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Valuing freshwater salmon habitat on the west coast of Canada

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Abstract

Changes in land use can potentially reduce the quality of fish habitat and affect the economic value of commercial and sport fisheries that rely on the affected stocks. Parks and protected areas that restrict land-use activities provide benefits, such as ecosystem services, in addition to recreation and preservation of wildlife. Placing values on these other benefits of protected areas poses a major challenge for land-use planning. In this paper, we present a framework for valuing benefits for fisheries from protecting areas from degradation, using the example of the Strait of Georgia coho salmon fishery in southern British Columbia, Canada. Our study improves upon previous methods used to value fish habitat in two major respects. First, we use a bioeconomic model of the coho fishery to derive estimates of value that are consistent with economic theory. Second, we estimate the value of changing the quality of fish habitat by using empirical analyses to link fish population dynamics with indices of land use in surrounding watersheds. In our example, we estimated that the value of protecting habitat ecosystem services is C$0.93 to C$2.63 per ha of drainage basin or about C$1322 to C$7010 per km of salmon stream length (C$1.00 = US$0.71). Sensitivity analyses suggest that these values are relatively robust to different assumptions, and if anything, are likely to be minimum estimates. Thus, when comparing alternative uses of land, managers should consider ecosystem services from maintaining habitat for productive fish populations along with other benefits of protected areas.

Keywords: Coho salmon; Valuation; Bioeconomic models; Fish habitat; British Columbia; Cost-benefit analysis

1. Introduction

Protected forest areas or parkland provide numerous benefits to society. Various researchers have advocated the concept of total economic value (TEV) to classify these values (Pearce and Turner, 1990). The TEV of forest areas can be divided into use and non-use values (Fig. 1). Non-use (existence) values capture the concerns that individuals may have about the continued existence of some environmental resource, such as a tropical forest or endangered wildlife species, even though they have no plans to visit or view it. Use values consist of consumptive activities, such as the harvesting of timber and other forest products, non-consumptive activities like recreation, and benefits from the ecological functions of protected forest areas.[1] For example, parkland may provide habitat for fish populations, prevent soil erosion, and regulate surface runoff. Even fish populations themselves are recognized now as providing use values (Holmlund and Hammer, 1999; Daily, 1997). For example, salmon carcasses potentially play an important role in nutrient cycles in forest ecosystems (Cederholm et al., 1999).

Competing uses for proposed and existing parkland create trade-offs between the components of TEV. In this case, consumptive uses such as logging and resource extraction can have large negative impacts on other components of TEV. For example, the benefits from protecting fish habitat may decline if these other activities disrupt natural ecosystem functions. To the extent that some alternative uses are incompatible with ecosystem functioning, all or a portion of these values may be lost. A significant challenge for resource managers is placing values on such ecosystem services provided by protected areas to help in assessing these trade-offs. In effect, measuring changes in value resulting from habitat degradation after an area is no longer protected provides an estimate of the use value associated with the protection of parkland.

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[1] Earlier versions of TEV included option use value, but this is now seen as an element in option price, which is the correct value measure when use values are elicited *ex ante* and there is uncertainty over future supply or demand (Freeman, 1993).

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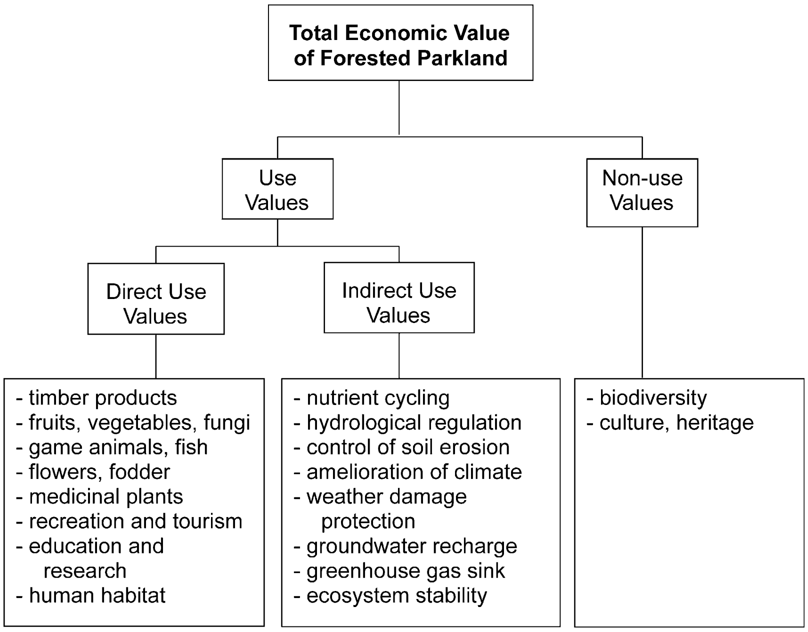

Fig. 1. Total economic value (TEV) of forested parkland. Adapted from Barbier (1991), Panayotou and Ashton (1992), Myers (1992), and Pearce and Warford (1993).

In this study, we develop an approach for valuing a particular use value associated with forested parkland. As a case study, we apply the approach to freshwater spawning and rearing habitat used by coho salmon (*Oncorhynchus kisutch*) on the west coast of Canada. We consider how changes in land use affect: (1) the productivity of coho salmon populations, and (2) the resulting economic impacts on coho salmon fisheries in the Strait of Georgia, British Columbia (BC), Canada.

Valuation of non-market environmental goods and services is now a well-recognized practice, as demonstrated by the development of legally defensible damage assessment methodologies (Arrow et al., 1993). However, relatively few valuation studies have considered the impact of land-use change on the quality of fish habitat and, consequently, on recreational and commercial fisheries. Bell (1972) incorporated the effect of water temperature, which can be affected by land-use alteration, into an empirical model of a fishery, but did not look at land use directly. More recent efforts analyze various types of influences. Several studies consider the outright loss of habitat, particularly coastal mangrove wetlands that support spawning and rearing of juvenile life stages of fish and shellfish (Barbier and Strand, 1998; Lynne et al., 1981). Other studies examine modifications in habitat quality brought about by pollution or other disturbances, as well as altered in-stream flow regimes and salinity levels (Knowler et al., 2001; Swallow, 1994; Fisher et al., 1991; Loomis, 1988; Kahn and Kemp, 1985; Vaughn and Russell, 1982). For a review of several such studies, see Knowler (2002).

In contrast to many of these studies, our analysis contains a number of innovative elements, including:

- the use of bioeconomic modeling and optimization techniques to estimate benefits from protecting freshwater fish habitat that are consistent with welfare measurement in economics, in contrast to simply measuring changes in revenue or similar approximations (Freeman, 1993);
- the estimation of a general coho stock-recruitment relationship at the aggregate population level (e.g. Strait of Georgia, BC), where production benefits from the fishery accrue, in contrast to the local or stream level;
- the incorporation of habitat quality into the stock-recruitment relationship (relating abundance of parental spawners to abundance of offspring that survive to recruitment) using data on abundance of coho salmon and land-use characteristics from a cross-section of small watersheds subject to varying levels of degradation.

Section 2 describes the approach and the data sources used to value coho salmon habitat. Following this, we present the bioeconomic model used in the study and derive the required valuation measures in general terms. We then estimate the necessary biological and economic relationships in the model and summarize our assumptions about the remaining parameters. To yield estimates of the value of habitat protection, we use the 'production function' technique (Hanley and Spash, 1993), making use of our bioeconomic model to estimate the total value of an optimally managed coho salmon fishery under different scenarios of habitat degradation. We conclude with a discussion of results and areas for further research to improve on our estimates.

2. Methods

2.1. Approach to valuation

The most common approach for valuing changes in fish habitat is to estimate changes in net revenue using a number of simplifying assumptions. For example, the total welfare from the fishery in a given year may be calculated as the product of net value per fish caught, size of the exploitable fish stock, and exploitation rate (i.e. the proportion of fish caught by the fishery). The exploitable fish stock may be related to a measure of the habitat available, allowing the estimation of a welfare effect from losses (or gains) in habitat area or quality. Generally, historical values are used for the parameters.

There are a number of potential problems with estimates of habitat value obtained using the above approach. First, the net value per fish may respond to changes in abundance caused by modifications in habitat. The supply of fish to the market may increase (decrease) with an increase (decrease) in habitat, or the cost to catch each fish may change. For example, a reduction in abundance usually leads to increasing unit costs to catch fish. Second, exploitation rates may change in response to changes in abundance. For example, if the fishery declines in productivity due to habitat degradation, fishing openings may be reduced. In addition, estimates of exploitation rates from historical data may not reflect optimal, or even sustainable, exploitation rates. Finally, estimates of recruitment derived from historical data may not reflect optimally managed stocks. For depleted stocks, the average abundance per unit of habitat may be too low and this has implications for economic returns in the associated fishery.

In this paper, we take an approach that is more consistent with welfare economics and the optimal management of natural resources, where habitat quality is an input into production or consumption. Following Freeman (1993), we assess the net social benefits available from the fishery, assuming that it is managed in an optimal and sustainable way. Then we estimate how these benefits change when habitat quality is altered. Optimal management of fisheries has not been the case in Canada nor in many other nations. Thus, long-run values associated with the freshwater fish habitat are likely to have been underestimated in relation to their potential magnitude, in a capital asset pricing sense.[2]

[2] For example, imagine valuing a farm tractor or other similar asset. When assessing its value, the farmer considers the work the tractor can accomplish when it is functioning well and is used correctly and efficiently, not in terms of what it can do when in poor repair.

Our approach differs from an evaluation of historical economic values reflecting past conditions in the fishery. Instead, our measurements ignore various management inefficiencies, such as *de facto* open-access management, dissipated economic rents, and depleted fish stocks.

The production function approach to environmental valuation is one of several revealed preference approaches to non-market valuation, as distinct from the stated preference techniques such as the contingent valuation method (CVM). In revealed preference methods, the underlying value of environmental quality is inferred from observations of actual behavior. More specifically, the production function approach links environmental quality to production relationships (Hanley and Spash, 1993). In our case, use of a production function approach requires the specification of a full bioeconomic model of the coho fishery.

To obtain an estimate of the appropriate welfare measure associated with habitat change, we start with the optimal values derived from the solution of this bioeconomic model, using an initial level of habitat quality. We then vary the level of environmental quality, and the bioeconomic model is solved again given this change in one of its parameters. The net social benefit of the fishery under the changed level of habitat quality is then compared to the net benefit estimated for the situation prior to the change. The difference between these two values constitutes a measure of the social gain or loss associated with the change in habitat quality, and as such it provides a better estimate of the true use value. Our approach differs from the traditional one because we take into account adjustments that take place within the fishery as the exploitable fish stock changes in response to habitat alteration (e.g. changes in fishing effort, catch efficiency, and, hence, costs associated with each harvested fish).

Finally, the optimal values calculated above are expressed in terms of the area of contributing watershed comprising a protected area (or length of stream). Averaging the resulting value over this protected area provides an estimate of the 'habitat value per hectare'. It is derived from the use value associated with freshwater spawning and rearing habitat used by coho salmon. Ultimately, this is only one of many use and non-use values associated with Canadian parks, so it is not intended as a comprehensive land-use value.

2.2. Case study area

Our case study concerns coho salmon spawning and rearing habitat located in BC, Canada. To examine the effects of habitat on coho salmon population dynamics, we rely on data from the Thompson River. As the largest tributary of the Fraser River, the Thompson River drains 54,600 km^2 of the southern interior of BC (Fig. 2). In portions of its catchment area, coho salmon stocks declined by as much as 90% in the last decade (Bradford and Irvine, 2000). Because of declines in these populations as well as others, total catches in the associated Strait of Georgia coho

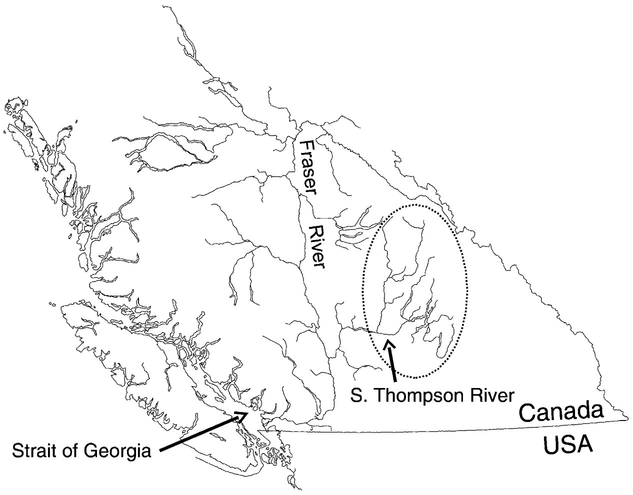

Fig. 2. The Fraser River Basin (British Columbia, Canada), showing the South Thompson River catchment (dotted ellipse).

fishery declined dramatically during the same period (Table 1), culminating in the eventual closure of the commercial fishery on BC coho salmon in 1998.

We linked the status of coho salmon with land use (e.g. habitat quality) at 16 stream sites in the South Thompson watershed (Bradford and Irvine, 2000), which contribute to fisheries in the Strait of Georgia. These streams comprise 503.2 km of habitat (measured in terms of stream length) accessible to coho salmon and drain an area of approximately 7130 km^2. The abundance of adult coho salmon recruits was not directly observable, so we estimated recruitment for each stream and year using data on spawner abundance and a time series of exploitation rates for Thompson River coho from Bradford and Irvine (2000). These authors estimate abundance of recruits using the relationship $X_t = \mathrm{SP}_t/(1-u_t)$, where SP is the actual or observed spawning population and u is the proportional exploitation rate.[3] We used historical exploitation rates for marked Thompson River hatchery coho salmon from Irvine et al. (1999a,b).

We assumed that the Strait of Georgia coho fishery is managed as a commercial troll fishery, selling salmon into an international market where its price is exogenously determined. Our case study is based on historical biological and ecological conditions, and during this earlier period the commercial fishery predominated (Table 1). This assumption does not reflect the recent shift in management emphasis to recreational fishing

[3] Exploitation rate estimates were taken from coded-wire tag recoveries from Thompson hatchery smolt releases (Irvine et al., 1999b) supplemented by DNA sampling of catches in fisheries during 1998 (Irvine et al., 1999a). Spawner abundance data were based on visual estimates of escapement from 1988 to 1998. Since older visual escapement estimates may be biased downwards, we multiplied abundance estimates prior to 1988 by an inflation factor of 2.09. This correction factor was calculated by taking the mean ratio of abundance estimates using new and old sampling/estimation methods in 1998 and 1999 in the streams in our data set.

Table 1
Average annual coho catch in the Canadian portion of the Strait of Georgia, by fishery, 1953–1998. Data from Argue et al. (1983) and Simpson et al. (1999)

Period	Troll		Nets		Sport		Total catch	
	(1000 s)	(%)	(1000 s)	(%)	(1000 s)	(%)	(1000 s)	(%)
1953–1959	333	55	84	14	193	32	610	100
1960–1969	230	47	54	11	201	41	486	100
1970–1977	129	18	54	8	541	75	725	100
1980–1989	139	21	13	2	506	77	658	100
1990–1998	71	24	3	1	227	75	301	100

before the commercial fishery was closed, but it is adopted here due to lack of data to model the recreational fishery. Our expectation was that the commercial fishery would provide a lower-bound estimate of habitat value. Economic data on the commercial troll fishery were available from a comprehensive economic analysis of BC's chinook and coho salmon fishery undertaken by ARA Consulting (1996), based upon a survey of 1138 vessels administered in 1994. We also derived parameter estimates from Argue et al.'s (1983) study of the Strait of Georgia chinook and coho fishery.

3. A bioeconomic model of the commercial coho fishery in the Strait of Georgia

3.1. The model

In this section, we develop the bioeconomic model that we used to estimate the value of freshwater habitat. Expressing this problem in discrete time, the objective of managers is to maximize welfare by choosing the number of fish harvested commercially (h). Accordingly, the expression for net social benefits from the fishery is:

$$W(X_t, h_t) = B(h_t) - C(X_t, h_t) \quad (1)$$

where $W(X,h)$ is the net social benefit from the coho stock in period t; X is the recruitment to the commercially exploitable stock of coho in the Strait of Georgia, measured in numbers of fish; $B(h)$ is the gross benefits from the coho catch; and $C(X,h)$ represents costs incurred by the commercial troll fishery.

The population dynamics for coho are presented as a transition equation showing the recruitment of young coho to the exploitable stock after a 3-year lag between spawning and recruitment to the adult population. Drawing on the delayed recruitment model suggested by Clark (1976), it is possible to incorporate this lag without resorting to a full age-structured model. Coho recruitment in year t is the following function of spawner escapement $(X-h)$ and habitat quality $(\bar{Q})$, which we treat as a fixed parameter initially:

$$X_t = R(X_{t-3} - h_{t-3}; \bar{Q}) \quad (2)$$

Following Clark (1990, p. 238), the planner's problem can be expressed as the following constrained dynamic optimization problem:

$$\max \sum_{t=0}^{\infty} \delta^t \{B(h_t) - C(X_t, h_t)\}$$

$$\text{s.t. } X_{t+1} = R(X_{t-2} - h_{t-2}; \bar{Q}), \; X_{-3}, \ldots, X_0 \text{ given} \quad (3)$$

where δ is the discount term, defined as $1/(1+r)^t$, with r denoting the social discount rate.

When the fish price is internationally determined, as is the case for salmon products, the demand curve is treated as perfectly elastic (horizontal) and this results in an absence of any consumer surplus benefits from the fishery. As a result, the gross benefits from the fishery, $B(h)$, comprise only the revenues earned in the commercial fishery, expressed as:

$$B(h_t) = ph_t \quad (4)$$

where p is the ex-vessel price of salmon less the skipper and crew shares, with these shares expressed as percentages of the ex-vessel price.

To derive the cost function, $C(X, h)$, we begin with the following catch relationship:

$$h(X_t, E_t) = X_t(1 - e^{-qE_t}) \quad (5)$$

where e is the base of natural logarithms, q is the catchability coefficient, and E is the total fishing effort expended over the fishing season, expressed in vessel-days. Inverting Eq. (5) to express it in terms of E, and pre-multiplying the resulting expression by the unit cost of fishing effort c, yields the desired cost function:

$$C(X_t, h_t) = cE_t = \frac{c}{q}[\ln X_t - \ln(X_t - h_t)] \quad (6)$$

Coho recruitment to the exploitable stock was modeled as a modified Beverton–Holt stock-recruitment function (Hilborn and Walters, 1992), with habitat quality ($\bar{Q}$) specified as a habitat quality factor inserted into the standard Beverton–Holt relationship:

$$R(X_{t-3} - h_{t-3}, \bar{Q}) = \frac{a\bar{Q}m(X_{t-3} - h_{t-3})}{1 + \frac{a}{b}(X_{t-3} - h_{t-3})} \quad (7)$$

where a is the productivity parameter, here defined as the number of smolts produced per spawner. Smolts are 1-year-old juvenile salmon that migrate from freshwater nursery areas to the ocean. The capacity parameter (b) is the maximum number of smolts that can be produced by the stream and m is the proportional marine survival rate (smolt-to-adult) for coho salmon. That survival rate applies to the period when the smolts migrate to sea from their freshwater habitat until they return as adults to coastal waters approximately 18 months later. The habitat quality factor ($\bar{Q}$) scales the relationship to reflect changes in the quality of freshwater habitat. For freshwater habitat in pristine condition, $\bar{Q} = 1$, whereas $0 < \bar{Q} < 1$ if habitat has been degraded and $\bar{Q} = 0$ if habitat has been completely lost.

Eqs. (4), (6), and (7) were then inserted into Eq. (3) and the resulting system was solved to provide the long-run equilibrium or steady-state conditions (Clark, 1990). After rearrangement, the steady-state solution consisted of the following two equations in the variables X and h :

$$X - \frac{a\bar{Q}m(X - h)}{1 + \frac{a}{b}(X - h)} = 0 \quad (8)$$

$$\frac{a\bar{Q}m\left(1 - \frac{c}{pqX}\right)}{\left[1 + \frac{a}{b}(X - h)\right]^2\left[1 - \frac{c}{pq(X-h)}\right]} = (1 + r)^3 \quad (9)$$

The above equation system comprises a biological and an economic equilibrium condition, respectively. Expression (8) states that for stock (X) to remain constant, the current stock less new recruits produced by the current cohort must equal zero. Expression (9) is a modified form of the 'fundamental equation of renewable resources' (Conrad, 1995, p. 415). It ensures that harvesting occurs so that fish left in the sea provide a rate of return just equal to that of financial assets (r). The system can be solved to give the long-run equilibrium or steady-state values for coho harvest and exploitable stock, h^* and X^*, respectively, where ($*$) indicates steady-state values derived from the optimization procedure.

The habitat value is calculated by comparing the net economic return (i.e. economic rent) under the pristine situation to the net economic return once the habitat is degraded or lost. To carry out the calculation, distinct Q's for the entire Strait of Georgia Basin are required for the situations with (Q^A) and without (Q^B) the presence of pristine habitat in the South Thompson streams, with $Q^A > Q^B$. This yields the following equation for the change in welfare from habitat protection (Freeman, 1993):

$$\Delta W(X^*, h^*) = \int_{Q^B}^{Q^A} \frac{\partial W(X^*, h^*)}{\partial Q} \mathrm{d}z = W(X^*, h_A^*; Q^A) - W(X^*, h_B^*; Q^B) \quad (10)$$

The middle term in expression (10) indicates that the integration is performed along a path where catch is continuously adjusted to its optimal value. Expression (10) can be stated more simply as the difference in welfare under the 'with' and 'without' pristine habitat situations, as indicated by the right-hand terms in expression (10).

3.2. Biological parameters

Biological parameter values were derived from several sources (Table 2). The productivity parameter (a) in

Table 2
Parameter values assumed for the empirical analysis (1994 Canadian dollars)

Parameter	Units	Value	Source
Ocean survival rate, m	Proportion	0.2	Bradford and Irvine (2000)
Productivity parameter, a	Smolts/spawner	40	Bradford et al. (2000)
Capacity parameter, b	Smolts	7,257,527	This study
Variable fishing cost, c	$/boat-day	109	ARA (1996)
Net salmon price, ex-vessel, p	$/fish	10.50	ARA (1996)
Commercial catchability, q	Proportion caught per unit effort per year	0.00003	Argue et al. (1983)
Social discount rate, r	% Per year	5.0	This study

the recruitment function (7) was set at 40 (Bradford et al., 2000). We used a marine survival rate (m) of 0.2, which is consistent with the natural mortality rate several decades ago in wild indicator stocks of coho salmon (Simpson et al., 1999). Current survival rates are far lower (0.02–0.05) and are unlikely to be sufficient for a viable commercial fishery given estimates of other model parameters. Therefore, we assumed a recovery in the coho stock leading to restoration of the commercial and sport fisheries. Later we discuss the implications for our estimates of habitat value if this recovery does not occur.

Values for the habitat capacity (b) and habitat quality ($\bar{Q}$) parameters were determined by a several-stage procedure using data from 16 streams in the South Thompson River drainage used by coho salmon. First, for each of these streams, we estimated the annual rate of change in abundance of our reconstructed estimates of adult coho recruits (X) using data for 1988–1998:

$$\ln(X_{it} + 1) = \alpha_i + \beta_i t + \varepsilon_t \qquad (11)$$

where α_i and β_i are parameters associated with stream i, t is the year, and ε_t is an error term. We refer to the slope of this equation (β_i) as the instantaneous average annual rate of change in abundance of recruits for stream i.

Next, we estimated a linear relationship between this estimated rate of change in abundance (β_i) and a 'habitat concerns index' (HCI_i) for each stream. The HCI was constructed from 10 major impact categories (indicators of human activity in forestry, agriculture, urbanization, recreation, mining, industrial development, roads and other linear development, hydro development, cumulative impacts, and special biophysical concerns). Each category was generated from up to six sub-attributes relating to aspects of the impact category that might affect stream condition, as observed from GIS data, other information, and local experience (Bradford and Irvine, 2000). Each sub-attribute was rated as 'low' or 'high' by local experts, with the latter referring to the case where the activity was likely to be impacting stream quality. We then used the sum of high scores as our HCI. Although this scheme is an admittedly crude way to estimate the effects of a diverse group of activities within any watershed on salmon habitat, Bradford and Irvine (2000) found a good correlation between the HCI and the rates of decline of coho salmon populations.

For our 16 streams, the values of HCI ranged from 1 to 19, with a weighted average of 9.6. The best-fit relationship between β_i from Eq. (11) for stream i and the HCI_i was:

$$\beta_i = -0.266 - 0.015\mathrm{HCI}_i$$

$$R^2 = 0.15 \qquad (12)$$

The negative slope indicates that streams with more-degraded habitat (i.e. a higher value for the HCI) experienced faster declines in abundance of adult coho than streams with less-degraded habitat (Fig. 3).

We derived the b and $\bar{Q}$ parameters by evaluating several sets of values in repeated simulation trials while comparing our projections of population abundance with the observed empirical relationship between rates of change in recruitment and habitat quality (Appendix A). These steps provided a general stock-recruitment relationship for coho salmon for the 16 streams in our data set, which we then 'scaled-up' to reflect the entire Strait of Georgia fishery. For the scaling procedure, we used an estimate of the total freshwater capacity (expressed in terms of maximum smolt abundance) for all coho salmon populations contributing to this fishery.

The calibration produced a value for the habitat capacity parameter (b) in the 16 case-study streams of 170,909 (smolts) and values for the Q parameter (Table 3). As the weighted average of the HCI for these streams was about 10, our results indicate that, during the years for our simulations, the South Thompson produced approximately 47% of the smolts that it could have produced under pristine conditions (HCI = 10, $Q = 0.47$).

The procedure described above provided a stock-recruitment relationship for coho in the 16 South Thompson

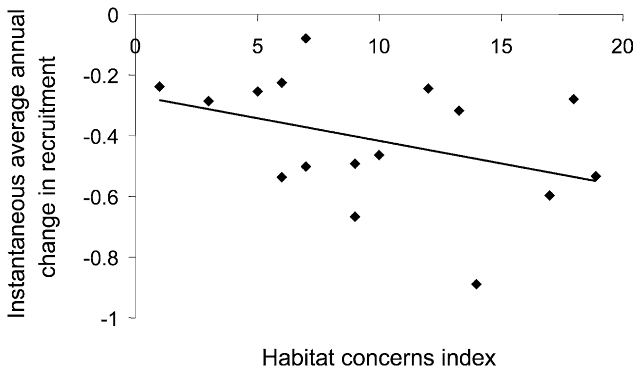

Fig. 3. Relationship between the instantaneous average annual change in recruitment of adult coho salmon (β) and the 'Habitat Concerns Index' (HCI) for 16 South Thompson River streams (1988–1998). Data from Bradford and Irvine (2000).

Table 3
Habitat Quality Factor (Q) as a function of the HCI

HCI	Habitat quality factor (Q)
0	1.00
1	0.91
5	0.67
10	0.47
15	0.34
20	0.27

streams in our data set as a function of habitat quality. However, coho from these streams are harvested along with many other coho stocks in the Strait of Georgia fishery. In our bioeconomic model, we assumed that all coho stocks contributing to the Strait of Georgia fishery are managed as a single unit. To derive a stock-recruitment relationship for the Strait of Georgia coho population aggregate, we scaled up the habitat capacity parameter (b) based on data on commercial and sport catches of coho salmon by Canadian fisheries, releases of coho juveniles from hatcheries, and data on survival and exploitation rates. These data were used to reconstruct the average historical abundance of wild coho salmon smolts contributing to Canadian fisheries in the Strait of Georgia for the 1977–1990 brood years (Appendix A). Assuming habitat throughout the Strait of Georgia basin was similar in quality to that of the South Thompson (i.e. HCI = 10, $Q = 0.47$), the habitat capacity parameter for the Strait of Georgia coho under pristine conditions was 7,257,527 smolts.

3.3. Habitat quality scenarios

We considered four combinations of habitat conditions in calculating the habitat values, depending upon the state of habitat outside the South Thompson case study area (pristine or degraded) and the extent of degradation that occurs within the South Thompson (partial or total). The habitat quality factor (Q) in the various basin or sub-basin combinations is indicated as follows. Habitat quality is denoted as Q_T in the South Thompson catchment, Q_G in the Strait of Georgia Basin in its entirety, and Q_{G-T} in the Strait of Georgia Basin excluding the South Thompson catchment.

The first habitat quality scenario (Scenario A) assumed that the entire Strait of Georgia Basin was pristine, including the South Thompson region, so that the value of Q_G^A, describing conditions prior to a change in habitat, was 1. To derive Q_G^B, representing the situation after the change in habitat, we assumed that the habitat within the South Thompson drainage area was degraded to its current status ($Q_T = 0.47$), with the rest of the Strait of Georgia Basin left undisturbed ($Q_{G-T} = 1$). We estimated that the 16 South Thompson streams contributed 2.3% of the smolt production that was the basis for the Strait of Georgia coho fishery. Since 97.7% of the Strait of Georgia coho stock would come from pristine habitat ($Q_{G-T} = 1$), while 2.3% originates from a degraded area ($Q_T = 0.47$), the weighted value of Q_G^B is 0.9878. We then solved the model using this value in place of $Q_G^A = 1$ (Scenario A in Table 4). The remaining habitat combinations (Scenarios B–D in Table 4) were derived using the same approach but with different values assumed for the state of habitat elsewhere in the Strait of Georgia Basin and for the change in Q within the South Thompson (Table 4).

As a result, the analysis compares the situation where habitat within the South Thompson is pristine (e.g. $Q_T = 1$) to the case where habitat is no longer protected and, consequently, becomes degraded to the level seen in the South Thompson catchment at present (e.g. $Q_T = 0.47$), or is lost altogether ($Q_T = 0$). This analysis is performed under two sets of assumptions about habitat quality elsewhere in the Strait of Georgia Basin ($Q_{G-T} = 1$ and $Q_{G-T} = 0.47$), leading to the four combinations of habitat conditions (Scenarios) indicated in Table 4.

3.4. Economic parameters

Two key economic parameters in the model are the net price per adult coho (p) and the annual vessel cost (c), assuming the fishery is a commercial troll fishery (Table 2). Taking an ex-vessel price for salmon of $2.66/lb ($5.86/kg), together with an average whole-fish weight of 6.56 lb (2.97 kg), yielded a gross price for salmon of $17.45/fish (ARA, 1996). The ARA study also indicated that the skipper and crew share averaged 40% of the gross revenues in the coho troll fishery, leaving a net price of approximately $10.50/fish. All prices are expressed in Canadian dollars (Note: C$1.00 is approximately equal to US$0.71).

Average daily fishing costs for the troll fleet were also derived from the ARA study. To capture the economic rent associated with the salmon catch, we included only those variable costs arising from daily decisions to enter the fishery. We ignored sunk costs such as insurance, off-season repairs, interest, depreciation, etc. We also left out license fees because these represent a redistribution of economic rent to resource owners rather than the opportunity cost of resources used in the fishery. On a daily per-vessel basis, the remaining costs were (all values in 1994 Canadian dollars):

fuel $47.20
food/trip expenses $38.66
gear repairs $6.40
other goods and services $16.70
total (per boat-day) $108.96 (used $109)

We assumed a catchability coefficient (q) of 3×10^{-5}, based upon a model of the commercial troll fleet fishing coho in the Strait of Georgia (Argue et al., 1983). Historical estimates for q varied seasonally from about 3×10^{-5} early in the season to just under 2×10^{-5} later in the season (Argue et al., 1983). We selected the higher value because there is greater effort expended during the earlier part of

Table 4
Optimal values for the Strait of Georgia coho fishery and valuation of habitat loss as change in economic rent,($W(X^*, h^*)$, in 16 South Thompson streams. Scenarios A through D reflect a weighted habitat quality factor for the entire Strait of Georgia Basin (Q_G) based on different habitat quality factors in the South Thompson River drainage (Q_T) and the rest of the Strait of Georgia Basin (Q_{G-T}). Values for economic rent per ha based on 713,000 ha, and values per km based on 503.2 km of stream length. All values for economic rent expressed as net present values (NPV) in perpetuity at a 5% social discount rate (1994 Canadian dollars)

Variable	Value prior to degradation of South Thompson	S. Thompson partially degraded		S. Thompson lost entirely	
		New value	Difference	New value	Difference
		Scenario A:		Scenario B:	
Habitat quality assumptions					
South Thompson only (Q_T)	1	0.47	-	0	-
Rest of Strait of Georgia Basin (Q_{G-T})	1	1	-	1	-
Weighted average for entire basin (Q_G)	1	0.9878	-	0.977	-
Recruitment (X^*), no. of fish	1,071,001	1,056,482	14,519	1,043,642	27,359
Catch (h^*), no. of fish	560,308	548,456	11,852	537,988	22,320
Fishing effort (E^*), days	24,686	24,406	280	24,154	532
Economic rent, $W(X^*, h^*)$	63,849,173	61,971,612	1,877,561	60,321,821	3,527,352
Habitat value calculation, $W(X^*, h^*)$:					
Value of habitat loss, all 16 streams	–	–	1,877,561	–	3,527,352
Value of habitat loss, per ha	–	–	2.63	–	4.95
Value of habitat loss, per km	–	–	3731.24	–	7009.84
		Scenario C:		Scenario D:	
Habitat quality assumptions					
South Thompson only (Q_T)	1	0.47	–	0	–
Rest of Strait of Georgia Basin (Q_{G-T})	0.47	0.47	–	0.47	–
Weighted average for entire basin (Q_G)	0.4822	0.47	–	0.4592	–
Recruitment (X^*), no. of fish	474,628	461,238	13,390	449,421	25,207
Catch (h^*), no. of fish	92,381	82,514	9867	73,841	18,540
Fishing effort (E^*), days	7215	6570	645	5983	1232
Economic rent, $W(X^*, h^*)$	3,670,268	3,004,870	665,398	2,463,772	1,206,496
Habitat value calculation, $W(X^*, h^*)$					
Value of habitat loss, all 16 streams	–	–	665,398	–	1,206,496
Value of habitat loss, per ha	–	–	0.93	–	1.69
Value of habitat loss, per km	–	–	1322.33	–	2397.65

the season when catchability is higher. We also explored the effect of the lower value as part of the sensitivity analysis. Finally, we assumed a social discount rate of 5%, but also considered a value of 10% in the sensitivity analysis.

4. Results

The initial set of parameter values ($Q_G = 1$) resulted in an optimal coho stock in the Strait of Georgia Basin (X^*) of just over one million fish and an optimal catch (h^*) of 560,308 fish, giving an optimal annual exploitation rate of 52.3% (Scenarios A and B, Table 4). In contrast, when the Strait of Georgia basin excluding the South Thompson was degraded but the South Thompson was not (weighted average, $Q_G = 0.4822$), the optimal coho stock was only 474,628 fish and the optimal exploitation rate was 19.5% (Scenarios C and D, Table 4). While this exploitation rate may seem low, it reflects an economic optimum and not a maximum sustainable yield. The latter is generally higher since cost factors are not taken into account.[4]

These results were used to derive the value of protecting salmon habitat in the 16 streams in our data set comprising the South Thompson River drainage area. In Scenario A (Table 4), the degradation of the South Thompson River habitat from pristine condition to its current state ($Q_T = 0.47$) reduced economic rents in the commercial troll fishery by $1.878 million in present value terms. This corresponds to a loss of $2.63/ha of watershed area or $3731/km of coho stream. These values can be interpreted as the benefits in the commercial coho fishery from protecting the South Thompson River salmon habitat, assuming that habitat would deteriorate to the current ambient level of disturbance in the absence of this protection. Results for the remaining scenarios are indicated in Table 4, and are calculated in

[4] In contrast, calculated optimal exploitation rates that achieve maximum sustainable yields (MSY), but which exclude any economic considerations, ranged from 49.0% ($Q_G = 0.4822$) to 64.6% ($Q_G = 1$).

Table 5
Sensitivity analyses showing the changes in economic rent, $W(X^*, h^*)$, for changes in various parameters from Scenario A in Table 4. All values are net present values (NPV) in perpetuity at a 5% social discount rate (1994 Canadian dollars). The column 'Difference on per ha basis' is based on a catchment area of 713,000 ha. Values in brackets are percent change from the base-case estimate of $2.63/ha

Sensitivity cases	Optimal value prior to degradation of South Thompson ($Q_G = 1$)	Optimal value after degradation of South Thompson ($Q_G = 0.9878$)	Difference due to habitat change	Difference on per ha basis ($/ha)
Social discount rate ($r = 10\%$)	31,776,301	30,841,888	934,413	1.31 (−50.2%)
Commercial catchability ($q = 0.00002$)	41,018,524	39,450,222	1,568,302	2.20 (−16.3%)
Net salmon price ($p = \$7.50$, $c/p = 14.5$)	32,234,129	31,067,669	1,166,460	1.64 (−37.6%)
($p = \$15$, $c/p = 7.25$)	114,671,980	111,748,082	2,923,898	4.10 (55.9%)
Ocean survival rate ($m = 0.1$)	4,729,165	4,359,413	369,752	0.52 (−80.2%)
Productivity parameter ($a = 50$)	72,294,877	70,286,141	2,008,736	2.82 (7.2%)
($a = 30$)	52,034,316	50,352,551	1,681,765	2.36 (−10.3%)
Capacity parameter ($b = 9,000,000$)	92,028,703	89,563,060	2,465,643	3.46 (31.6%)
($b = 5,500,000$)	36,841,990	35,565,880	1,276,110	1.79 (−31.9%)

a similar manner. Considering all four scenarios, the value of habitat ranges from $0.93/ha to $4.95/ha, and $1322/km to $7010/km of coho stream.

Using a sensitivity analysis (Table 5), we assessed how changes in key parameters influenced the results, while maintaining the main assumptions about habitat degradation used in our initial calculations (based on Scenario A). Raising the discount rate from 5 to 10% reduced the habitat value per ha by about 50% from its baseline value of $2.63/ha, while reducing the catchability coefficient from 3×10^{-5} to 2×10^{-5} had only a relatively small effect (Table 5). Variations in the salmon price from its initial value of $10.50/fish had pronounced impacts on habitat value: an increase to $15/fish raised the habitat value per ha from $2.63 to more than $4, an increase of 56%. A halving of the ocean survival rate from 0.2 led to a dramatic reduction in habitat value (by 80%); if fewer juvenile salmon survive the rearing stage to eventually contribute to commercial harvests, the value of the spawning and rearing habitat is lower. Mortality rates in the marine life stage of Pacific salmon vary considerably and are perhaps related to climate patterns (Hobday and Boehlert, 2001; Peterman et al., 1998); thus, the derived economic values of coho habitat are subject to similar fluctuation. Variations in the a and b recruitment parameters of about 25% led to varying changes in the habitat value; for the former, the impact is minor (only about 7%) while the latter has a more substantial effect on the habitat value (32%) (Table 5).

5. Discussion

The steady state optimal management results for stock and catch from our model can be compared with historical data for the period 1953–1977 (Argue et al., 1983), which indicate a mid-range value of 714,000 for the average Strait of Georgia coho stock, and a much higher exploitation rate (83.6%) than we estimated would be optimal in an economic sense. The catch per unit of effort (CPUE) for the troll fishery under historical conditions was only 9 fish/boat-day, reflecting the relatively unregulated fisheries management system in place at the time, which permitted large numbers of vessel-days. In contrast, our optimal management results yield an average CPUE of 23 fish/boat-day. Our analysis suggests that estimates of habitat value based upon the historical conditions in the fishery would underestimate that value because higher commercial fishery profits could have been earned for any level of habitat conditions. Of course, such a comparison concentrates on economic rent earned in the fishery and ignores the many other objectives of management that no doubt played a role historically.

As might be expected, the complete loss of habitat in the South Thompson ($Q_T^A = 1$, $Q_T^B = 0$) leads to a value attributed to habitat that is much greater than if only partial degradation occurs ($Q_T^A = 1$ to $Q_T^B = 0.47$). Which value should be attributed to habitat depends on the nature of the analysis. If protection affords a benefit that is incremental to the surrounding state of degradation, then the lower habitat value is correct as a measure of the benefits from this protection. Instead, if we are interested in measuring the use value of habitat (i.e. valuing the full contribution this natural capital makes to human welfare), then the higher habitat value is appropriate.

An additional feature of our results is the importance of the status of habitat elsewhere in the Strait of Georgia Basin for measuring habitat value within a contributing watershed (e.g. the South Thompson). When the habitat elsewhere in the Strait of Georgia Basin is pristine, the coho fishery is far more productive and any loss of habitat, such as in the South Thompson, has a substantial cost ($2.63/ha under Scenario A). If the Strait of Georgia Basin outside of the South Thompson is highly degraded, the resultant lower productivity and profits in the fishery mean that the loss of pristine habitat in the South Thompson has less impact ($0.93/ha under Scenario C). Ironically, this pristine habitat contributes far more to the total basin-wide catch when the rest of the basin is highly degraded. It is valued less because of the poor conditions in the fishery overall (e.g. a low CPUE leading to low profits per fish), which outweigh this factor.

Our sensitivity analyses indicate that the results were fairly robust to our numerous assumptions. However, several limitations could have caused us to underestimate the value of habitat associated with coho stocks in the South Thompson. First, our model makes the implicit assumption that the coho salmon fishery is managed independently of other fisheries. However, if habitat degradation leads to a moratorium on commercial catches of coho (similar to the closure in many areas of southern BC in 1998–2002), this may also require the closure of associated mixed-stock fisheries that mainly target other species (e.g. the higher-priced sockeye salmon) but incidentally catch coho salmon. In this case, protecting coho salmon habitat has an additional benefit of allowing other fisheries to remain open by slowing or preventing declines in coho salmon abundance that might lead to such wider, more costly closures.

Second, our estimate of smolt production within the South Thomson was about 340 smolts/km of stream under current degraded conditions, rising to about 700 smolts/km under pristine conditions. In studies of coho smolt production in the coastal area of BC (Bradford et al., 1997), some production rates are higher. To assess the impact of underestimating the smolt production rate in the South Thompson on our results, we carried out an additional sensitivity calculation. Rather than use our estimate that the South Thompson accounts for 2.3% of smolt production within the Strait of Georgia Basin, we used 5% combined with the other parameter assumptions used in Scenario A of Table 4. In this case, the value of coho habitat increases to \$5.69/ha of watershed, or \$8067/km of stream, from \$2.63/ha and \$3731/km under our baseline assumptions.

Third, we considered only a commercial coho fishery and ignored the recreational coho fishery, which has become more important in recent years. While the data needed to model the recreational fishery were not available, a simple calculation sheds light on the implications of our approach. Freeman (1995) reviewed a number of recreational fishing studies that estimate the value of incremental salmon to recreational anglers on the west coast of North America, as measured by their willingness to pay for additional catches. These values ranged from US\$3.13 to as high as US\$85 per fish (1991 prices), although most values fall within a narrower range of US\$10–US\$30 per fish. Taking a mid-range value of US\$20 per fish, we converted this value to a 1994 Canadian dollar figure of \$23.68 per fish using a conversion factor of 1.184, to account for the exchange rate and inflation.

Under Scenario A, the protection of habitat leads to incremental catches in the commercial fishery of 11,852 fish/year. If these fish were caught instead by the recreational fishery, and valued at \$23.68 each, the habitat value would be \$5.6 million in present value terms. This value compares to our estimate of \$1.9 million based only on the commercial fishery. This comparison suggests that if the recreational fishery were considered, the value of habitat might increase several-fold. In reality, the marginal value of a coho caught and kept would vary with the total catch and might be expected to show diminishing returns (Cameron and James, 1987). A fully specified demand function for the complete recreational experience, of which catching a fish is just one element, is needed to capture the recreational value of incremental coho more appropriately.

Finally, land-use data outside of our South Thompson case study streams were not available for other areas contributing to the Strait of Georgia coho population. To provide a range of habitat conditions, we made the simplifying assumption that these areas were either pristine or degraded to conditions currently seen within the South Thompson drainage area. As discussed above, our analysis indicates that the state of freshwater habitat outside protected areas but within the same fishery has a substantial influence on estimates of habitat value; thus, better information about habitat conditions throughout the entire basin would improve our estimates. Similarly, because Pacific salmon stocks have been subject to longer-term shifts in ocean survival rates that are not fully understood (Peterman et al., 1998), we were required to make assumptions about future survival rates. Without some recovery in these rates, no commercial fishery will be viable, so we assumed that these would eventually be restored to historic levels.

6. Conclusion

Protection of salmon-producing habitat can lead to important benefits for commercial or sport fisheries. Our analysis valued the quality of habitat used by the Strait of Georgia coho salmon stocks in British Columbia, Canada. We considered a hypothetically pristine watershed and compared this to degraded habitat to estimate one of the use values associated with such an area. We made various assumptions about the level of habitat degradation and the state of habitat throughout the Strait of Georgia Basin because coho from various watersheds mix and may be caught within the same commercial fishery. The resulting values for habitat ranged from \$0.93 to \$4.95/ha of watershed, or \$1322 to \$7010/km of spawning stream.

In estimating these values, we assumed that the salmon fishery dependent on this habitat was managed efficiently as a commercial troll fishery. This approach captures an upper bound value of habitat that is independent of how the commercial coho fishery was managed in the past. Comparison of our results with historical data indicates how efficiently (in an economic sense) the stock has been managed (or mismanaged) over time. However, our use of a commercial fishery in our model may provide a lower bound estimate of the value of coho habitat: it ignores the recreational fishery, which has been growing in importance and may be more valuable on a unit basis. Further research is required to verify this hypothesis and to incorporate the recreational fishery into estimates of habitat value. Finally, we do not perform a full cost-benefit analysis of change in land use, which requires discounting the annual streams of benefits and costs associated with alternative land uses to determine the net economic benefit of each. Instead, we calculate the equilibrium benefits afforded by protection and compare these under different scenarios that describe the extent of habitat degradation that would otherwise ensue.

Despite the limitations of our analysis, we have shown that conserving freshwater fish habitat within protected areas has a clearly identifiable benefit. This has been measured as the net value of commercially caught fish that would not otherwise be available to the fishery. Estimating this benefit helps strengthen the case for protecting habitat by demonstrating how it supports economic activity.

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Appendix A. Calibration of the recruitment model parameters

Calibration of the parameters in the recruitment model made use of expression (12) and a simulation procedure. The steps in the simulation are illustrated in Fig. A1 and described in detail below.

Step A. We used expression (12) to calculate the value of the instantaneous average annual change in recruitment (β) from the best-fit empirical relationship for different values of the HCI. We used HCI values of 0, 1, 5, 10, 15, and 20, which represent the range of HCI values found in the South Thompson drainage area.

Step B. We then calibrated the habitat capacity parameter, b, for the 16 streams in our data set assuming pristine conditions ($Q = 1$, where $0 < Q < 1$). After calibrating b, we calculated values for Q corresponding to the values of the HCI given in Step A.

Step C. We used the estimated spawner abundance in the 16 streams in our data set from the years 1985–1987 to initialize our simulations, whereas spawner abundance in

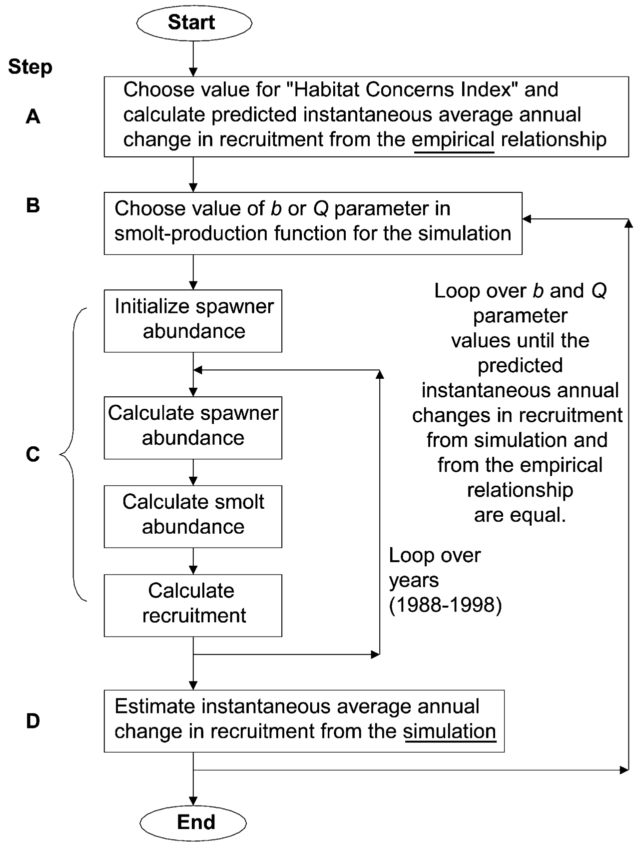

Fig. A1. Flow chart for the simulation and calibration of parameters for the stock-recruitment model, which incorporates the effects of freshwater habitat quality.

subsequent years was calculated as:

$$X_t - h_t = R(X_{t-3} - h_{t-3}, Q)(1 - u_t) \quad \text{(A1)}$$

where $X_t - h_t$ is spawner abundance or escapement, $R(\cdot)$ is the recruitment function, and u_t is the proportional exploitation rate.

Step D. After simulating the population dynamics of South Thompson coho from 1988 to 1998, we estimated the instantaneous average annual change in recruitment (β) from the time series of recruits generated by the simulation. The simulation model continued to loop over different values of the parameter being calibrated (b and Q) until β from the simulation equaled the value predicted by the empirical relationship (12) for each of the selected values of the HCI.

To scale up the habitat capacity parameter, b, to the entire Strait of Georgia fishery, we first calculated the average catch of wild salmon in southern BC fisheries by deducting estimated catches of Canadian and US hatchery coho from total catch, based on data from Simpson et al. (1999), Coronado and Hilborn (1998) and Weitkamp et al. (1995). This yielded an estimate of 1,925,705 wild coho caught annually in southern BC fisheries during the 1977–1990 brood years. We estimated the abundance of wild smolts contributing to southern BC fisheries by dividing our estimate of wild catch by exploitation rates estimated for BC hatchery stocks and average smolt-to-adult survival rates for four wild stocks (Baillie et al., 1999; Anonymous, 1998). We assumed wild stocks were subject to the same exploitation rate as BC hatchery stocks. Under these assumptions, the average annual abundance of wild smolts contributing to the southern BC coho fishery was 16,993,577 for the 1977–1990 brood years.

Next, we estimated the number of smolts (3,444,451) contributing to the Strait of Georgia fishery alone by multiplying our estimate of wild smolt abundance for all of southern BC fisheries by the percent of total catch attributable to the Strait of Georgia fishery (20.3% for 1980–1998) (Simpson et al., 1999). Assuming habitat throughout the Strait of Georgia basin was similar in quality to that of the South Thompson (i.e. HCI = 10, $Q = 0.47$), the habitat capacity parameter (b) for the Strait of Georgia coho under pristine conditions was 3,444,451/ 0.47 = 7,257,527 smolts.

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