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Game Theory, Population Dynamics, And the Fish that Got Away

By Barry A. Cipra

When the Lewis and Clark expedition reached the Columbia River in 1805, the native Wishram Indians they encountered there offered them a virtually endless supply of salmon, one of the area's abundant delicacies. The explorers declined, preferring to stick to their customary fare: dog meat.

Times, and tastes, have changed. Pacific salmon now ranks as one of the more popular items on restaurant menus—with the result that the "harvesting" of salmon has come to dominate the population dynamics of several species. The economic importance of salmon is underscored by the fact that fishing treaties are a serious bone of contention between the United States and Canada. In recent years, "fish wars" between competing interests in the two countries have placed a strain on U.S.–Canadian relations.

The problems posed by Pacific salmon were among the topics treated in a minisymposium on fisheries at the 1998 SIAM Annual Meeting in Toronto. Session organizer Ransom Myers, a mathematical biologist at Dalhousie University in Halifax, Nova Scotia, described the mechanisms that underlie population cycles for one species of Pacific salmon, for which the abundance often changes by orders of magnitude from one year to the next. Robert McKelvey, a mathematical ecologist at the University of Montana, spoke on game-theoretic aspects of the North American salmon treaties.

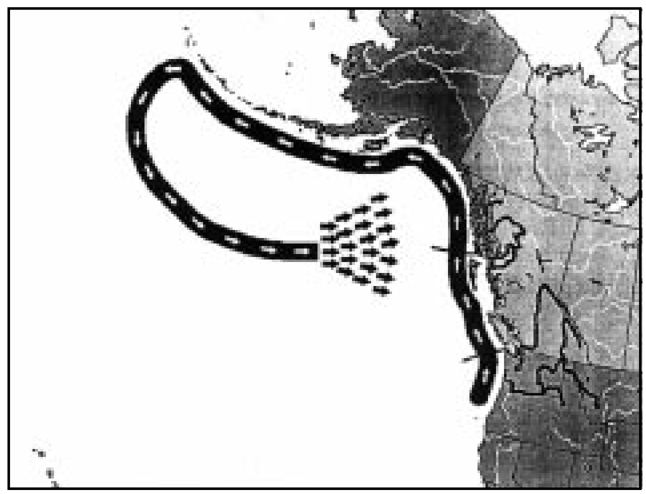

Figure 1. *The general migratory pattern of Pacific salmon raises an obvious question: Whose fish are they? (Figure from the Department of Fisheries and Oceans, Canada, 1997.)*

The Poissonnier's Dilemma

There are five major species of Pacific salmon: the highly valued sockeye, coho, and chinook, and the cheaper pink and chum. The fish spawn and die in the Columbia River system in Washington and Oregon and the Fraser River system in British Columbia. The fundamental problem, in terms of fishery management, is that in the years in between, the salmon migrate out to sea, up along the coasts of Canada and Alaska, and out into the northern Pacific Ocean (Figure 1). That raises an obvious question: Whose fish are they?

The question has no definitive answer—it's a subject for negotiation. That's where game theory enters in. Game theory, McKelvey explains, can help predict the likely results of agreements between competing parties. It can also help identify some of the crucial elements, such as side payments (discussed below), required to make agreements stick.

"A game-theory model is of course only a caricature; its analysis provides only a parable, suggestive of the real world," McKelvey wrote in an article on game-theoretic insights into international fishing agreements, published in the journal *Natural Resource Modeling* (Spring 1997). "Still, the story it tells can be quite compelling and, when treated with caution, also instructive."

Roughly speaking, a fishing treaty is an agreement by each side to limit its harvest in some respect. Without such an agreement, each party is inclined to grab all the fish it can, so as not to be taken advantage of, even when depletion of the stock is clearly the end result. The situation is analogous to the classic Prisoner's Dilemma of game theory.

The problem is to work out an agreement that's advantageous to both sides. "You're not going to get parties to a dispute to agree unless each one of them feels he's better off by cooperating than he would be by going it alone," McKelvey points out. The U.S.–Canadian salmon treaty is further complicated by the fact that there are more than just two sides: Alaska's interests are different from those of Oregon and Washington, and Native Americans also have a voice in the matter.

The current salmon treaty was ratified in 1985. The treaty doesn't directly specify management plans, however. Instead, it establishes the Pacific Salmon Commission, with representatives from each country, charged with reaching consensus on the allocation of harvests. The treaty requires the commission to respect two basic principles in making the allocations: (1) prevent overfishing and provide for optimum production; and (2) provide for each party to receive benefits equivalent to the production of salmon originating in its waters.

This approach worked well for several years. But beginning in 1993, the commission was unable to reach the requisite consensus. A sudden "collapse" of the coho and chinook fisheries in Washington and Oregon upset the balance between Canadian interceptions of those fish and American interceptions of Canadian-produced sockeye and pink. Making matters worse, American interceptions were being made primarily by Alaskans, who had little incentive to reduce their level of fishing just to bail out Washington and Oregon.

The impasse led to deleteriously competitive behavior, precisely as game theory predicts: "Fish wars" broke out. The term is apt, McKelvey says, in that fish wars are "a pretty good proxy for the kinds of squabbles that countries get into that lead into real wars."

Tensions escalated for the next four years. An attempt in early 1997 to resolve the situation through talks between "stakeholders" representing fishers and industry workers from the two countries broke down in May. On July 19, Canadian fishers blockaded the Alaskan ferry Malaspina at the British Columbia port of Prince Rupert, denying the ferry and its passengers (mostly American tourists) departure for three days. The incident included the burning of an American flag by a Canadian fisher (who turned out to have American citizenship). It drew harsh words from Washington, DC, and prompted a lawsuit by the state of Alaska.

The blockaders' tactic was roundly criticized in Canada as well (for one thing, it led to millions of dollars in lost revenues when Alaska retaliated by cancelling all ferry stops at Prince Rupert), but it may have helped spur action toward a settlement. Days later, the two countries commissioned a high-level report on the salmon treaty impasse, to be conducted by two "eminent persons." William Ruckelshaus, former director of the Environmental Protection Agency, represented the U.S., and David Strangway, former president of the University of British Columbia, represented Canada.

The Strangway/Ruckelshaus report, issued in January 1998, recommended that the "stakeholder" approach to negotiation be abandoned in favor of an interim, two-year agreement—during which time the two countries were to rethink the original 1985 treaty. The report renewed optimism that the fish wars would be settled, and by early July, agreements were in place between Washington State and Canada regarding the southern sockeye fisheries. Negotiations between Canada and Alaska regarding northern coho stocks, however, ended on July 9 without agreement.

General principles of game theory suggest that the impasse may truly be impassable if negotiators limit their bargaining to fishing rights, McKelvey says. The best—perhaps the only—way out is to include side payments: in effect, an exchange of dollars for fishing rights. Side payments can be tricky to negotiate, however. Straight economics isn't the only factor; national pride and ethnic identity play important roles. The mayor of one Canadian fishing community, for example, has gone on record opposing "what amounts to fish welfare."

Even when only two parties are involved and side payments are acceptable, cooperative management agreements can be highly unstable because of another fact of fishing life: No one ever knows for sure how good or bad the coming catch will be. Negotiations are tough enough when the stakes are clear. Random variation complicates the calculations. And the worst occurs when the two sides have different information or expectations.

McKelvey looked at that problem in his paper in *Natural Resource Modeling*. "In an environment of incomplete information," he writes, "mis-estimations by the parties, both of values and likelihoods, can lead them to rash and precipitate actions that can easily destabilize a cooperative regime and degrade the fishery, both biologically and economically." The best bet for resolving the conflict, McKelvey suggests, is a binational authority, with access to funds for side payments if necessary, whose role is to propose "rental" arrangements for fishing rights to both sides—and whose game-theoretic goal is to maximize its own return from the rentals (which, if positive, could be used to enhance the fisheries).

It remains to be seen whether the U.S. and Canada can settle their differences and reach agreements that will halt the decline of the salmon stocks. Groups on each side claim rights that must be respected. But as McKelvey optimistically observes, "From a game-theoretic perspective, it's not a matter of rights, it's a matter of possibilities."

Making Sense of Salmon Cycles

Even in a world of perfect harmony, fishing is risky business. Harvests are highly variable. One year's bounty can be followed by the next year's bust.

Pacific salmon are particularly problematic. The annual abundance of sal-mon in their rivers of origin often varies by orders of magnitude (see Figure 2). Consequently, one year's harvest can be a hundred times larger—or smaller—than the previous year's. The fluctuations tend to follow four-year cycles. But why? Understanding the dynamics of salmon populations, with an eye on the role of human intervention, is an important problem, both environmentally and economically.

Ransom Myers and colleagues Gordon Mertz and Jessica Bridson of the Department of Fisheries and Oceans in St. John's, Newfoundland, and Michael Bradford of Simon Fraser University in British Columbia have analyzed mathematical models with data for sockeye salmon in the river systems of British Columbia and Alaska. In a paper that appeared in the *Canadian Journal of Fisheries and Aquatic Science* (October 1998), they argue that the observed four-year cycles are the result of stochastic forcing. The

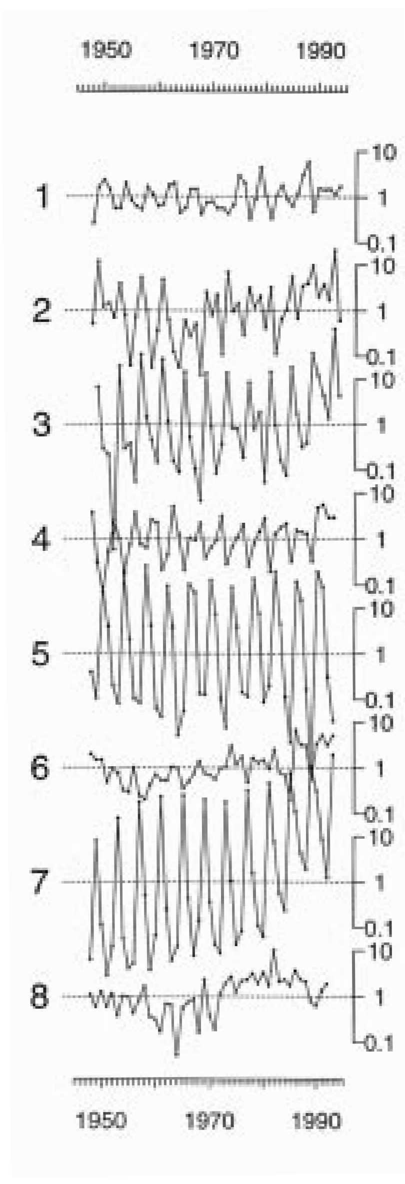

Figure 2. *Variability in salmon populations on eight tributaries of the Fraser River (from* Canadian Journal of Fisheries and Aquatic Science, *Volume 55, Number 10, October 1998, pages 2355–2364).*

best way to damp the cycle (and ultimately increase the annual yield), they suggest, may be to reduce the harvest rate during the lean years.

Offhand, a four-year sockeye cycle is understandable. Salmon have a natural four-year life cycle. They hatch in freshwater river systems, hang around for a year or two, and then head out to sea for a couple of years, returning at the age of four to spawn in their river of origin. (Actually, some salmon have five- or six-year cycles, but four is the norm.) Consequently, the stock on a given river can be viewed as consisting of four separate lines. Roughly speaking, $S(t)$ determines $S(t + 4)$ but not $S(t + 1, 2, \text{or } 3)$. The four-year cycle seems self-explanatThe standard deterministic model, though, implies that all four lines should converge on the same equilibrium value. The basic equation is $S(t + 4) = aS(t)\exp(-S(t))$, where $S(t)$ represents the stock level in year t (normalized to nondimensional units) and the "constant" a includes the effects of harvesting. If $a > 1$, this equation predicts an equilibrium population level $S_0 = \ln(a)$. There's nothing in the model to sustain cyclic variations.

The standard model, of course, is highly simplistic. Two possible complications are readily apparent. First, there's always some random variability in real populations. Second, it's simplistic to assume that there is *no* interaction among the four lines of fish. Because salmon spend a year or two at home before heading out to sea, three groups are competing for food and dodging predators at any given time.

Myers and colleagues have examined a model that incorporates both complications. The equation becomes $S(t + 4) = aS(t)\exp(-S(t) - bS(t - 1) - cS(t - 2) + e(t))$, where b and c are parameters reflecting the delayed density dependence and $e(t)$ is a random Gaussian variable of mean zero. Mathematically, the problem is to see how the parameters a, b, c, and σ (the standard deviation of the Gaussian variable) affect the dynamics. Statistically, the problem is to test the model against actual data, to see if a compelling case can be made for any explanation of the four-year cycles.

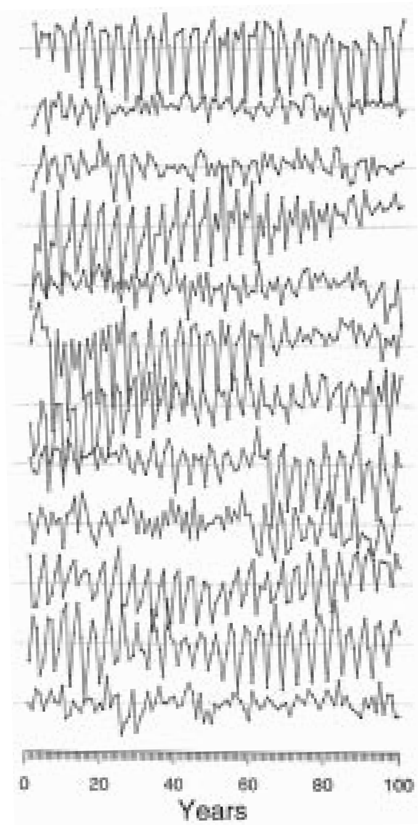

Figure 3. *A simulated century of salmon cycles, with values a = 1.2, 2, and 3, and standard deviation σ = 1 (from* Canadian Journal of Fisheries and Aquatic Science, *Volume 55, Number 10, October 1998, pages 2355–2364).*

The Canadian researchers have done a "meta-analysis" of 34 time series of sockeye data from lakes and rivers in the Fraser River watershed of British Columbia and the Bristol Bay system in Alaska, looking for evidence of delayed density dependence. They found a hint of a one-year delay ($b > 0$), but not enough to account for the pronounced cycles.

Analytically, the deterministic model with a one-year delay has an equilibrium value S_0 of $\ln(a)/(1 + b)$. For small departures from equilibrium, the model can be linearized to the equation $s(t + 4) = ps(t) - qs(t - 1)$, where $s(t) = \ln(S(t)/S_0)$, $p = 1 - S_0$, and $q = bS_0$. The linearization is stable as long as $p - q = N - \ln(a)$ has absolute value less than 1—that is, for $1 < a < e^2$. In this interval (which is thought to include the real-istic range of values), the linearized dynamics drive all departures to zero.

More recently, the researchers have analyzed the effects of stochastic forcing ($\sigma > 0$), with and without delayed density dependence. In the simplest case ($b = c = 0$), the linearized equation is $s(t + 4) = ps(t) + e(t)$, with $p = 1 - \ln(a)$. The departures from equilibrium are random variables. If it is assumed (or proven) that their probability distributions tend to an equilibrium distribution s, then the averaging equation $<s(t + 4)^2> <(ps(t) + e(t))^2> = p^2<s(t)^2> + \sigma^2$ (the "cross term" $<s(t)e(t)>$ vanishes, be-cause the Gaussians can correlate only with future populations) implies that $<s^2> = \sigma^2/(1 - p^2)$.

Cycles can be accounted for by the presence of four-year correlations: $<s(t)s(t + 4)> = <ps(t)^2 + s(t)e(t)> = p<s(t)^2> \approx p\sigma^2/(1 - p^2)$. This suggests that four-year cycles should be pronounced when a (and hence p) is close to 1, and lost among the noise when $a \approx e$. Moreover, the negative correlation when $e < a < e^2$ suggests that what's seen in that regime is an eight-year cycle.

Computer simulations indicate that even when the linear approximation $\exp(-s) \approx 1 - s$ is way off, the con-clusions are qualitatively correct. Hundred-year runs with $a = 1.2$ (a reasonably realistic value) are dramatically different from runs with $a = 2$ or 3 (see Figure 3).

The results have implications for fishery management. They suggest that relaxing the harvest rate on the "non-dominant" lines should suppress the cyclic tendency and—more important, as far as fishermen are concerned—ultimately pay off with increased yields. In short, mathematics confirms the wisdom of the rod and reel: Have patience, and don't forget to brag about the one that got away.

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