that has been attributed to the 'habitual' component in allocation decisions.

Given the wide range in individual behavior with regards to allocation decision rules, it is legitimate to question whether can we hope to predict this behavior through more sophisticated economic and behavioral models. An alternative 'model-free' approach to the problem is to form probability distributions of the various alternative outcomes (allocation decisions), based on intensive time-series data collections from individual vessels comprising the métiers of interest. Such a probabilistic approach is suggested by Hassager and Lassen (1993) for a simple single-species shrimp fishery off Greenland. The probabilistic approach may have considerable merit given the advent of more intensive sea sampling programs instituted to monitor compliance and collect specific data on tow-by-tow catches. These very intensive data collection schemes may, for the first time, allow researchers to validate the factors influencing targeting decisions. Time-series data collected for the same vessel and similar vessels comprising operational 'fleets' can be the basis for forming testable hypotheses of factors influencing targeting and allocation decisions. It is recommended that consideration be given to the collection of appropriate economic and behavioral data in addition to fishery performance information so as to test the importance of various factors in determining where and why fishermen choose to fish where they do.

Are fishermen prudent predators? If they operated in a perfectly deterministic environment, where the costs and benefits associated with each investment decision were known (Lane 1988), it might be so. The reality is that the choice of alternatives is clouded by uncertainty of the outcomes, so much so that

what may appear as a 'habitual' effort allocation pattern may actually be a sophisticated bet hedging strategy in reaction to the considerable uncertainty in the potential pay-offs from alternative fishing strategies. In any event, the development of models of effort allocation will increasingly be focused on the appropriate time and space scales at which these decisions are made (year, month, trip, gear set).

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OTTER TRAWL FISHERY LANDINGS & EFFORT

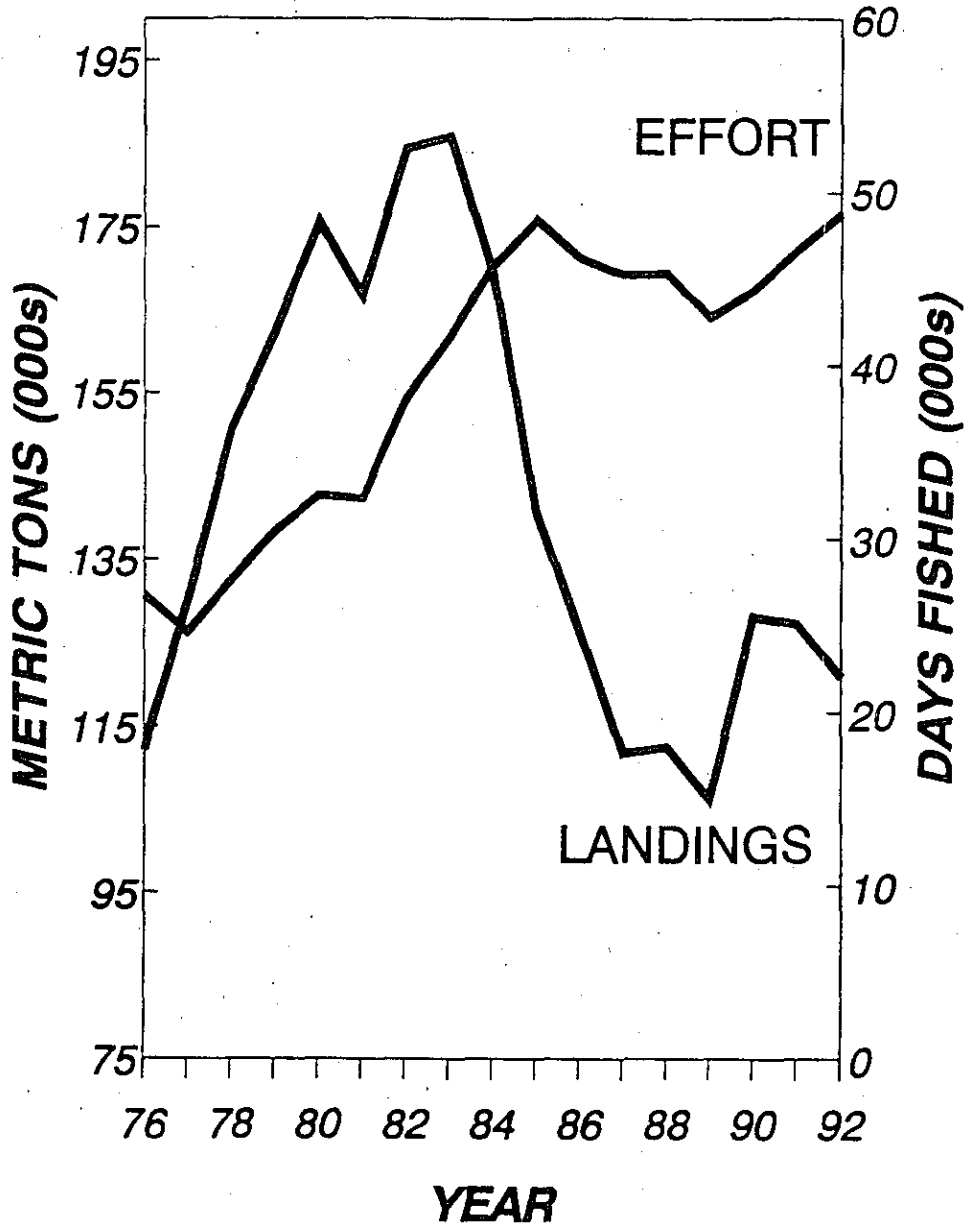


Figure 1. Total landings (000s metric tons) and fishing effort (000s of standardized days fished) in USA otter trawl fisheries off the northeast coast, 1976-1992.

SWITCHING BEHAVIOR

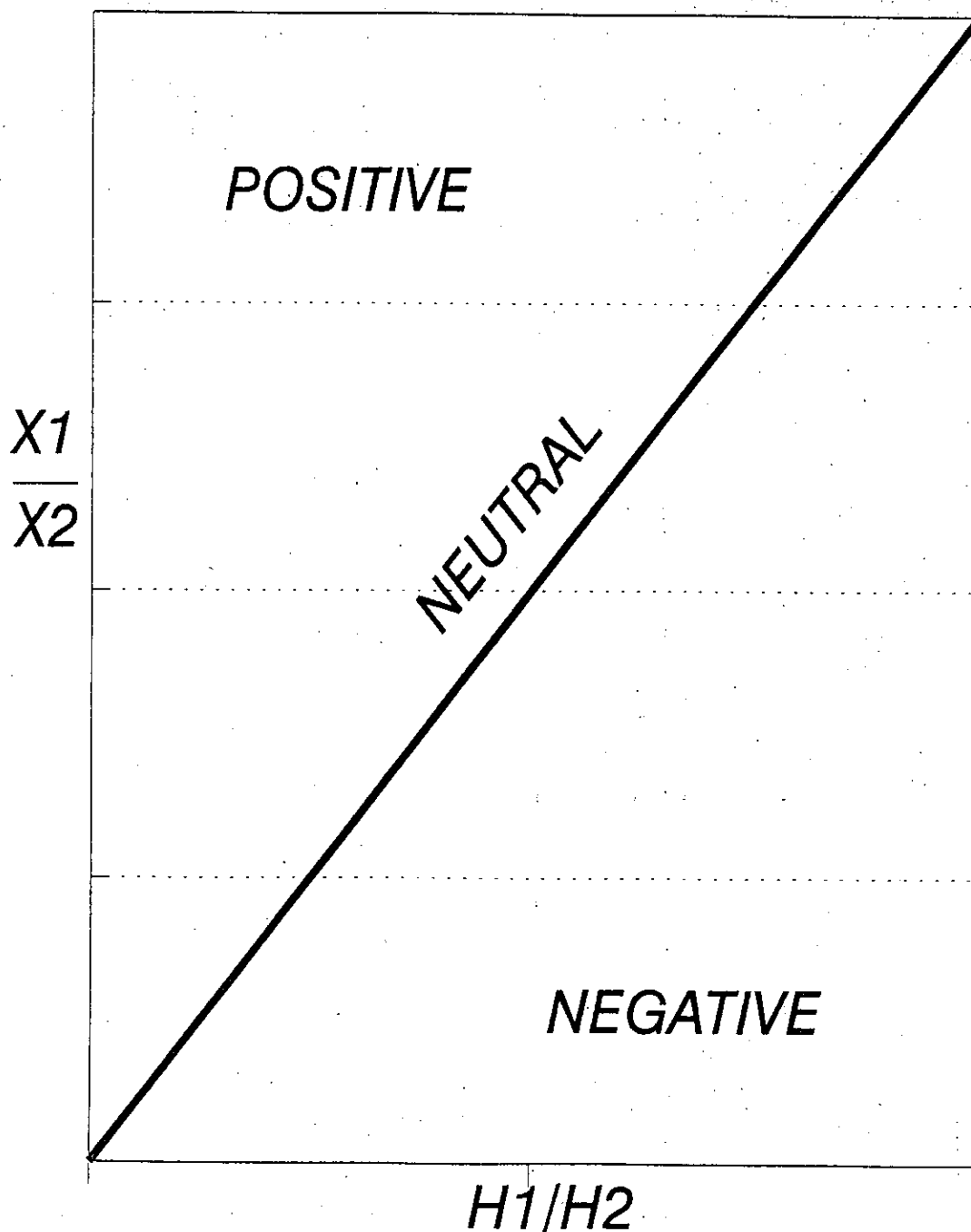


Figure 2. Relationships between the ratio of abundances of two prey populations H_1 , H_2 and their consumptions, N_1 , N_2 by a predator. If the ratio of consumptions to abundances is increasing over levels of prey abundance positive switching occurs, if the ratio of consumptions to abundances decreases, then negative switching occurs (Chesson 1984).

EFFORT BY MÉTIER FOR DIFFERENT PROFITS

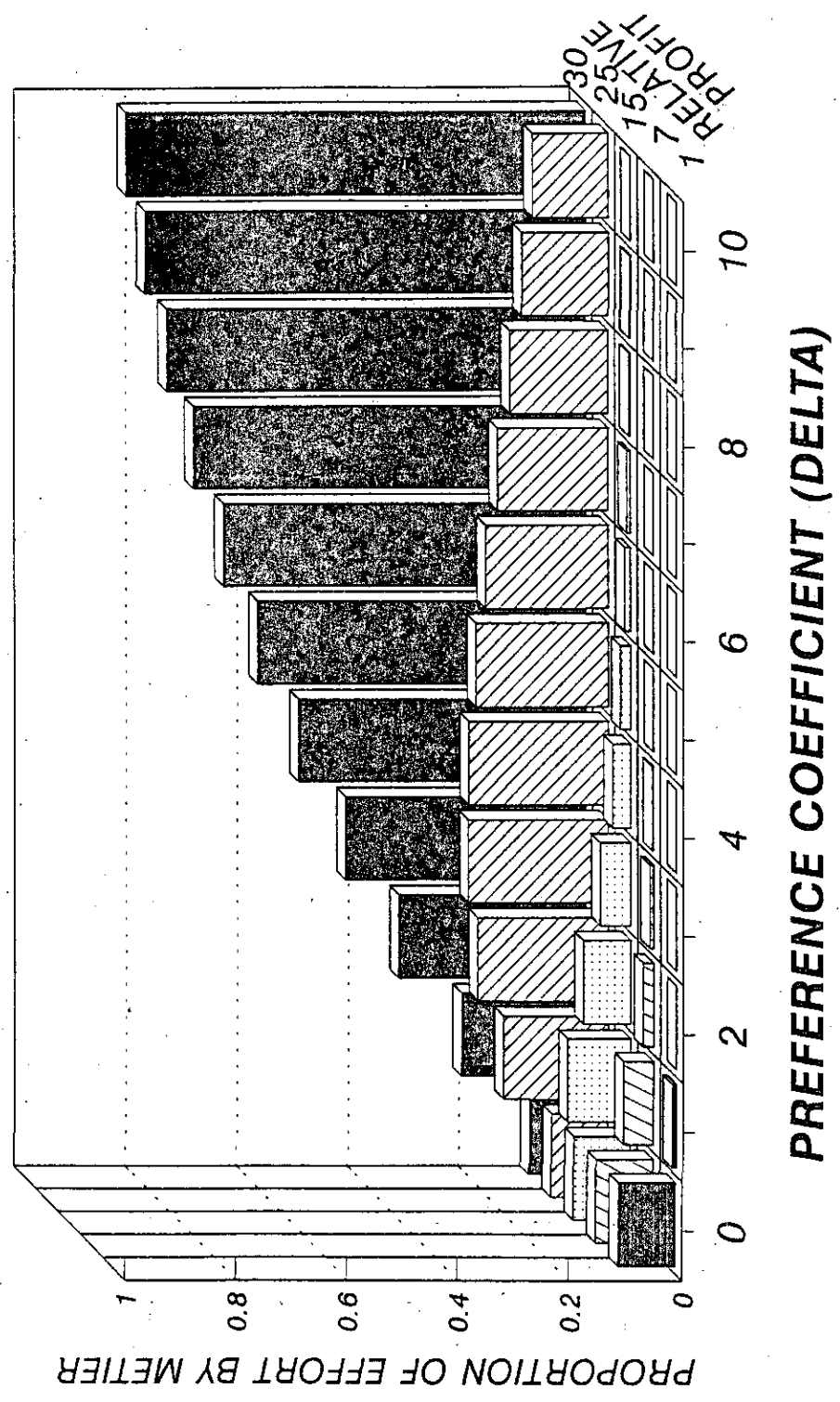


Figure 3. Relative proportions of effort by one fleet allocated to 5 different métiers, as a function of relative profitability and the preference coefficient (θ) of Laurec et al. (1991). The analysis considered 10 hypothetical métiers, each having 10% of the initial effort at time 0. The extreme values of relative profitability per unit fishing time were 1 to 30. Results for four of the métiers are presented. Preference coefficients varied from 0 to 10.

DIFFERENCE IN EFFORT ALLOCATED BY MÉTIER

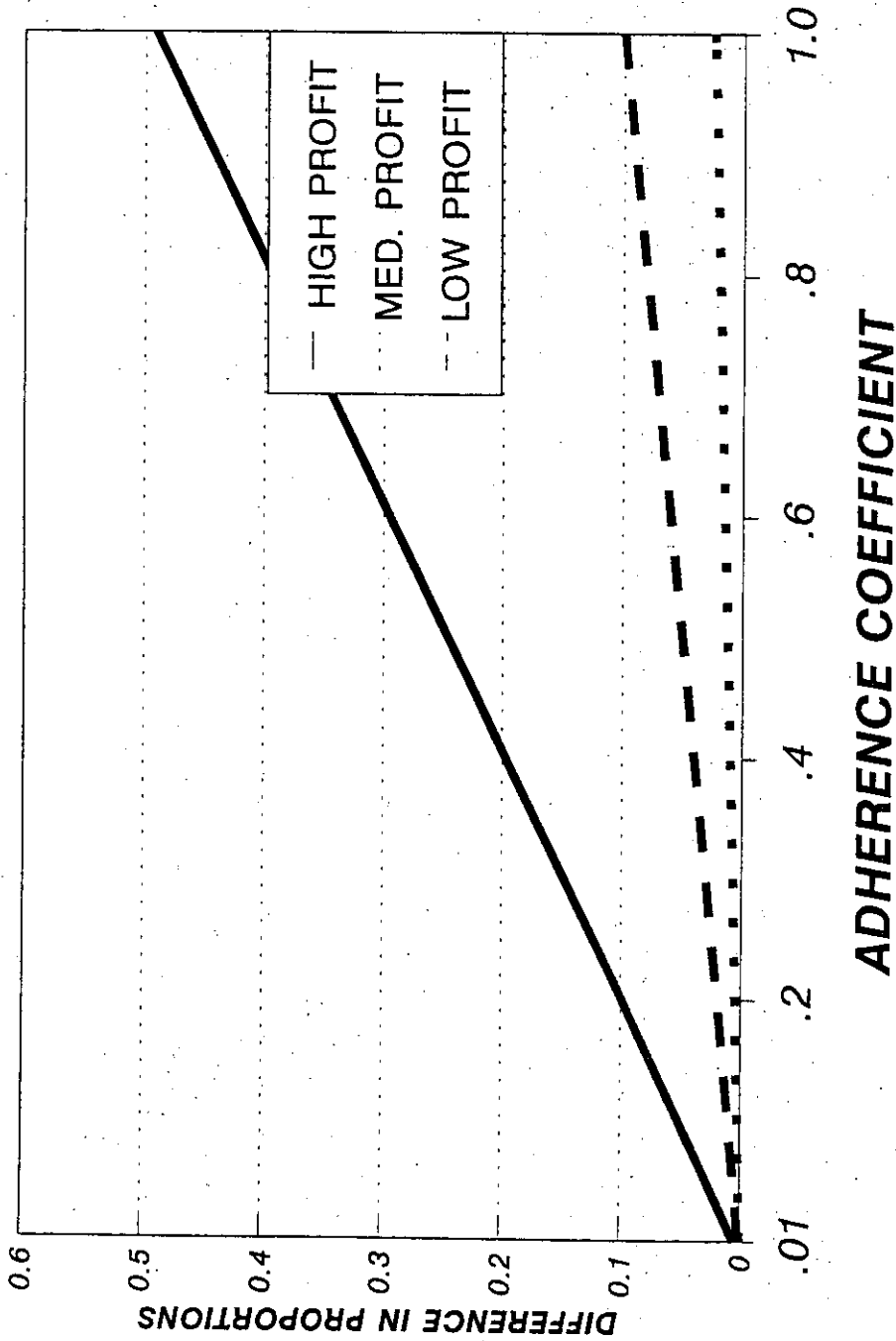


Figure 4. Calculated relative differences in the proportion of calculated effort allocated by métier, based on economic preference, and the final effort allocated, considering the habitual pattern of effort (based on the adherence coefficient, μ of Laurec et al. 1991). Data are presented for three of the métiers given in Figure 2.