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Hard Work versus Patience: Simulation of Fishing Strategies in Nova Scotian Herring Purse Seining

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ABSTRACT: Before electronic fish-finding equipment, herring seiners put their nets in the water whenever felt fish bump against lines held in the water. Now that sonar makes schools of fish visible, skippers are confronted with a new element: deciding the smallest size school of fish that is worth their effort. Skippers disagree with one another regarding the appropriate decision threshold, some favoring a "hard work" strategy (set on small schools) and others favoring a "patience" strategy (wait for large schools). This paper describes a computer simulation that addresses this optimal foraging problem.

KEY WORDS: Simulation, fishing strategies, skipper effect, Nova Scotian herring seining

1. INTRODUCTION

Commercial fishing involves myriad decisions, most of which are made under uncertainty, yet it is generally thought that skippers can and do develop adaptive fishing strategies. Despite the fact that fishing takes place in a very complex ecology, making it difficult to assess the effects of strategy amidst all the other variables that may contribute to differences in catches, both fishermen and scientists tend to belive that skippers' skills are important determinants of catching success.

The causes and implications of variation in skippers' skills are, however, generally neglected in the biological fisheries literature. Some exceptions are Hilborn (1985), who discusses the problems that arise from a failure to understand and manage fishermen, and Hilborn and Ledbetter (1985), who conclude that skipper skills are more important than vessel attributes in determining catching power, although there is some question about the validity of their analytical methods (Smith and Green 1986).

In contrast, social scientists have placed much more emphasis on the importance of decisions made by skippers in influencing overall fishing success (e.g., Davenport 1960; Barth 1966; Cove 1973; Gatewood 1983,

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1984a; Orth 1986; White 1989). Such studies generally focus, though, on the decision of where to fish and how information is gathered.

More recently, a few authors have denied the importance of skippers' skills to overall catch, at least in some fisheries (Palsson and Durrenberger 1982, 1983; Durrenberger and Palsson 1983, 1986). Not surprisingly, this has sparked a lively controversy (Gatewood 1984b; McNabb 1985; Jepson, Thomas and Robbins 1987; Thorlindsson 1988; Palsson and Durrenberger 1984, 1990; Durrenberger and Palsson 1985).

The empirical studies that have tried to assess quantitatively the skipper effect, whether focusing simply on the determinants of catch or the folk ideology of success, are similar in that they try to gauge the statistical effect of skippers' decisions through multi-variate examination of catch records over time, using techniques such as path analysis, analysis of variance, and multiple regression. Here we take a different approach.

With detailed information on fish school distributions for herring in the Bay of Fundy as a data base, we developed a computer simulation to see which fishing strategies would work better than others. In particular, we were interested in assessing the relative effects of location, setting strategy, gear-handling skill, and luck as determinants of overall catch. Before describing the details of the simulation, the specific questions it was designed to answer, and what we have learned from it, we provide a brief ethnographic background to the Nova Scotian herring purse seine fishery.

II. ETHNOGRAPHIC BACKGROUND

Each fishery has its own characteristics that influence the types and relative importance of the decisions that need to be made. Fish biology and behavior, technology, government regulations, and the structure of the processing industry all interact to provide a unique context in which a fishery operates. In the NAFO DIVISION 4X herring fishery (North Atlantic Fisheries Organization, Bay of Fundy and surrounding areas of eastern Canada), technological innovation and government intervention in the industry have radically altered both the structure of the fishery and the kinds of decisions that must be made.

Herring are a schooling species that follow a semi-predictable migration pattern. As juveniles, they are found in a number of specific rearing areas within the Bay of Fundy and along the coasts of New Brunswick, Maine, and Nova Scotia (Sinclair *et al.* 1985). Fish of 2–3 years and older migrate to the northeast coast of Nova Scotia to overwinter. With the approach of spring, they move back down the coast, actively feeding along the way. Spawning takes place in late summer and early fall at several near-shore locations in the Bay of Fundy and along the coast of southwest Nova Scotia.

Population size can be extremely variable from year to year. Estimates of adult stock size have ranged from 97,000 tons to 470,000 tons over the period 1965–84 (Sinclair *et al.* 1985; Stephenson *et al.* 1985). Their tendency to school makes herring particularly vulnerable to purse seine gear, and this, together with wide fluctuations in recruitment, means that they are extremely susceptible to over-exploitation.

Around the mid-1950s, the primary end use for herring became fish oil and fertilizer products. Following this change in the primary market, the fishermen focused their efforts on the summer concentrations of large adult fish instead of targeting juvenile fish for a canned sardine market.

By the mid-1960s, many of the herring stocks in the northeastern Atlantic and Canadian west coast were in a state of collapse, creating what appeared to be a virtually limitless fish meal market for Canadian east coast herring. Through a government loan subsidy program, the Canadian east coast herring fleet grew from 20 vessels in 1964 to 93 in 1967. At least 107 seine boats were active in the Bay of Fundy and surrounding areas by 1968, and they landed an estimated 175,000 tons of herring per year. The resource, however, could not stand this level of exploitation, and by 1971 the landings had fallen to 92,500 tons per year.

In response to the deteriorating catches, the government imposed limited entry licensing in 1970 and a fleet catch quota in 1972. These measures came too late to sustain profitability for the enlarged fleet, and by 1975 there were only 57 vessels, most of whose skippers requested financial assistance from the government. During this crisis, a series of industry negotiations culminated in conversion of the industry from a reduction (fish meal) fishery back to a food fishery to increase the unit value of herring. A fishermen's cooperative was also formed to control the supply of fish to the shore and act as a marketing liaison between fishermen and processors. Fishermen also agreed to comply with a voluntary catch allocation system based on annual and weekly individual vessel quotas: one third of the total fleet quota was to be divided equally among all vessels, one third on the basis of vessel size, and one third according to historical performance. Weekly quotas were set by the fishermen's cooperative to match shore processing capacity.

Although the new regulatory regime (Bay of Fundy Project) was almost immediately successful, its effects were short-lived. Even with a reduction in the fleet to about 50 vessels, the fleet still had the capacity to land the quota several times over. The success of the new system depended, then, on the industry's willingness to cooperate or, failing that, the government's willingness to enforce the catch quotas. Whereas the industry response was cooperative so long as a "crisis" situation prevailed, it regained its competitive spirit as soon as the regulatory scheme appeared to succeed in stabilizing and restoring the herring population. Deals were formed between individual fishermen and plant operators to bypass the marketing and bargaining systems implemented by the fishermen's cooperative and to falsify landing reports. Mace (1985) estimates that actual catches differed from recorded landings by a factor of 1.20 in 1979 and increased steadily over the period 1980—84 in the sequence 1.45, 1.55, 1.55, 1.63, and 1.77.[1]

In 1983, the voluntary system of individual vessel quotas was surplanted by governmental legislation. Larger vessels were alloted an individual vessel allocation of 2.7% of the fleet's annual total allowable catch (TAC), smaller vessels 1.6%. Under this new legally sanctioned system, quota amalgamation is possible within limits. Vessels can buy out other vessels' quotas (up to a maximum of 4.0% of the TAC per vessel), and vessels that sell their quotas must exit from the fishery. Fishing vessels and gear can be upgraded or replaced, but the total number of vessels in the fishery must either remain static or decrease (due to quota amalgamation). Apart from this limitation on fleet size (i.e., number of vessels), there are no regulations affecting skipper turnover.

Today, most herring are caught during a summer purse seine fishery in which about 70%—80% of the landings are taken along the southwest Nova Scotia coast from late June to mid-October. Herring school formation, and hence fishing activity, follows a daily cycle. During daylight hours, the herring are dispersed deep in the water, near the bottom. After sunset, the herring rise from the bottom and begin forming large schools. Thus, it is during the evening that the fleet of 40 or so purse seiners, ranging in size from 16—34 meters, set their nets in the water to entrap the fish — searching, setting, searching until dawn. A season contains 40 to 50 such nights, each with about 8 hours of fishing time.

Within these general constraints, skippers are confronted with a hierarchy of decisions. Each decision provides an opportunity for a skipper to exercise his skill (or lack thereof). Five of the major decisions include:

1. *Market Arrangement*

The first, and probably most important, decision a skipper must make concerns the sale of his vessel's catch. All purse seiners belong to one of two fishermen's cooperatives, in name at least. They are not compelled to market their fish through the cooperatives, and in fact few do so. Most set up independent arrangements with particular processors. Some skippers have relationships with buyers that have endured over many years, whereas others form new arrangements periodically on an opportunistic basis. It is common knowledge that these often involve mechanisms for under-reporting landings, in addition to purchase agreements. Hard information on this aspect of the fishing process is difficult to obtain, but rumor has it that under-the-table payments are common and that certain vessels have been able to land two or three times their legal quota. This suggests

that the major determinant of "success" may well be the ability to beat the regulatory system. Business skills and connections could outweigh fishing skills in overall importance, provided the skipper is capable of catching fish at the same rate he and his buyer are able to mis-report them.

If a skipper knew that his individual vessel quota would be enforced and he had no obligation to conform with his buyer's requirements for type of fish (e.g., juveniles, non-feeding adults, spawning adults), his decisions on the allocation of fishing effort would be fairly clear cut: choose the product types with the highest net values and fish only when these are available and on the grounds where they are most abundant. Lack of predictability in enforcement levels, fluctuations in herring population size and markets, and the need to establish or maintain a harmonious relationship with the buyer combine, however, to create considerable uncertainty regarding the "best" business strategy. In consequence, these fundamental business decisions are largely dictated by external circumstances.

2. *Fishing Location*

Choice of where to fish is also restricted, including both the initial choice and mid-trip changes. At any given time of the season, there are essentially only two general locations where schools are concentrated (Mace n.d.). Other factors that need to be taken into account are the amount of congestion on each ground, the depth and topography of the seabed in relation to the depth of the net, strength of the tides, and distance to the grounds. The tendency for herring schools to congregate in a few specific areas means that it is usually advantageous to search with the fleet, rather than to explore new grounds independently. Not only does the independent searcher risk isolated failure, but if he is successful in finding fish, the fleet will learn of it quickly (it is very difficult to conceal catch information given the geography of this fishery) and descend upon the new grounds (Allen and McGlade 1986; see also White 1989 for a discussion of the "fleet effect" in the Gulf coast shrimp fishery).

3. *Threshold Strategy*

Once a fishing ground has been selected, skippers need to develop a set of strategies for where and when to set. The problem is to determine whether to set on a sighted school, or to continue searching for a larger or more suitably positioned school. The costs of making a set are high as retrieval of the gear and handling time average about 1.5 hours out of a total of only 8—9 hours of fishing time per night. On the other hand, it does no good to leave the seine on deck all night while searching for a large school. As we describe in more detail below, skippers vary among themselves in terms of the smallest school of fish they will typically set upon, and different thresholds have significant effects on overall catch.

4. *Setting Tactics (Gear-Handling or Catching Skill)*

The next decision in the hierarchy is how to set: whether to attempt to encircle the entire school or just a portion, whether to encircle slowly or quickly, in which direction to position the boat, and how fast to purse the net.

5. *Social Use of a Set's Catch*

Finally, skippers need to decide whether to load the catch, give it away, or release it. The intended use of one's catch is, of course, to meet one's own marketing arrangement. If, however, fish are unsuitable for the night's market category (too small, too large, immature, or with full stomachs), they are often transferred to another vessel fishing for a different type of market. This wastes more time than simply releasing the end of the seine (negative short-term payoff), but it is also a means of repaying or investing in potentially beneficial social relationships, and it has the ecological benefit of reducing incidental and unnecessary fish mortality (postive long-term payoffs).

III. THRESHOLD STRATEGY AND THE SIMULATION MODEL

In the past, skippers could detect only the presence or absence of herring schools, by holding a weighted line in the water. Today, seiners use a variety of electronic detection equipment to detect their prey below the surface, scanning up to about one kilometer around the boat. Schools of fish show up as densities of blips on the screen or, on other machines, as density-dependent colors, and fishermen have learned to estimate the size of a school with a fair degree of accuracy (to within approximately 10—20% if the school is close). These improvements in detection ability have created a new kind of decision situation for seine skippers and a new possibility for skippers' skill to come into play, referred to above as a "threshold strategy." Our simulation focuses on this threshold strategy. We can illustrate the decision complexities that arise in the real-life situation with an analogy.

Imagine you are playing a card game where an ace is worth 1 point, a deuce 2 points, a king 13 points, etc. We shuffle the deck and deal you one card at a time. For each card dealt, you must either pass the card or take it. Should you decide to pass a card, then we deal the next one, and you have the same options as before. If you take a card, however, then you get to add its point value to your total score, but you cannot take the next five cards in the deck — they are discarded, sight unseen. In other words, taking a card entails a penalty in the form of "lost opportunities." The objective of the game is to pass and take cards in such a way that you maximize your total score.

Given these rules of play, one would certainly take a king, for this is the highest point value card. The problem inherent in the game, however, is deciding upon the lowest card you should take — a jack? a seven? a three?

With the advent of electronic detection equipment, herring seining involves a very similar choice. When the skipper encounters a school and sets his seine in the water, he commits his boat from one to two hours of work. During this time, the boat is essentially immobilized and cannot chase after other schools of fish that may pass by. For example, if the skipper has begun setting on a school of 20 tons, he can do nothing should a school of 100 tons suddenly appear on the scope. On the other hand, he might waste the whole night if he passes over smaller schools waiting for a chance to set on a 100 ton school. Given that making a set entails lost opportunities, what is the smallest school of fish that he should set on?

This problem corresponds to the so-called "prey model" (e.g., Stephens and Krebs 1986) in optimal foraging theory. The selection of a decision threshold — the lowest card to take or the smallest herring school to set on — must balance a certain gain against a lost opportunity known only probabilistically, and the options can be viewed as either take the "prey" as it is encountered or pass it. We will use the prey model to determine, via simulation, what the optimal decision strategy would be, if any.

PREY MODEL: Assume that searching (the time between encounters) costs s cost-units (e.g., energy) per time unit. Let there be a set of n possible prey types. Four variables characterize each prey type, i:

h_i = the expected handling time spent with an individual prey item of type i, if it is attacked upon encounter.

e_i = the expected net energy gain from an individual prey item of type i (if it is attacked upon encounter) plus the cost of search for h_i seconds (sh_i). If e_i' is the net gain from an item of type i, then $e_i = e_i' + sh_i$. The modified energy value e_i is the difference in gain between eating a type i item (and gaining e_i') and ignoring a type i item (and "gaining" $- sh_i$).

r_i = the rate at which the forager encounters items of type i when *searching*.

p_i = the probability that items of type i will be attacked upon encounter (the decision variable, zero-or-one).

PREY ALGORITHM: Rank the n prey types such that $e_1/h_1 > e_2/h_2$

. . . > e_n/h_n. Add the types to the "diet" in order of increasing rank until

$$\frac{\sum_i^j r_i e_i}{1 + \sum_i^j r_i h_i} > \frac{e_{j+1}}{h_{j+1}}$$

The highest j that satisfies this expression is the lowest ranking prey type in the "diet." If this inequality obtains for no $j < n$, then take all n items upon encounter (from Stevens and Krebs 1986: 17—23).

Note that the formula for determining the optimal decision threshold presumes that the organism knows the frequency distribution of the various prey types. Such knowledge is embedded in the encounter rates (i.e., r_i) as well as the costs per unit of time of the lost opportunities (the constant, s).

In the card game, this assumption is valid. We know how many cards of each point value are in the deck (4 kings, 4 queens, etc.), and using this information, we can compute the optimal decision threshold. When the penalty for taking a card is five missed opportunities, the optimal decision threshold is: take no card lower than a nine; that is, take all kings, queens jacks, tens, and nines, but pass all cards lower than a nine.

The world of herring fishermen is not so simple. Fishermen do not know the actual frequency distribution of herring schools by size classes, and even if this information were obtainable, its utility would be short lived. Natural biological fluctuations make every year different; the spawning cycle of herring changes the distribution within a season (i.e., between nights); and the very act of fishing may change the distribution within a single night. Thus, fishermen base their decision thresholds on imperfect knowledge about the frequency distribution of herring schools, based primarily on recent and present nights.

In point of fact, the herring fleet is quite heterogeneous when it comes to this aspect of fishing strategy. No single strategy, no single decision threshold predominates. Some skippers espouse what might be called a "hard work" strategy, arguing that you catch no fish with the seine on deck. They would rather keep busy setting on relative smaller schools than continue searching in the hopes of discovering a few large schools. For others, the key word to successful fishing is "patience." They are willing to forego numerous smaller schools and wait patiently for the few big ones. These are the extremes of opinion, which range, in this limited context, from relatively more risk-aversive (hard work, take the bird in the hand) to relatively more risk-seeking (patience, wait for the birds in the bush) strategies. Also, there are limits at each end. No one would be interested in a school estimated at 5 tons or less, and similarly no one would hesitate to set on a school estimated at 100 tons or more.[2]

What is puzzling about this state of affairs, and what makes the case interesting for ecologically-based theories of human behavior, is not that different skippers subscribe to different fishing strategies, but that the diversity *persists*. If there is a single optimum for a given fish distribution, why do some skippers continue to fish with sub-optimal foraging strategies? Why hasn't selection acted to favor those who accidentally hit upon the optimal threshold and thereby winnowed the initial diversity to a uniform response? Why haven't fishermen learned from experience, individually and collectively, what the "correct" threshold is?

To address these questions, we first need to demonstrate that there is a single optimal decision threshold for each distribution of herring schools. Then we must estimate the magnitude of the differences that different decision thresholds have for seasonal catch. Once these results are obtained, we can speculate on the broader issue of why some fishermen persist in using sub-optimal thresholds.

To examine these questions, we developed a computer simulation of the decisions that must be made. The simulation uses data on the size of herring schools, encounter rates, handling time, and so forth, collected by the second author during 1983 and 1984 as part of an observer program of the Nova Scotian herring purse seine fleet. They are based on several hundred hours of watching fish-finder scopes in the wheelhouses of Nova Scotian herring boats.

We begin by dividing the fish distribution data into two-week intervals and the total fishing territory into discrete spatial units. For the simulation, we selected three of these time-space "strata" (see Table I). There were two criteria guiding our selection: (1) we wanted strata for which we had at least 1,000 observations of herring schools, and (2) we wanted strata from different stages of the herring annual cycle, e.g., feeding, early spawning, and peak spawning.

Given this information, it might appear that we could compute the optimal threshold for each fish distribution using the prey model's formula given above, but there are several non-linearities in real fishing that complicate the simple prey model solution. First of all, only the larger vessels can handle a set greater than 100 tons, and the boats' holds can accommodate only an average of about 200 tons before it becomes necessary to unload the catch.[3] Thus, if a boat should be so fortunate as to fill its hold to capacity, it heads for port, and the fishing excursion ends. Another ethnographic wrinkle is that fishermen routinely make "desperation sets," that is, as daylight approaches (and the fish disperse and dive toward the bottom), skippers ignore their usual decision thresholds and cast their seines on any school that comes within range.

These ceilings and diurnal changes in strategy make a "brute force" computer simulation an easier way to discover the optimal threshold for a given distribution. Further, the artificial environment of a computer allows us to manipulate some variables while holding others constant and in this way to determine the relative effects of different factors.

The simulation incorporates the ethnographic wrinkles just noted and

TABLE I
Three time-space distributions of herring schools

	Stratum # 3 Gannet Weeks 2–3 Feeding (n = 1614)		Stratum # 12 Trinity Weeks 6–7 Some Spawning (n = 1656)		Stratum # 17 Trinity Weeks 8–9 Peak Spawning (n = 3170)	
SIZE RANGE (tons)	%	Cum%	%	Cum%	%	Cum%
1–9	69.4	69.4	43.8	43.8	16.0	16.0
10–19	15.3	84.7	35.5	79.3	44.4	60.4
20–29	5.8	90.5	4.9	84.2	14.9	75.3
30–39	1.3	91.8	3.4	87.6	7.1	82.4
40–49	1.9	93.7	4.0	91.6	3.6	86.0
50–59	4.9	98.6	2.2	93.8	3.1	89.1
60–69	0.5	99.1	1.5	95.3	1.2	90.3
70–79	0.1	99.2	0.2	95.5	0.9	91.2
80–89	0.3	99.5	2.1	97.6	1.4	92.6
90–99	0	99.5	0	97.6	2.1	94.7
100–109	0.1	99.6	0.3	97.9	1.7	96.4
110–119	0.1	99.7	0.2	98.1	0.1	96.5
120–129	0	99.7	1.2	99.3	0.9	97.4
130–139	0.1	99.8	0	99.3	0	97.4
140–149	0.1	99.9	0.1	99.4	0.1	97.5
150–159	0	99.9	0.2	99.6	0.4	97.9
160–169	0	99.9	0	99.6	0	97.9
170–179	0	99.9	0	99.6	0.1	98.0
180–189	0	99.9	0	99.6	0	98.0
190–199	0	99.9	0	99.6	0	98.0
200–249	0	99.9	0.2	99.8	1.3	99.3
250–299	0	99.9	0	99.8	0.1	99.4
300–349	0	99.9	0	99.8	0.1	99.5
350–399	0	99.9	0.1	99.9	0	99.5
400–499	0.1	100.0	0	99.9	0	99.5
500–1200	0	100.0	0.1	100.0	0.5	100.0
Mean Tons	12.91		19.69		31.93	

includes four possible sources of differential catch.[4] These are: (1) the frequency distribution of herring schools, (2) the decision threshold, (3) catching ability or skill, modeled as the proportion of a school actually caught when set upon,[5] and (4) luck, in the sense of randomized presentation of schools from the same distribution.

In all, 21 "skippers" — 7 decision thresholds × 3 skill levels — fish three different herring distributions (an example of the programs that produced these distributions and a table showing how closely they correspond to the empirical data are given in Appendix A). Each run of the program is calibrated to simulate one season (or 50 eight-hour nights) during which 1,000 schools of herring are presented sequentially at a rate of 2.5 schools per hour. The penalty for setting on a school consists of missing the next 4 to 6 schools, the exact number depending on how much fish are being caught in the current set as large hauls take longer to retrieve than smaller ones. In any given run of the program, all 21 skippers encounter herring schools in exactly the same random sequence; thus, the only sources of variation are decision threshold and skill level (see Appendix B for details of the "skill" and "catching" code). Figures 1, 2, and 3 illustrate some typical results.

The top portion of each figure shows the distribution of herring schools being fished, and the bottom shows the pattern of catches produced in a single run of the program by the 21 threshold-skill combinations. Note that each of the three distributions has an optimal decision threshold, but that it varies from one distribution to another.

In Figure 1, the optimal foraging strategy is to set on any school larger than 10 tons, in Figure 2 the optimum is 20 tons, and in Figure 3 the best threshold is 30 tons. Also, note that threshold strategy, by itself, has a substantial effect on catch in each of the three distributions. For example, reading along the high skill curve in Figure 3, a 10-ton decision threshold resulted in a seasonal catch of about 4,500 tons, whereas a 30-ton threshold caught around 6,000 tons, or one third more fish.

By running the program several times on the same fish distribution, we can determine the relative effect of each independent variable in the model. Table II shows the results of an analysis of variance performed on the output of 32 runs of the program for each of three different fish distributions. The data, thus, consist of 2,016 "yearly catch records."

As the statistical analysis demonstrates, fishing location, decision threshold, and catching skill are each significant variables in explaining differential seasonal catch, whereas luck (the effect of random presentation order) balances out and is statistically insignificant. In the complete model and ignoring interaction effects, which are also highly significant, the three distributions of herring schools — that is to say, when and where the skipper has decided to fish — accounts for 79.9% of the variance in catch, catching skill accounts for 6.4%, and the different decision thresholds account for 6.2%. Given that the simulation contains only these three controlled variables (plus any interaction effects among them), the small residual variance of 1.7% may be interpreted as the effect of random presentation of schools, or luck.

When one analyzes the relative consequences of catching skill, decision threshold, and luck while holding the fish distribution constant, the importance of threshold strategy is more apparent. This may be a better situation to analyze because it is comparable to the real-life situation

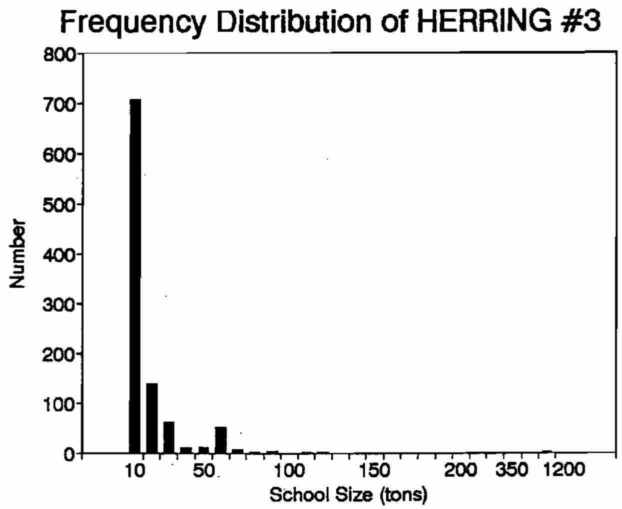

Fig. 1a.

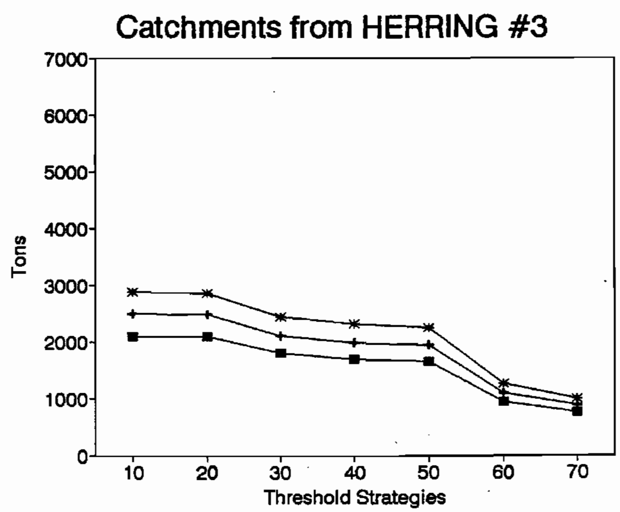

Fig. 1b.

Figs. 1a—b. Herring #3 distribution of schools by size classes and resulting seasonal catchment patterns.

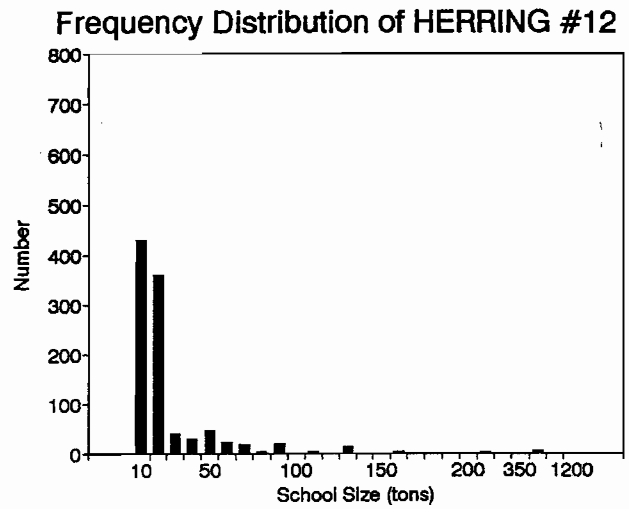

Fig. 2a.

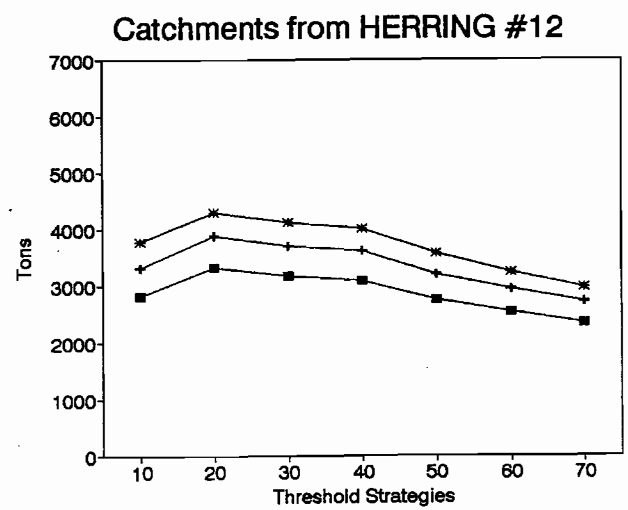

Fig. 2b.

Figs. 2a—b. Herring #12 distribution of schools by size classes and resulting seasonal catchment patterns.

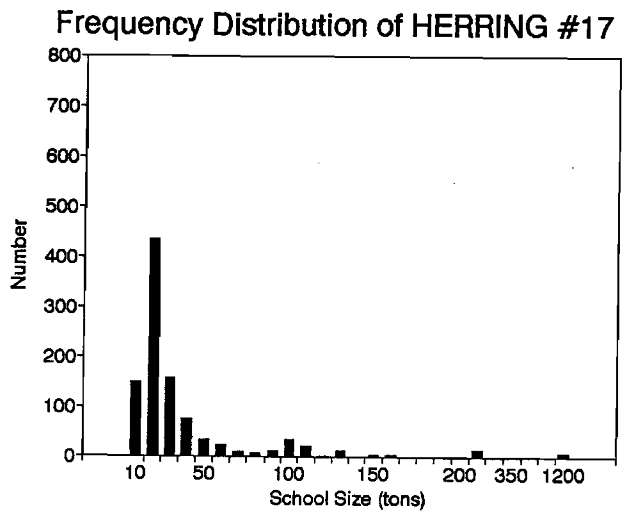

Fig. 3a.

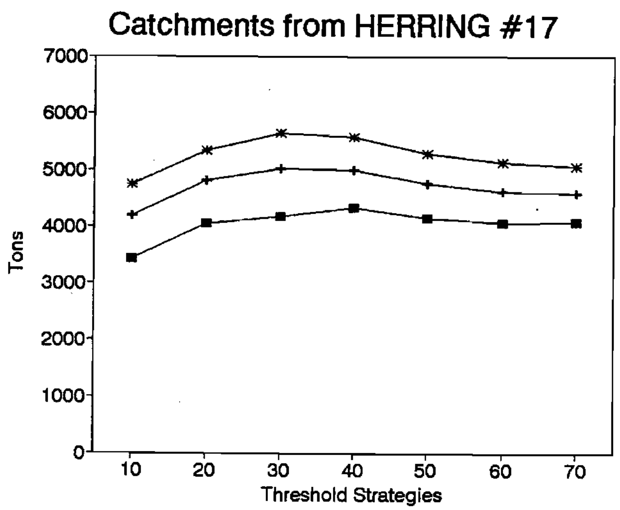

Fig. 3b.

Figs. 3a–b. Herring #17 distribution of schools by size classes and resulting seasonal catchment patterns.

TABLE II

Analysis of variance — Seasonal catch by fish distribution, gear-handling skill, and threshold strategy

Source of variation	Sum of squares	Df	Percent variance accounted for
MAIN EFFECTS	3,510.00 E + 6	10	92.6%
Distribution	3,030.00 E + 6	2	79.9%
Skill	241.00 E + 6	2	6.4%
Strategy	234.00 E + 6	6	6.2%
2-WAY INTERACTIONS	215.00 E + 6	28	5.7%
Distri Strategy	185.00 E + 6	12	4.9%
Distri Skill	26.00 E + 6	4	0.7%
Strategy Skill	3.51 E + 6	12	0.1%
3-WAY INTERACTIONS	1.97 E + 6	24	0.1%
Distri Skill Strategy	1.97 E + 6	24	0.1%
EXPLAINED	3,720.00 E + 6	62	98.2%
RESIDUAL	66.30 E + 6	1953	1.7%
TOTAL	3,790.00 E + 6	2015	

where different boats are fishing in the same area at the same time. Catch information among such boats is usually superior to that which spreads from one area to another, and because they are all fishing in essentially the same spot, differences in catch only intensify the psychological tension among skill, strategy, and luck as explanatory concepts in fishermen's thinking. Table III summarizes the results of three analyses of variance, where each fish distribution is considered separately.

TABLE III

Percent of variance accounted for by threshold strategy, gear-handling skill, and luck when holding fish distribution constant

Fish distribution	Mean size of fish schools	Strategy	Skill	Luck
Herring #3	12.84 tons	87.9%	9.1%	1.8%
Herring #12	20.71 tons	42.7%	43.5%	13.3%
Herring #17	34.38 tons	27.8%	58.5%	13.2%
AVERAGES	22.64 tons	52.8%	37.1%	9.4%

In these partial models, threshold strategy emerges as more important than catching skill in explaining differences in seasonal catch. The variance attributable to catching skill ranges from 9.1% to 58.8%., with the average for the three tests being 37.1%. Threshold strategy accounts for 27.8% to 87.9% of the variance, for an average of 52.8%. As a rule, the relative importance of strategy versus catching skill decreases as the average school-size increases across the three fish distributions.

IV. BROADER IMPLICATIONS

The simulation demonstrates that there is an optimal fishing strategy for each herring distribution and that a skipper's threshold strategy has a substantial impact on his seasonal catch. It also guides us in speculating about the larger question of why some fishermen persist in sub-optimal fishing strategies.

It appears that real fishermen do not learn the correct decision threshold from their collective experience because, as we see in the simulation results, differential catch is a result of several factors. Although fishermen are quite aware of differences in catch and the fact that their peers employ different decision thresholds, in the ever-changing state of affairs in the fishery, skippers are not able to sort out consciously the effect of strategy from the effects of location, skill, and luck. In the natural environment of herring seining, these variables are heavily confounded; hence, the failure of skippers to converge on the optimal strategy through trial-and-error learning does not imply irrationality. On the contrary, it would be irrational for a skipper in this situation to claim he knows the optimal threshold.[6]

Granting that conscious learning is unlikely, the question remains as to why blind variation and selective retention (Campbell 1965, 1970) has not acted in an unconscious way to eliminate skippers employing suboptimal threshold strategies, leaving the fleet relatively uniform in this respect. There are two plausible answers to this, two reasons why selection might *not* be effective in filtering the wheat from the chaff as regards threshold strategies in this fishery:

1. External selection has not exerted itself to winnow threshold strategies because the number of independent trials is very small compared to the amount of "noise" in the fishing ecosystem, i.e., there is an insufficient "through-put" of skippers in the fishery for the filtering action of selection to have much effect. The current quota and license system has, especially, reduced the role of competitive advantage as a factor governing entrance or exit of personnel in the fishery. Since implementation of the individual vessel allocation regulations, there has been little turnover among skippers in the fleet.

2. As noted previously, the single most significant decision affecting overall success in this fishery is a skipper's marketing arrangement. To the extent, then, that successful marketing negotiations are independent of skippers' threshold strategies (and we have no reason to suspect otherwise), threshold strategies will be buffered from direct selection.

As an alternative to offering specific "apologies" for the persistence of diversity, we might also consider whether the simulation's finding that a single optimum exists for any given herring distribution derives from faulty or inappropriate assumptions. In particular, the simulation does not include the effect fishing may have on a given herring distribution — i.e., there is no feedback between predation and the distribution of school sizes in the water — with the result being that each skipper encounters exactly the same distribution. But, if fishing strategies did affect the distribution of schools encountered by skippers employing other strategies, then it is possible there might be more than a single optimal strategy. For example, suppose some skippers take only large schools. If schools exhibit low dispersal in space, then neighboring skippers would experience a local depletion of large schools, enhancing the value of a "take what you can get" strategy in that neighborhood. In such a case, as the frequency of skippers taking only large schools rises (localized in space), the value of the latter strategy would also rise; conversely, as the frequency of a "take what you can get" strategy (locally) rises, the value of taking only large schools would rise. In this way, a decision polymorphism, measured by the degree of skipper patience for the large schools, would result. Under these circumstances, then, the existence of diverse threshold strategies should be regarded as a consequence of selection, rather than a puzzling persistence. In this view, the diversity of opinion among Nova Scotian skippers is itself an adaptation, but an adaptation to the behavior of other fishermen rather than to the behavior of herring.

While such a scenario is logically possible, it does not apply to the case under study for two reasons, both related to the behavior of herring in the Bay of Fundy. Firstly, recall that herring form into schools and disperse on a daily cycle, which means the distribution of schools by size category is re-constituted anew each day. Hence, any effect that human predation may have on the distribution of herring schools would last only a portion of the evening's fishing time. Secondly, there are sufficiently many herring schools in the region and they are sufficiently mobile over the span of an evening that "localized depletions" of particular size categories, if they occur, are of little significance. Together, these two facts warrant the usual assumption of optimal foraging theory that prey distributions are unaffected by the strategies of conspecific predators, which is how the simulation is designed.

In summary, the persistence of diversity in Nova Scotian fishing strategies shows there may be limits to human adaptation, but it does not imply irrationality. On the one hand, fishermen have only imperfect knowledge of the frequency distributions of herring schools. This information deficiency prohibits an *a priori* computation of optimal strategy. On the other hand, the fishermen do not learn from their collective mistakes, as evolutionary theory would normally predict, because the individual vessel allocation regulatory regime artificially insulates active skippers from selection and because the environmental feedback (the meaning of catch records) is ambiguous. In consequence, mistaken behavior can persist; adaptation does not always occur.

V. DISCUSSION

Most of the work spent on assessing the role of human skill as a determinant of fishing success uses familiar statistical procedures to analyze historical catch data. The findings of such studies remain susceptible to differing interpretations, however, because the critical variables (skipper's decision, crew's skill, motivational factors, etc.) have not been measured directly. Instead, they are relegated to the status of residual effects, or part of what is left after assessing the effects of vessel characteristics and temporal effort (Gatewood 1989). Computer simulations, such as the one described here, appear to offer a means of circumventing the ambiguities inherent in data sets such as historical catch records.

Granted, the simulation we developed analyzes only one component of a Nova Scotian skipper's seining skill. It does not address his skill in making marketing arrangements, deciding on locations, using the flow of information while fishing, or assessing the alternative social uses of a set's catch, all of which, presumably, contribute to, and are embedded in, historical catch data. Further, the simulation used here is only a one-person, static model. It does not include other skippers, or how the activity of fishing may alter the distribution of fish schools in the water. We acknowledge these limitations, but would note that there is nothing, in principle, to prohibit incorporation of additional features in future elaborations of the model. For example, with more work, the model could become an *n*-person, dynamic simulation and include additional variables, such as size of vessel (which influences hold capacity, size of net, and ability to fish in different weather conditions).

Although the simulation is limited, it is useful for addressing some questions that fishermen and others continue to debate. Firstly, we identified the optimal threshold strategy for each of three fish school distributions. Secondly, we showed how much difference the correct threshold strategy can make, other things being equal, when fishing a given distribution of fish schools. Thirdly, we estimated the relative importance of threshold strategy compared to gear-handling skill and luck. On average, threshold strategy was about equal in importance to gear-handling skill, and both were much more important than luck. Determining these matters (i.e., the consequences of skippers' skill) has proven to be exceedingly difficult using more standard methods, whereas they can be addressed directly and easily through simulation.

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NOTES

[1] Misrepresentation of actual landings in the official catch records is another reason for seeking an alternative to the usual approaches at quantification of the skipper effect.

[2] For expositional clarity, the discussion of reasonings underlying the hard work versus patience threshold strategies assumes "all other things being equal." Ethnographically, there are other factors that enter into a skipper's decision whether or not to set on a given school, and these interact with his normal threshold reasoning. For example, if the particular location has shoals, then skippers may well forego a school that they otherwise would attempt to take. Also, the reason some skippers may prefer a "patience" strategy derives from self-appraisals of catching skill, i.e., less skillful skippers recognize they might not catch *any* fish from a small school and, knowing this, they feel they virtually have to wait for larger schools.

[3] The vessels range in terms of their hold capacities from about 40 to 800 tons, but some of the smaller vessels hire "carriers" (other boats that off-load fish) to follow them on the fishing grounds. Thus, the simulation uses a uniform maximum hold capacity of 200 tons, which is near the fleet average.

[4] The simulation uses seasonal catch, measured in tons of fish, as the dependent variable. Currently, it does not convert this to a dollar value, that is, to profitability. If we had the necessary economic data (e.g., price per ton, equipment costs per set, fuel costs for searching time), it would be a relatively easy task to revise the program to plot profitability rather than just catch.

[5] The program treats gear-handling or catching skill as a simple multiplier, a fraction of the current school's size, but allows for three realizations. Firstly, high, average, and low skill levels are assigned constant multipliers of 0.6, 0.5, and 0.4, respectively. Secondly, the skill levels are regarded as ranges of equiprobability, where high skill ranges between multipliers of 0.4 and 0.8, average between 0.3 and 0.7, and low ranges between 0.2 and 0.6. Finally, the skill multipliers are treated as binomial probability distributions ($n=8$) with

means of 0.6, 0.5, and 0.4, respectively. The data reported in this paper uses this last (and more plausible) realization of catching skill.

[6] Using the card game analogy of the prey model, the first author conducted an informal experiment with his mathematically inclined teenage son. Beginning with a "penalty" of five missed opportunities for taking a card, we played ten games, shuffling the deck after each, and recorded his score for each round. He then played ten more games, but with the penalty set at seven. Finally, we went through the deck ten more times with the penalty set at three.

The interesting finding of this experiment is that toward the end of each ten game set, the subject intuitively discerned the optimal strategy. That is, through trial-and-error learning, he converged on the proper decision threshold for each of the three penalty situations. Thus, it is quite possible for a person to adapt to prey model problems *provided* that: (1) the problem is presented several times, and (2) the only factor accounting for differential success is the decision threshold itself as modulated by the luck involved in different random orders of presentation. Conscious adaptation, thus, seems to require unambiguous environmental feedback.

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APPENDIX A
FISH3.BAS — Code for Generating Herring # 3 Distribution

Characteristics:

- Cumulative percentages inserted using arrays and READ . . . DATA statements
- Embeds a FOR . . . NEXT loop for interval and cumulative percentage arrays within the main FOR . . . NEXT loop, obviating the need to write a separate IF . . . THEN statement for each interval
  - --› provides maximum adaptability, i.e., to edit the program for different distributions just insert new DATA statements
- Random assignment of values within interval ranges

```
100   N=1000 : D=26 : DIM F(N), I(D), P(D)
110   FOR X=1 TO D : READ I(X), P(X) : NEXT X '|intervals & cum. %'s|
120   FOR T=1 TO N : R1=INT(RND*1000+1) : FOR X=1 TO D
130     IF R1 <=P (X) THEN F (T) = INT(RND* (I(X) −I(X−1)) + I(X−1) +1) :
        SUM=SUM+F(T) : X=D
140   NEXT X : NEXT T
1000  '----- 1st No. = Interval --- 2nd No. = Cumulative % ------
1010  DATA 9,694
1020  DATA 19,847
1030  DATA 29,905
1040  DATA 39,918
1050  DATA 49,937
1060  DATA 59,986
1070  DATA 69,991
1080  DATA 79,992
1090  DATA 89,995
1100  DATA 99,995
1110  DATA 109,996
1120  DATA 119,997
1130  DATA 129,997
1140  DATA 139,998
1150  DATA 149,999
1160  DATA 159,999
1170  DATA 169,999
1180  DATA 179,999
1190  DATA 189,999
1200  DATA 199,999
1210  DATA 249,999
1220  DATA 299,999
1230  DATA 349,999
1240  DATA 399,999
1250  DATA 499,1000
1260  DATA 1200,1000
```


Appendix A (continued)
Simulated versus Actual Distributions of Herring # 3

Stratum # 3
Gannet
Weeks 2—3
Feeding
1614 Observations

SIZE RANGE (tons)	Actual %	Sim1 %	Sim2 %	Sim3 %	Sim4 %	Mean Sim − Actual
1—9	69.4	70.7	69.5	69.8	71.0	0.85
10—19	15.3	14.0	14.3	15.4	14.4	−0.775
20—29	5.8	6.2	5.7	5.3	5.8	−0.05
30—39	1.3	1.1	1.3	0.9	1.0	−0.225
40—49	1.9	1.2	2.5	2.1	2.5	0.175
50—59	4.9	5.2	5.4	4.7	3.9	−0.1
60—69	0.5	0.6	0.7	0.8	0.4	0.125
70—79	0.1	0.2	0.1	0.1	0.2	0.05
80—89	0.3	0.3	0.1	0.3	0.3	−0.05
90—99	0	0	0	0	0	0
100—109	0.1	0.1	0.1	0.3	0.1	0.05
110—119	0.1	0.2	0	0	0.3	0.025
120—129	0	0	0	0	0	0
130—139	0.1	0	0.2	0	0.1	−0.025
140—149	0.1	0	0.1	0.2	0	−0.025
150—159	0	0	0	0	0	0
160—169	0	0	0	0	0	0
170—179	0	0	0	0	0	0
180—189	0	0	0	0	0	0
190—199	0	0	0	0	0	0
200—249	0	0	0	0	0	0
250—299	0	0	0	0	0	0
300—349	0	0	0	0	0	0
350—399	0	0	0	0	0	0
400—499	0.1	0.2	0	0.1	0	−0.025
500—1200	0	0	0	0	0	0
Mean Tons	12.91	12.84	12.67	12.72	11.78	−0.408