Title

Control Team 51

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Abstract

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Contents

1 Introduction: Ms. Jones always said "Reduce, Reuse, and Recycle"

In elementary school geology we all learn about the importance of conserving non-renewable resources–oil, water, coal–because when we use them all up, they will be gone forever. However, it is usually in the same lesson that we learn to recycle paper, because deforestation has depleted so much of the world's natural woodlands. But trees grow back; it just takes a long time, and the rate at which we log forests is faster than they can be replenished. In fact, it is the same with other "nonrenewable" resources: oil and coal will eventually compound again, though it may take thousands of years, and water will clean itself of pollutants. This brings about the question: **What constitutes a "nonrenewable" natural resource?**

From Webster's New Millennium Dictionary we take the definition:

nonrenewable resource: Any natural resource from the Earth that exists in limited supply and cannot be replaced if it is used up; also, any natural resource that cannot be replenished by natural means at the same rates that it is consumed.[4]

This definition is similar to the concept of *effectively nonrenewable* proposed by Barton, Reitan, Kieffer, and Palmer. Says Barton et al., "However, if the rate of resource consumption is high, even "renewable" materials can become effectively nonrenewable."[5] Using this conception of nonrenewable, one could claim that with a rate of consumption greater than the rate of reproduction or replenishment, any resource could be considered nonrenewable. Certainly this is the case with our depleted woodlands.

The resource we choose to model is fish. Fish is a staple source of protein in the diets of nearly all coastal societies and plays a large role in the world economy. Both fish catch and fish consumption is project to increase drastically over the next 30 years.

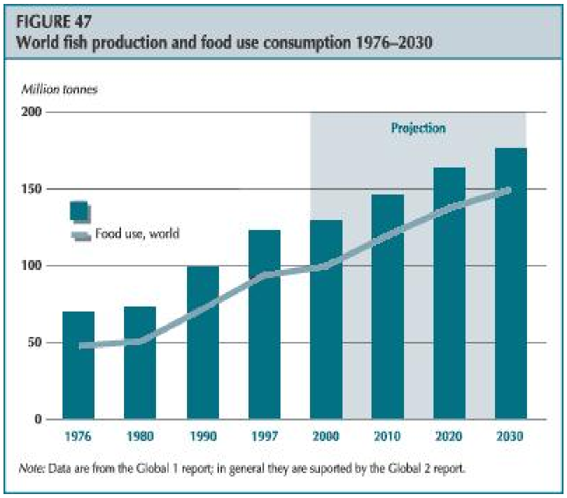


FIGURE 47
World fish production and food use consumption 1976–2030

Note: Data are from the Global 1 report; in general they are suported by the Global 2 report.

Unfortunately, such increase is not necessarily a good thing for all parties involved. As technology has improved, overfishing has resulted in the endangerment of many species of fish. Making the problem worse is the loss of habitat that handicaps the fish in the reproduction/consumption battle. The real losers, however, will be the economies of the world when the results of this unintentional "tragedy of the commons" is felt.

In particular, we choose to inquire into **quantitative population dynamics** for the wild population of Southeast Alaskan Coho Salmon. While Coho populations in other parts of the Pacific have suffered in recent decades (with, for example, the Coho population of the Snake River in Washington having been declared extinct by the Fish and Wildlife Service [6]), the Coho population of the Southeastern Alaskan Peninsula have done comparably well for three reasons:

- **Favorable natural environment conditions.** Fluctuations in natural environment, especially current, water temperature and water level have a large effect on the prosperity. Such conditions have favored Alaskan salmon over Pacific Northwest Salmon for approximately the past two decades. As a general rule, in the years before, during, and after El Niño, environment conditions tend to favor Alaskan salmon.
- **Low level of human imposed environmental hazards.** Human imposed environmental hazards such as a dams, polluted streams, and eroded river banks have the effect of not allowing salmon to reach suitable spawning grounds. However because Alaska is quite underdeveloped compared to other salmon habitats, these human imposed hazards have not greatly affected the fish population to date.
- **Close governmental controls protecting against overfishing.** Through treaties such as the Pacific Salmon Treaty between the U.S. Federal Government and the Canadian Government and through careful control by the Alaska Department of Fish and Game, agencies were proactive from an early stage about protecting Alaskan salmon.

However, we would hypothesize that an unfavorable shift in any of these areas without suitable compensation would translate into depletion of salmon population.

2 Objectives

- Construct a realistic model of the dynamics of the Coho Salmon Population accounting for both environmental conditions and amount harvested.
- Use the model to predict the future of the Coho population both in a situation of controlled and uncontrolled fishing and given various future environmental trends.

- Use the model to calculate a maximum allowable annual harvest and still ensure enough salmon will spawn to replenish the population (herein termed "maximum sustainable yield").
- Create a fair and practical policy to allocate the available catch to the fishers of the region.
- To consider alternatives within the region to wild harvested salmon.

3 Terms

The terms defined here are specific concepts in ichthyology. In several cases multiple terms may be found in the literature to express the same or similar concepts. We will define the term that we prefer and list alternate terms. In a few other cases we use a term slightly differently than it is used

Ichthyology The scientific study of fishes.

fishery

Stock A countable population of fish sharing the same fishery and/or spawning area. We use this term interchangeably with fish population. Some literature attaches a more precise meaning to the term *Stock* as specifying fish of a certain maturity, but note that we *do not* attach any such connotation.

Smolt The number of fish in a given *stock* that survive after being spawned to a level of maturity when they are prepared to begin migration to a marine habitat.

Run The group of fish in a fishery that survive until maturation and prepare to migrate back to their fresh water habitats to spawn. Referred to in data as *Run Size* for number of fish in a run.

Escapement The portion of a *run* that is not fished and survives to reach the spawning grounds or hatchery. also sometimes *Spawning Population* or *Spawners*.

Recruitment The group or size of the group out of those spawned by a given *escapement* that survive to a level of maturity when they are prepared to begin migration to a marine habitat. In our usage of the terms, this is **IDENTICAL** to the term *smolt*, but we specify that the *recruitment* from year x is produced from *escapement* of year x and then becomes the *smolt* for year $x + 1$. For example the *recruitment* from 1995 in a single fishery are the same as the *smolt* for 1996.

Mortality The NUMBER of fish in a *stock* that die between the stage of being in the *smolt* and in the *escapement*.

Natural Mortality The NUMBER of fish that die as a result of any cause *other* than being fished.

Instantaneous Natural Mortality A **rate** calculation for natural mortality. Calculated as a solution to the differential equation given in the Baranov Catch Equation.

Exploitation Rate The PERCENT of the fish out of a *run* that are harvested. Also *Harvest Rate* or *Catch Percent*.

4 Southeast Alaskan Coho Salmon

Southeast Alaska is the region of coastline and offshore islands belonging to the United States bordering British Columbia. Sometimes the region is referred as the Alaska Panhandle, but we will call it Southeast Alaska Throughout. The primary industry of the region is salmon fishing, but tourism and logging also contribute. The group of several thousand islands making up the Alexander Archipelago off the shore offer protection to the inland coastal waters from large waves, making both an ideal environment for salmon and relatively easily navigable waters for fishing vessels.

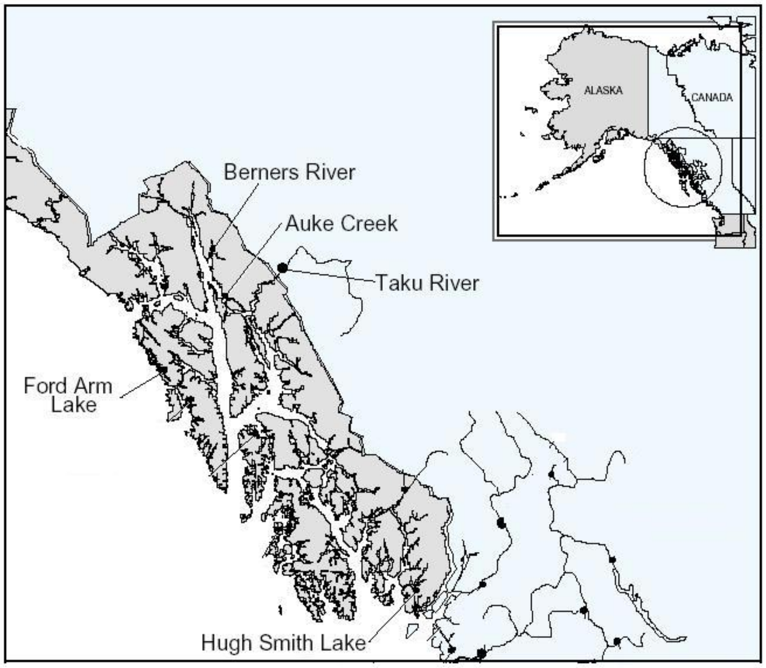


Figure 1: The Southeast Alaska region with the rivers and lakes which we will analyze specified.

4.1 The Importance of Fishing to Alaska and the Southeast

In 1994 commercial fishing produced \$223.6 million in income for residents and employed 7,529 people, accounting for around 45% of the private sector employment. If the Southeast Alaska region was an a 51st state, it would be the second largest seafood producer in the United States, a close second only to the remainder of Alaska[9]. As for the importance of Coho salmon in the region, in 2004 an estimated 2,755,000 Coho were fished in the region, over half the state-wide total of 5,066,000 Coho[10].

4.2 The Life Cycle of Coho Salmon

The life cycle of the Coho salmon lasts approximately three years. Salmon (the *escapement*) return to spawning streams where they were spawned between July and November, depending in part on regional temperature. They are a semelparous species, meaning that they die after they spawn once. Juvenile salmon (the *smolt*) make their way back to the ocean approximately twenty months after their embryos emerge from the gravel riverbeds in May or June. They spend eighteen months in the ocean before they prepare to return to their spawning streams. They are now the *run*, and it is during the beginning of this return trip to their spawning grounds that they are fished.[12]

Assumptions regarding the life cycle of the Coho:

- The life cycle lasts three years.
- Juvenile salmon, **smolts**, spend 3 years subject to natural mortality, assuming the natural mortality to be constant across freshwater and ocean over time.
- Salmon are subject to fishing mortality only once in their lifetime. The fisheries catch salmon on their way back to the spawning rivers, so this is a reasonable assumption.

4.3 Coho Salmon Data Sets

In order to construct our model, we use data sets from a 2003 paper, "Stock Status and Escapement Goals for Coho Salmon Stocks in Southeast Alaska" by Leon Shaul, Scott McPherson, Edgar Jones, and Kent Crabtree, a Special by the Alaska Department of Fish and Game[11]. The data used gives counts of the salmon stock from several different fisheries in the region: number of *smolt*, *catch size* by fishing method (troll, seine, gillnet, sport, etc.), and *escapement*. Also Shaul et. al use this data to calculate the other variables: *run size* (used interchangeably with *total return*), *exploitation rate* (referred to in other literature, and used by us interchangeably with *harvest rate*. These data are given by the formulas:

$$\textit{run size} \;=\; \textit{escapement} \;+\; \textit{catch size}$$

$$exploitation\ rate \ = \ \frac{total\ catch}{run\ size}$$

From the complete set of data we select five fisheries for which the most complete and regionally representative data is given. These are **Auke Creek**, **Berners River**, **Ford Arm Lake**, **Hugh Smith Lake**, and **Taku River** Using data from these fisheries, we will set parameters for our model, and then make future predictions for each river in the model, then, under the assumption that **over time, the behavior of the coho populations from these fisheries is roughly representative of behavior of the population from the entire region**, we will make predictions about future salmon populations from the region.

5 Developing a Model

We model Coho population as a feedback loop of the life cycle. For the sake of simplicity, we assume that noncommercial fishing is a negligible effect. Considering that recreational (noncommercial) catch of Coho salmon in Southeast Alaska reached its peak in 1998 at 163,500 fish, a mere 5.3 percent of the total Coho catch in the region for the year, we consider this a reasonable assumption. (coho salmon stocks (1).pdf, pg. xiv) In the model, we take mortality to be the sum of natural death and fisheries catches alone; thus, we assume both predators and sport fishermen fall under the natural mortality rate.

Each class of salmon that return to spawn are considered stock and subjected to a standard stock-recruitment model (Ricker, discussion below). From Ricker's model, we calculate the number of recruits that are available for fishing the next year. Natural mortality is computed using a version of Baranov's Catch Equation (see below), modified for a finite fishing season, and the returning salmon are the stock for the next year.

We use catch data from the past twenty years as inputs to the catch mortality. With regards to projecting catches in the future, we make the following assumptions:

- Fishing technology will not improve drastically. That is, CPUE will remain dependent on salmon population and not on other factors, such as new fish-finding sensors.
- The "tragedy of the commons" concept – that common goods will be abused since no individual has an incentive to limit his or her own use of the good, as exemplified historically by common cattle grazing pastures -- implies that unless the price of salmon plummets or quotas are increased beyond possible catch, fishing capacity will be determined by quotas alone. Fisherman will always meet their quotas. In the case of no quotas, we assume a risk averse strategy is adopted to maximize the salmon harvest over a long time scale.

5.1 Ricker Model

Since we are interested in overall trends of the population of salmon over time, and not specific estimates of the number of recruits for any given year, we model recruitment based on a stock-recruitment relationship, namely Ricker's model, rather than a Markov process. Ricker's model is preferable to similar stock-recruitment models (such as the Beverton-Holt model) for modeling Pacific salmon such as Coho, since recruits are often measured as adults, and thus it is natural to call them the stock for the next year (Hilborn/Waters).

Ricker's model (in one form) is given by the equation

$$R = Se^{a(1-S/b)}$$

where R is the recruitment, S is the stock, and a and b are parameters governing the shape of the curve. Biologically, a is proportional to reproductive capacity, while b is a measure of density-dependence. For a derivation, see Quinn and Deriso.

5.1.1 Implicit Assumptions and Limitations of the Ricker Model

- Ricker's model explicitly assumes that when there is no stock, there are no recruits. This means that the population is implicitly closed – there are no immigrations from other populations. This is a reasonable assumption in our case because every Coho salmon returns to its place of origin.
- Spawning stock size is inherently difficult to measure, and the stock-recruitment analysis is extremely sensitive to errors in spawning stock size (Hilborn and Walters, Walters and Ludwig). Although our data is the official data used by the state of Alaska to determine fishing policy, Hilborn and Walters assert that the biases in the model, mainly underestimating the correllation between recruitment and stock size, have led to overfishing. In choosing a stock-recruitment model, we may be falling subject to the same biases.

5.1.2 Estimating Parameters for the Ricker Model

For each of the five rivers, we fitted the Ricker curve to the data sets using a least squares approximation to find suitable values of a and b following the procedure described in Hilborn and Walters(cite). We begin by rewriting

$$R = Se^{a(1-S/b)}$$

as

$$log(\frac{R}{S}) = a - \frac{a}{b}S$$

and then treating the latter equation as a linear regression

$$y = b_0 + b_1 X + w$$

where $y = log(R/S)$ is the dependent variable, $b_0 = a$ is the intercept, $-a/b$ is the slope, and w the residual.

(table with: a, b, sigma=stnd deviation of residuals, for all rivers)

5.2 Modified Baranov Catch Equation

We want to model mortality of fish until their return to spawning grounds. To do so, we use a simple deterministic model of fishing and modify it to account for the specifics of the Coho fisheries industry.

The standard Baranov Catch Equation is given by

$$C = \frac{F}{Z} N_0 (1 - e^{-Z\tau})$$

where C is the total catch, F is the instantaneous fishing mortality, N_0 is the initial population, $Z = F + M$, where M is the instantaneous natural mortality, and τ is the maximum age, which by assumption is three years.

This is the solution of the differential equation

$$dN/dt = -FN - MN$$
$$N(t) = N_0 e^{-Zt}$$

[19]

This is the correct general expression for $N(t)$, but since Coho are not caught their whole lives (only the last year before they enter the stream from the ocean), we can break this equation up into two parts: the amount of fish left after natural mortality and then subtracting the amount of fish caught. We assume that no natural mortality occurs after the fish are caught since it makes the math simpler and there is not relatively too much time for them to die. Thus for a limited fishing season ($\tau = 3$ months in the case of Alaskan Coho life cycle) it is best to model the surviving population (i.e. escapement) as

$$\text{escapment} = (N_0 e^{-3M}) - C$$

The first term on the right-hand side gives the run size, where N_0 is the recruitment and M is the natural mortality value. We calculate M by solving for the formula

$$\text{Run} = N_0 e^{-3M}.$$

The solution is

$$M = -\frac{\ln(\frac{\text{Run}}{N_0})}{3}$$

5.2.1 Implicit Assumptions and Limitations of the Baranov Catch Equation

- There is no variation in catch. In reality, catch is more similar to a stochastic process, since it is determined by many factors, including the dynamics and migratory patterns of the population, the fishing industry, and the environment.

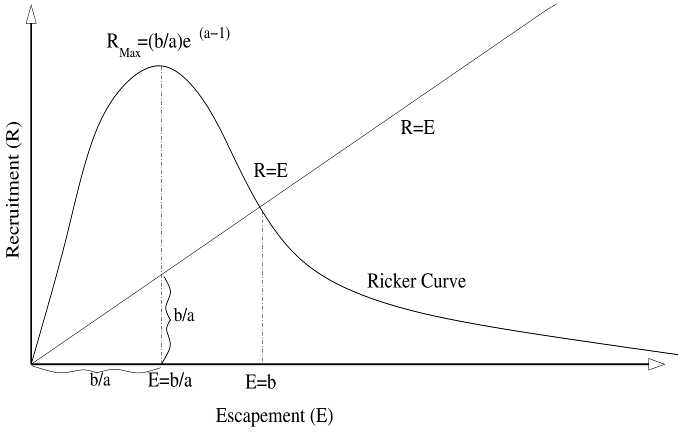
- Mortality during fishing season is solely due to catch and not to natural mortality.
- Natural mortality is constant over time. This may seem improbable, given the graphs of natural mortality for each of the rivers. If we consider environmental variation to be random over time within bounds, then these environmental effects, averaged over time, result in the same error margin as those for a constant mortality model.
- Catch is proportional to stock. We assume that fisheries employ a risk-averse harvest strategy, mainly one in which catch is proportional to stock. This maximizes the logarithm of the catches [18]. This is equivalent to assuming that fisheries strive to sustain maximum profit over the long run.

We calculate C by averaging (by river) the percent of the total run caught, and assume that fisheries will strive to maintain this percent, following our third assumption. We take M to be the average of mortalities (by river) over time, and assume this also to be constant, neglecting environmental factors.

(table with C and M values for each river, and std. deviations of diff, mortality vs. time river data and Baranov eq, graphs with increased and decreased values of M)

5.3 Using the Catch to obtain the MSY

There are two humanly modifiable variables in our model; environment (i.e. dams, pollution, etc.) and yearly catch. The easiest to modify is catch. As we will show, if it is possible to regulate the amount of catch in order spawn the maximum amount of recruitment, then the largest about of catch can be given the follow year while still achieving equilibrium. First, let us examine the geometric qualities of the Ricker Model curve.



The most interesting point is where $E = \frac{b}{a}$. If the abundance of Coho is enough to reach this point, then you will get the maximum amount of recruits.

This is commonly referred to as the Maximum Sustainable Yield (MSY). Furthermore, if

$$C = R_{\max} - (\text{Nat.Mort}) - \frac{b}{a},$$

then the next following escapements will equal b/a. Thus a cycle is produced that continually produces the most amount of catch while keeping the salmon population stable. Another form we can write this is

$$C = (C\%)\text{run},$$

where $C\% = \frac{C}{\text{run}}$. This form is used to compute the IFQ, as defined later in the paper.

This is an ideal model. In reality there is uncertainty in the mortality, which affect the predicted value of C from the equation above. This in turn creates uncertainty in the escapements about b/a. If the uncertainty is large enough, the model will become unstable and produce an oscillatory abundance from year to year, which increases the chance of completely kill off the Coho. Thus it is important to know more specifically what it means for an uncertainty to be large.

The uncertainty is dependant on many variables. The two biggest are the concavity of Ricker curve at $E = b/a$ and the unpredictable natural mortality of the coho. However, as a first approximation, it can be shown by way of a plot that if the percentage error with respect to Escapement (i.e. b/a) is held constant between multiple Ricker plots, they produce about the same ratio of Recruitment to Max Recruitment. Thus if the percentage error is *epsilon* and $b' > b$, then the standard error, $\delta_{b'} = \epsilon(\text{Escapment}) = \epsilon(\frac{b'}{a})$, has the property that $\delta_{b'} > \delta_b$. These facts can be seen in the following graphs of Escapement verses Time.

[a=3, b=5000 and 8000]

It is also worth noting what should be done when

$$C > R_{\max} - (\text{Nat.Mort}) - a/b,$$

In this case, the recruitment and escapement will become oscillatory and there is no way to efficiently bring the value of escapement up unless C=0 for a duration of time until it once again reaches b/a.

The other consideration is what should be done if the coho are inherently less than $b/a - (nat.Mort)$ to begin with. Many things can be done, but the most drastic and most direct is to make C=0 until it reaches this point of MSY.

6 Consequences of the Model

To our surprise, given a constant exploitation rate, our model is robust with respect to the magnitude of the exploitation rate (add and explain figures).[1] This

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[1] Of course, for a non-constant exploitation rate it still remains possible to"fish a population out", as long as

$$\text{Catch} > (\text{Recruitment}) - (\text{Natural Mortality}) - (b/a)$$

remains true with high levels of natural mortality (figs), indicating that fishing alone cannot extinguish the species. What, then? We hypothesize that environmental factors, specifically those affecting recruitment in the Ricker model, are the main threat to the salmon population.

The book *Upstream*, a report by the National Research Council on the the status of salmon stocks in the Pacific Northwest, lists a number of reasons for the precipitous decline in fish population, only one of which is fishing. Instead, the list is dominated human environmental interventions, such as forestry, industrial activities, urbanization, and dams [17]. Currently, these effects largely do not exist in Alaska.

Recall our original three hypotheses from the introduction about why Alaskan salmon did well compared to Pacific salmon: favorable natural environmental conditions, low level of human-imposed environmental hazards, and close governmental controls protecting against overfishing. Over the long term, human-imposed environmental conditions are the best predictor of salmon stock, because these are permanent stressors that will affect the stock over an extended if not indefinite period of time. Human-imposed environmental conditions include global warming, dams, forestation, and pollution of river beds. For year to year fluctuations in population, environmental conditions are a better predictor because they are more likely to vary from year to year – consider current, water temperature, or river height. Finally, we can consider fishing strictures far less important in the long-term forecast of salmon stock, again maintaining the previous assumption of a constant exploitation rate.

How can we model the aforementioned and other environmental factors? We are interested in how the stock-recruitment relationship (Ricker Model) is modified by environment. However, there are numerous environmental variables, each with an unknown effect on the stock-recruitment curve because the effect a single environmental variable cannot possibly be measured in isolation from the others.

We have said previously that current conditions are favorable for Alaskan Coho. We thus take a and b values over the past twenty years to encapsulate favorable environmental conditions. Environmental variables effect Ricker's model in the following extension suggested by Chen and Irvine:

$$R = Se^{a-bS+c_1Z_1+\ldots c_pZ_p}$$

(A semiparametric model to examine stock-recruitment relationships incorporating environmental data)

We then explore the effect of introducing negative generic environmental effects of various orders of magnitude (without trying to specify by what or to what degree the environment is being altered). (Figures)

Ricker's model is extremely sensitive to negative environmental effects. We thus conclude that the fate of the salmon stock is largely dependent on mitigating these negative environmental factors, although we cannot say which ones are most germane.

7

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9 Policy Recommendations

While we have seen that under current conditions Southeast Alaskan Coho Salmon runs are not in serious danger and could even be considered to be thriving, we also note from the ever so slight adjustments to environmental constants in the Ricker Model that any negative shift in environment could be devastating to fish populations. Thus we see two areas in which Alaskan lawmakers should effect policy in order to ensure the preservation of Southeastern Coho salmon:

- Ensure the protection of the environment and in particular salmon freshwater habits by limiting development around the Southeastern rivers and the Alexander Archipelago.
- Enact a well advised Individual Fishing Quota (IFQ) system now, before it is needed so that if conditions deem one necessary, it is already in place and functional.

9.1 Preserving Salmon Habitats

In salmon and many other respects, Alaska holds the advantage over other regions such as the Pacific Northwest and British Columbia in that Alaska boasts a vast abundance of resources, but without a dense population or harmful urban centers. As an example, while Southeastern Alaska alone harvested more salmon in 2004 than the states of Washington, Oregon, and California combined[13], the entire state's population, 648,818 people[7], is only slightly larger than the 570,426 who live in Seattle proper[8], Washington's largest city.

9.2 Individual Fishing Quotas (IFQs)

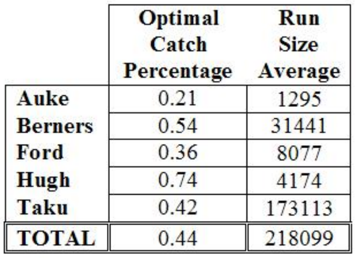
An Individual Fishing Quota is an amount of the annual harvest of a particular fish out of a particular fishery that is

9.2.1 Establishing Total Allowable Catch (TAC)

We make the assertion that **the Total Allowable Catch should be the run size times the exploitation rate that gives the Maximum Sustainable Yield (MSY) for the system (Optimal Exploitation Rate).** Using the algorithm given in section (FILL IN SECTION HERE) for calculating the Optimal Exploitation Rate, we calculate this independently for each of the five river systems (under the condition that current environmental trends continue). These rates are the values in the first column of the table below. Then we use the assumption that Coho salmon stocks from these five river systems are roughly representative of stocks from entire region (see **Section 4.2**) to calculate a Optimal Exploitation Rate for the region. To do this we first take the average of the run size for each river or lake (data in second column of table), then use this to calculate a weighted average of the Optimal Exploitation Rate according to the formula:

$$\text{Regional Optimal Exploitation} = \frac{\sum [(\text{Optimal Exploit})_i \cdot (\text{Aver Run Size})_i]}{\sum [(\text{Average Run Size})_i]}$$

where the i subscripts indicate a river or lake and we are taking the sum over each of the 5 systems.



	Optimal Catch Percentage	**Run Size Average**
Auke	0.21	1295
Berners	0.54	31441
Ford	0.36	8077
Hugh	0.74	4174
Taku	0.42	173113
TOTAL	0.44	218099

Thus we take .44 to be the Optimal Exploitation Rate for Coho Salmon in the Southeast Alaska region. In the literature, there is great deal of debate over choosing an appropriate Total Allowable Catch. We propose the following to compute Regional TAC using Regional Run Size:

$$\text{TAC} = \text{Run Size} \cdot \text{Optimal Exploitation Rate}$$

Many think that TAC should be some figure less than the Optimal Exploitation Rate as a safeguard against overfishing, being that this is the most compelling argument for IFQs to begin with. Such logic seems valid in fisheries where the stock is severely threatened and IFQs are being implemented as a sort of last resort effort to save the population. However, in the instance of the Southeast Coho, this is currently not the case, and one of the advantages of implementing an IFQ structure now while the stock is strong is that if the TAC is slightly off, the thriving fish population will be able to handle it without devastation (recall the robustness of the model), and the TAC can be adjusted for the following year. In the interests of maximum fish harvests, this solution is superior to the alternative of setting a lower TAC.

9.2.2 Allocating Catch Shares

9.2.3 Advantages to IFQs

9.2.4 Costs of IFQs

10 Alternatives and Technology

The main alternative to wild Coho, and wild salmon in general, is farmed salmon. Farmed salmon have much higher levels of a contaminant known as PCB, primarily because their feed (aquaculture) consists of meal and fish oil made from small wild fish. [14]. Studies conducted by the Environmental Protection Agency conclude that PCBs are likely responsible for myriad negative health effects, including cancer, stinted brain development, immune deficiency, and decreased birth weight and conception rates[15]. In addition to adverse health effects, farmed salmon have a deleterious impact on the population of wild salmon. Pens of farmed salmon generate waste that then burdens the local ecosystem. The high densities of fish in the pens promote disease, which sometimes carries over into the wild population. In addition, accidentally released farmed salmon could interbreed with, and potentially overcome, wild populations. [16].

At the moment, farmed salmon are not a substitute. This is not to say that they could not become one. In the event of poor future environmental conditions, it may be necessary to severely reduce fishing wild salmon, in which case an improved farmed salmon industry would be able to fulfil demand for salmon. Such an industry would limit its environmental impact and alter its aquaculture policy to reduce PCBs in the farmed salmon it produces.

Hatcheries are the classic example of a technology introduced to increase or replace salmon populations. Over a hundred years ago, hatcheries were introduced with the assumption that the ocean could support an unlimited number of salmon, and that the hatchery could improve on nature by producing more salmon. This turned out not to be the case:

> Hatcheries have resulted in reduced genetic diversity within and between salmon populations, increased the effects of mixed-population fisheries on depleted natural populations, altered behavior of fish, caused ecological problems by eliminating the nutritive contributions of carcasses of spawning salmon from streams, and displaced the remnants of wild runs.

[17]

The committee goes on to say that the reason for this failure stems from the fact that hatcheries have carried the burden of population substitution, rather than being used as research laboratories. They suggest that hatcheries could, in fact, provide invaluable data on the life history of salmon.

10.1 Research Policy Recommendations

Our model indicates that human-imposed environmental damage, more than anything, is responsible for declining salmon stock. In order to mitigate the exhaustion of salmon, we propose a three-fold research policy:

- First, a study of which environmental factors are most relevant to salmon stock. We would like to know, for example, whether water pollution or deforestation causes greater reduction of stock from year to year. In particular, we propose a cross-study of salmon tagged from hatcheries in areas subject to different environmental conditions over time.
- Second, a study of an improved salmon farm. This would include comparisons of aquacultures, pen designs, and appropriate waste-management systems.
- Third, better data on spawning, recruitment, and natural mortality rates would much improve our chance of determining how best to protect salmon. We propose a study on implanting small computer chips (similar to those used in house pets) into pre-juvenile salmon, with an accompanying computer tracking system, giving data on location over the life-span.

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