FISH GILL PHOTO AND COMMENT

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This picture is of a salmon's gills, showing the damage caused from contact with either the fishers hands or the net mesh and often occurs with a gill-net which is designed to catch fish by the gills or body. The left side (bottom section) is a healthy red color as it should be, but the right side or upper section has been damaged by the web getting into the gill area and while physical damage isn't apparent, what is apparent is the trauma caused by contact with the webbing has caused mucus to build on the fiilliments causing the filliments to "die" and the fish will suffocate and die. For the fisher using a regular gill-type net, a first glance at the fish would have suggested it was fine, but after holding this fish in our live tanks for a day, even though it hadn't yet died (we killed it for natural live harvested and rested processing) a decade of experience has taught us this fish will die - for absolute certain. This photo was taken back in the mid-90's just prior to us taking up the obvious need for better gear to prevent this to boost our percentage of live for processing salmon. What this is showing is, for the fisher using the regular gill-net, a false sense of compliance is being fostered and non-target salmon are dying needlessly andworse, unaccounted for.

TOOTH TANGLE NET

STUDY 2001

TOOTH TANGLE NET
STUDY 2001

PREPARED FOR

FRED HAWKSHAW

AND

FISHERIES AND OCEANS CANADA

PREPARED BY

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1.0 SUMMARY

A Selective gillnet fishing experiment was conducted during July and August 2001 by five Area C licensed vessels. The experiment was designed to test a 100 fathom long, 4 inch mesh tooth/tangle net to determine a viable net that provides satisfactory target species catch with decreased by-catch, and more importantly decreased by-catch mortality. This fishery occurred in the mouth of the Skeena River.

The by-catch species of greatest concern in this study is coho, although steelhead impacts are also of historical concern to the Skeena River gillnet fishery.

The study began on July 6, 2001 and continued until August 23, 2001. Fishing operations included both commercial openings and test payment days. A total of 34,889 sockeye and 4,262 pink were caught with a by-catch of 415 chinook, 396 coho, 181 steelhead and 85 chum salmon. The tooth tangle net was an effective harvester of salmon compared to the conventional gillnets used in the same fishing area, particularly when considering their abbreviated length and depth. Fish quality as measured by the number of fish delivered live to the vessel and the low mortality observed for coho, chinook and steelhead was excellent.

2.0 INTRODUCTION

2.1 History of Selective Fishing Practices

Selective fishing practices are now an integral part of fishery management practices for the Pacific Region. Selective fishing practices endeavor to minimize the impact of fishing activities on non-target species while maintaining a viable catch of the target species. Canada's agreement with the United Nation's Food and Agriculture Organization's Code of Conduct for Responsible Fisheries compels us to reduce the by-catch of all non-target species in all of our fisheries. However, more immediate concerns for the conservation of species such as steelhead, chinook, and coho have been a problem for the management of mixed stock Pacific salmon fisheries for some time.

Catch and release (non-retention/non-possession) of by-catch species have been used as a management tool in troll fisheries as well as mesh size restrictions in gillnet fisheries. However, as conservation concerns have become more pronounced in recent years, the variety and implementation of various methods of selective fishing have become more numerous. Other than time and area closures, some examples of selective fishing measures that have recently been implemented are the use of weedlines, daylight only fishing, and Alaska Twist mesh in gillnet fisheries. Brailing and sorting of all catch in seine fisheries was first employed in the sockeye fishery conducted at the mouth of the Skeena River.

2.2 The Coho Recovery Plan

On June 19th, 1998 the Minister of Fisheries announced details of the *Coho Recovery Plan* in response to mounting concerns for coho as well as chinook and steelhead stocks. The expected returns of coho to both the Upper Skeena and Thompson river systems in 1998 were expected to be critically low, resulting in serious conservation problems. Part of this plan was a coast-wide ban on the retention and possession of coho. Fishing areas would also be restricted to have zero mortality on coho where Upper Skeena and Thompson River stocks are prevalent and to allow only minimal by-catch mortality of coho where these stocks are not prevalent. In his announcement, the minister stated that all future salmon fisheries would adhere to selective fishing practices.

2.3 Current Selective Fishing Practices

In addition to non-retention and non-possession of by-catch in most instances and area and time closures, current regulations for selective fishing practices include mandatory fish revival tanks for all vessels participating in commercial salmon fisheries. There are specifications for the minimum requirements for these revival tanks with larger more complex design required for seine vessels. Seine vessels are also required to brail (use a large dip net) their catch onboard and sort it prior to placing it in the hold to facilitate the identification and release of by-catch.

Gillnets are often limited to short duration sets to minimize the time that fish spend entangled in the net. Some gillnet fisheries are limited to daylight hours and some allow for greater depths of Alaska Twist mesh either in conjunction with or without weedlines. Most if not all gillnet fisheries require the release of coho, but some only request the release of all chinook and steelhead to the water with the least possible harm. Troll fisheries are now restricted to using barbless hooks to assist in the release of any non-target species.

2.4 Methods/Theory of Selective Fishing

Selective fishing methods can be divided into two categories: those that reduce the encounters with the by-catch species and those that allow the successful release of any by-catch species that are captured. Modifications to fishing gear and/or fishing patterns can often reduce the proportion of non-target species in the catch. Modifications can also be made to fishing gear and/or fishing patterns to facilitate the live release of non-target species by reducing injury to the fish.

The 2001 Tooth Tangle Net Project was designed to determine the efficiency of the net to capture sockeye and pink, and examine related mortality effects on by-catch species. The efficiency of the tooth tangle net was assessed by comparing the catch per effort of sockeye between the test group and the conventional fleet fishing in the River/Gap/Slough area of the Skeena River. Within test group catch success, as well as associated by-catch mortality was also evaluated to investigate the ability of the fishers to learn and apply the best fishing technique. Of particular interest to the test group assessment was to compare the results of catch, effort and mortality between four vessels new to the use of this selective gear and one experienced vessel (Fred Hawkshaw). An important question involved determining the influence on the study results of Fred Hawkshaw.

3.0 METHODS

3.1 Study Design

Selective nets, by definition, avoid or allow for the live release of restricted species. The tooth tangle net is not designed to target sockeye, but rather to apply minimal physical damage to all catch, allowing the release of non-target fish in good condition and the retention of quality product for sale. The study hopes to prove that this net can be used in areas and at times where traditional gillnet use is of concern, with little or no impact on sensitive species.

Five vessels were chosen to participate in the study. All were required to supply and fish identical test nets in regular commercial openings, in the style they would normally fish. Vessels fished independently of one another in the river/gap/slough area at the mouth of the Skeena River (FOC management areas 4-12 and 4-15). Although the nets were similar, the fishing styles and experiences of the five boats were varied, in hopes of better representing the fleet. Observers from J.O. Thomas & Associates were present on each vessel to monitor all sets made and record data. FOC hail information from vessels participating in the commercial openings was used to compare and contrast sockeye catch per effort.

3.2 Data Collection

Observers were responsible for documenting data pertaining to set methodology, timing, location, composition and fish capture condition. For restricted species, information was also recorded on fish condition at release.

Data was recorded on a set-by-set basis onto three data forms (Appendix B): a catch log form, a catch tally form, and a revival box form. For each set made, information was recorded as to set number, location (FOC management statistical and sub areas, as well as common location names), and set timing. The set started when the first cork entered the water, and ended when the last cork was hauled out of the water.

Fish condition and vitality was evaluated using the following guidelines:

1-vigorous, not bleeding
2-vigorous, bleeding
3-lethargic, not bleeding
4-lethargic, bleeding
5-dead

Observers were asked to look for any obvious causes of fish mortality, when possible. Mortality was categorized into the following conditions:

- Net morts: fish that died as a result of the net causing injury
- Seal morts: fish that died as a result of predation by seals
- Procedural morts: fish that died as a result of handling methods or mechanical problems. This could be from the fish falling from the net onto the deck, from fishermen (or observer) mishandling, or problems in the recovery tank such as insufficient flow or decreased oxygen from overcrowding.
- Previously caught morts: fish that had most likely been caught and released before by other gears.

Observers submitted data forms and comments to the J.O. Thomas & Associates Ltd. (JOT) field office in Prince Rupert when in port. Data was entered and analyzed using Microsoft Excel. Preliminary summaries were provided to FOC Management at the completion of the test portion of the project.

3.3 Fishing Operations

3.3.1 Net Construction

All 5 participating vessels fished identical test nets. Nets were constructed using 4 strand, 1.5 mm monofilament twine hung along the corkline at 2.2:1 for a total net length of 100 fathoms. All nets were 60 meshes deep, with 4” mesh. The color used was UR-32. All nets had standard weedlines.

3.3.2 Fishing Schedule

The test group fished all commercial openings in Area 4 from July 6th to August 6th, 2001. The participants were also given opportunities to fish when the commercial fleet was not fishing. These “payment” days in the peak season were granted to compensate for fishing later in the season when sockeye catch would be low but pink, chum and coho encounters were expected to be elevated. To begin with, the group was granted one extra test payment day after every commercial opening. When the area was closed to the commercial fleet after the August 6th opening, the test group was given an additional 6 openings. There were 2 days when only one test boat fished (July 31st – Tricia Lynn and August 7th – Raven Explorer), in compensation for previously missed opportunities.

4.0 RESULTS

There are three issues relevant for the tooth tangle net to be considered for approval for future use. The first is whether or not the net can catch fish. Though an issue more important for the users than the fishery managers, it is imperative to test the relevance of the net in practice. The second is whether or not bycatch mortality is at an acceptable level. Knowing that the purpose of the net is not to avoid certain species, but to allow the safe and gentle capture and release of all fish, it is important to prove that these fish can be released with little harm. The third issue is to determine the condition of the fish that are to be retained. This is related closely to the issue of bycatch condition, but is an important detail with the possible expansion of the sales market for quality product originating from processing live salmon.

4.1 Viability of Net for Capturing Fish

The first opportunity for the test boats to fish was during the commercial Area 4 opening on July 6th, 2001. The group fished all 16 commercial openings following that date, as well as 15 additional days in Area 4 granted by FOC as payment days, for a total of 32 fishing days. In all, the test boats made a combined 2,547 sets and encountered 34,889 sockeye, 4,262 pink, 415 chinook, 396 coho, 85 chum, and 181 steelhead (Table 1).

Table 1. Summary of catch by vessel.

Vessel	#Sets	Total Observed Catch						Av.set
	Obs	Sockeye	Pink	Chum	Coho	Chinook	Sthd	Length
Debbie Dee	509	8,371	921	23	93	138	62	30.6
Harlynn	452	6,363	981	13	67	58	26	34.7
Raven Explorer	386	6,629	846	24	39	38	29	35.8
Sherry Shan	490	8,227	848	14	35	84	21	30.3
Tricia Lynn	710	5,299	666	11	162	97	43	20.8
Total	2,547	34,889	4,262	85	396	415	181	29.3

Comments among the test group focused on the increased challenge of the net to catch fish during the commercial openings when there was other gear in the water. Reduced catch per effort on coincident fleet fishing days suggests that the tangle net was less efficient as a function of reduced sockeye abundance or from changes in fish behaviour as sockeye responded to the increased array of nets. It is also possible that conventional gillnets were removing sockeye having the optimal tangle size. A comparison between the tooth tangle net on payment days versus commercial days (Table 2) shows that there is in fact a difference in catch per set, with three times as many sockeye caught during payment days. The comparison between average daily catches between the test nets and the rest of the fleet (traditional nets) also confirms the test fishers' comments (Table 3). Test nets caught considerably fewer fish than those fishing around them in the river/gap/slough portion of Area 4.

From July 6 to August 7, 2001, 1,106 sets were made using the tooth-tangle net during commercial openings, and 645 sets were made during payment days when only test nets were fishing. On payment days, the tooth-tangle net averaged 28.6 sockeye per set, but only 9.2 sockeye per set when fishing concurrently with the gillnet fleet. Comparing daily catch statistics, the test nets averaged 160.9 sockeye per boat on commercial days, and 511.6 sockeye per boat on payment days. Three times as many chinook were caught on payment days than commercial days (2.1 chinook/boat). Pink and chum catches were similar. There was little difference in average daily pink and chum catches between fishery types (payment days: 12.8 pink/boat, 0.4 chum/boat; commercial days: 13.1 pink/boat and 0.4 chum/boat). Slightly more steelhead were encountered on payment days (1.5 steelhead/boat) vs. commercial days (0.8 steelhead/boat).

Table 2. Comparison of tooth tangle net catches during commercial vs payment days from Jul 6 to Aug 7, 2001.

Fishery Type	# Sets Observed	Average Catch Per Set					
		Sockeye	Pink	Chum	Coho	Chinook	Sthd
Commercial Days	1,106	9.2	0.7	0.02	0.1	0.1	0.05
Payment Days	645	28.6	0.7	0.02	0.1	0.4	0.08
Commercial Days	82	160.9	13.1	0.4	1.4	2.1	0.8
Payment Days	36	511.6	12.8	0.4	1.7	6.6	1.5

When compared with daily averages from FOC (Table 3), the test boats averaged only slightly lower daily sockeye catches than daily averages of the traditional nets of the commercial fleet (160.9 sockeye/day vs 164.2 sockeye/day respectively) in all of Area 4. Test nets also averaged lower daily pink catches (13.1 pink/day vs traditional 22.0 pink/day), as well as lower chum catches (0.4 chum/day vs traditional 1.5 chum/day). However, when comparing the sockeye catches of the test boats to other boats in the river/sap/slough region of Area 4, we see that the test nets caught far fewer fish than those traditional nets around them. Traditional nets in the r/g/s caught approximately 50 more sockeye per day than the test nets (212.2 sockeye/day and 160.9 sockeye/day respectively).

Table 3. Comparison of average daily catch from tooth tangle nets and traditional nets during commercial openings July 6 to Aug 6, 2001.

Net Type	# Boat Days*	Average Daily Catch Per Boat					
		Sockeye	Pink	Chum	Coho	Chinook	Sthd
Tooth-Tangle Nets	82	160.9	13.1	0.4	1.4	2.1	0.8
Traditional Nets – Entire Area 4**	7,462	164.2	22.0	1.5	N/a	N/a	N/a
Traditional Nets – River/ Gap/Slough**	2,457	212.2	N/a	N/a	N/a	N/a	N/a

*boat days equal sum of all boats fishing on each of the commercial opening days

**data from FOC Management

4.2 Bycatch Mortality

It is difficult to compare the performance of the net with respect to bycatch mortality when information regarding bycatch encounters and mortality from the commercial fleet is not available. However, observed coho mortality from the tooth-tangle test nets was substantively lower than the FOC standard rate of 60% for traditional gillnets. Only 6 of the 396 coho encountered in this study were released dead.

The condition of bycatch species at capture is summarized in Table 4. For coho, 47% of fish encountered were captured vigorous and not bleeding and 46% were landed lethargic not bleeding. Two percent were vigorous and bleeding, 4% were lethargic and bleeding and 1% were dead on arrival.

Of the 415 chinook encountered in the study, the capture condition of 377 of these fish was recorded. Sixty percent of chinook were captured in a vigorous/not bleeding condition (228 fish), 25% (93 fish) were lethargic and not bleeding, 5% were bleeding at capture (13 vigorous not bleeding and 7 lethargic not bleeding), and 9% (33 fish) were dead on arrival.

Fifty percent of steelhead caught were assessed as vigorous and not bleeding (86 fish) and 39% were lethargic and not bleeding (67 fish). In total, 7% were bleeding (2 vigorous and 10 lethargic), and 5% were dead on arrival (8 steelhead). Nine of the 181 steelhead encountered were released without record of capture condition.

Table 4. Summary of bycatch condition at capture.

Condition at Capture	Coho	Chinook	Steelhead
Vigorous/not bleeding	184	228	86
Vigorous/bleeding	8	13	2
Lethargic/not bleeding	179	93	67
Lethargic/bleeding	14	7	10
Dead	4	33	8
Unknown	7	38	9
Total	396	415	181

Table 5 summarizes the data recorded on the recovery box forms. Whereas set data forms recorded fish condition at capture, the revival box forms provided information of fish condition at release. Revival box forms were only used for restricted species when time and circumstances permitted. Some fish were released immediately upon capture, whether shaken from the net or after being brought aboard the boat for release from the net. For the most part, these were fish in good condition that seemed as though revival time was unnecessary. Once heavy numbers of restricted species began to appear, there simply wasn't room in the revival tanks to hold all of the fish; therefore, in these circumstances only fish in lethargic condition were held. Though most fish that appeared dead were placed in the box, fish with obvious mortality indicators (seal attacks, rigor mortis, etc) were, needless to say, not held for potential revival.

In addition to the five standard condition assessments (vigorous/not bleeding, vigorous/bleeding, lethargic/not bleeding, lethargic/bleeding and dead), observers also encountered fish that initially did not appear alive. There was little noticeable movement or ventilation in these fish. When possible, these fish were placed in the revival tanks, an after holding, their condition was better assessed. In Table 5, these fish are summarized as "appears dead."

Although this is not a complete data set, it does show interesting trends in fish revival. For coho, all 9 fish that "appeared dead" at capture were revived to a vigorous/not bleeding state after holding. For chinook (large adults), 1 was released vigorous/not bleeding and 1 was released dead. All 3 chinook jacks were revived to a vigorous/not bleeding state. Of the 7 steelhead categorized as appears dead, 6 were released vigorous/not bleeding and one was released dead. Of those fish lethargic at capture, 98% of coho, 83% of chinook, 93% of steelhead and 94% of chinook jacks were released in good condition after being held in the revival box.

Table 5. Bycatch mortality as recorded on revival box holding forms.

Condition	Coho		Chinook		Chinook Jack		Steelhead	
	Capture	Release	Capture	Release	Capture	Release	Capture	Release
Vigorous/not bleeding	108	282	7	13	63	109	43	114
Vigorous/ bleeding	5	2	0	0	2	1	4	0
Lethargic/not bleeding	157	1	6	1	45	2	61	2
Lethargic/ bleeding	8	0	0	0	1	0	5	0
Dead	0	2	0	1	0	2	0	4
Appears Dead	9	0	2	0	3	0	7	0
Total	287		15		114		120	

Observers were asked to qualify obvious fish mortality into one of 4 possible situations: net, seal, procedural or previously caught mortalities (see Methods section for description). Of the discernable coho mortalities, two were direct results of seals, two appeared to be previously caught fish, one died in the net, and one had no obvious cause of death. The “net” mortality was due to the net wrapping tightly around the head of the fish, keeping the mouth and operculum closed. Table 6 breaks down the coho mortalities, relating the size and length of the set, the area the fish was caught, the capture condition. Because of the small number of observed coho mortalities, it is difficult to confidently correlate fish death to areas fished, set size or specific vessel.

Table 6. Breakdown of coho mortalities.

Vessel	Set Size (# fish)	Capture Location	Capture Condition	Mortality Explanation	Soak Time
RE	3	4-12 Matthews Rock	D	Net	23
RE	14	4-15 Longnose	D	Prev	26
TL	17	4-12 Hicks Pt	D	Seal	21
H	11	4-12 Glory Hole	LB	Seal	31
RE	5	4-15 Longnose	LB	Prev	23
RE	2	4-12 Glory Hole	D	Unk	46

In recent years, the length of sets has been linked to bycatch mortality. The longer fish are caught and kept in the net, the lower their chances for survival. Survival decreases due to increased probability of predation, physiological stress responses, as well as "suffocation" (depending on how the fish is caught in the net, ie. mouth or operculum held shut, respiration is hindered if water cannot pass the gills). Surprisingly, there is little evidence of this mortality trend here. As expected, the proportion of coho in good condition at capture (vigorous/not bleeding) is highest for short sets, but is lowest for sets 30 to 39 minutes long. Fifty eight percent of the coho caught in sets under 20 minutes were in good condition (vigorous/not bleeding), 48% were in good condition when sets lasted between 20 & 29 minutes and only 23% were recorded in good condition for sets that lasted between 30 & 39 minutes. However, the percentage of coho landed in good condition increases to around 50% for sets 40 minutes and longer.

Table 7. Coho condition by set length.

Set Length	# Sets	Total Coho	Total Coho Encountered by Capture Condition					Dead at Release
			VNB	VB	LNB	LB	D	
1-19 min	754	119	69	3	45	1	0	0
20-29 min	833	162	77	3	71	7	3	4
30-39 min	474	73	17	2	47	4	0	1
40-59 min	288	34	16	0	14	2	1	1
60+min	189	4	2	0	2	0	0	0

Just as encounter rates vary between test boats, it is also reasonable to expect variances in mortality between boats (Table 8). Both the Harlynn and Raven Explorer averaged similar set lengths (34.7 minutes and 35.8 minutes respectively), but the Raven Explorer had 10.3% coho mortality (4 fish deaths) compared to the Harlynn's 1.5% coho mortality (1 fish death). The Tricia Lynn averaged the shortest set lengths, and had one coho mortality, whereas the Sherry Shan and Debbie Dee averaged sets approximately 10 minutes longer than the Tricia Lynn without any coho deaths.

Table 8. Coho condition by vessel.

Vessel	# Sets	Total Coho	Dead at Release	Coho Mortality	Average Set Length
Debbie Dee	509	93	0	0.0%	30.6
Harlynn	452	67	1	1.5%	34.7
Raven Explorer	386	39	4	10.3%	35.8
Sherry Shan	490	35	0	0.0%	30.3
Tricia Lynn	710	162	1	0.6%	20.8
Grand Total	2,547	396	6	1.5%	29.3

4.3 Target Species Condition

One observer diligently recorded the capture position of the net on sockeye throughout the study. These results are summarized in Table 9. Thirty-six percent of the sockeye recorded were caught in the net by the mandible or maxillary, and 34% were caught around the pre-operculum. Less than 3% of all sockeye caught in the tooth tangle net were observed to have been gilled, and only 9% were caught on or around the body. Only a small number of sockeye (0.5%) were retrieved which had been wrapped only in the net.

Table 9. Net catch location on sockeye.

Net Placement	# Sockeye
Mouth	2
Premaxillary	0
Maxillary	731
Mandible	799
Jaw	0
Head	0
Gilled	108
Operculum	16
Preoperculum	1,429
Wrapped	19
Body	360
Pelvic	0
Tail	5
Pectoral Area/Fin	624
Fins	36
Dorsal	10
Total Sockeye	4,204

Observers commented that smaller fish, such as pinks and chinook jacks, were more frequently gilled in the small mesh. Even those small fish that were not gilled sometimes swam into the net in such a way that the net kept the operculum shut, thereby hindering respiration.

Although no formal data was taken on fish appearance, both fishers and observers commented that very few fish caught had evidence of net marks or scale loss on the body. Depending on how the fish was caught, and the struggle the fish put up, there was sometimes evidence of net marks around the head.

5.0 DISCUSSION

It is important to note that this is a controlled study, and human nature dictates that behaviour will change when being observed. This study has proven that the tooth tangle can catch large numbers of sockeye and have minimal impacts on by-catch species. The positive results of catch success and low mortality were achieved recognizing that four of five vessels had no prior experience with this net. So clearly the net plays a major role in reducing mortality, but fisher abilities and attitude to proper fish handling are also important. Proper handling, short set lengths and an attitude to ensure optimal fish health all combine to make the tooth tangle net a successful tool.

Catch rates of the tooth tangle net were lower than those of traditional nets fishing in the same area at the same time; however, it cannot be concluded that the net cannot compete with conventional gillnets. In comparisons with traditional half-length nets in commercial openings in the Skeena, the tooth-tangle net caught on average 161 sockeye per day, 50 fewer than the traditional nets (Table 1). However, on payment days when the nets were fished apart from the commercial fleet (usually one day following the commercial opening), the average sockeye catches were an impressive 511 fish per day.

Fishers speculate that the lower comparable catch rates are due in part to the size of the net, as well as the frequency of dropouts and break-throughs. The net seemed to be at a disadvantage in its depth. Even compared to traditional 60 mesh nets, the fact that the tooth tangle nets are a small mesh (4”) net makes them shorter than the others, which could be configured with mesh size up to 5-3/8”. As well, the commercial openings up until July 18th, traditional nets were fished at the standard 200 fathom length. Only after this opening were the traditional nets limited to 100 fathoms.

Although there may have been some disappointment in the catch ability of the net, the condition of the fish caught in the net was exceptional. Both fishers and observers commented on the lack of physical markings on the fish as compared with traditional gillnet caught fish. The large percentage of fish caught, revived and released in good condition (Table 5) suggests that the configuration of the net contributes strongly to enhanced survivability. Ninety-eight percent of lethargic coho, 83% of chinook, 94% of chinook jacks and 93% of steelhead were released in vigorous condition after holding in revival box.

The overall good condition of the fish at capture, as well as the ability to successfully revive many fish to an vigorous condition is valuable not only in preventing restricted species mortality, but also in catching and keeping target species in excellent condition for sale. Some fish buyers are beginning to pay a higher price for quality product, and this net can deliver the quality industry is looking for.

Because only 6 coho died during the course of the study, it is difficult to identify any trends that may have influenced fish death. Two mortalities were attributed to seals. Seals will always contribute to fish mortality in any form of gillnet or tooth-tangle net. As long as the fish is so openly exposed to predation, mortality is a real possibility, particularly in a seal-rich environment such as the mouth of the Skeena. Two more of the dead coho appeared to have been previously caught fish. This is an extremely difficult assessment to make based on visual evaluation. Necropsies were not performed on dead fish, as observers were not trained to recognize signs of internal damage as a result of net capture. Observers were instructed to record mortalities under the caption of “previously caught” only when obvious signs of previous capture, such as net or hook marks, were present on the fish. One DOA coho died as a result of the net wrapping around the mouth and thereby restricting oxygen to the gills. There was no apparent cause of death for the final mortality. No mortalities were attributed to procedural influences. All fishermen were briefed in the proper handling and reviving of restricted species, though any time a fish is handled, there is potential for damage. Observers did not report fishermen to be rough with restricted species; in fact, observers were very complimentary of the attitude of the fishers and the lengths gone to revive non-retention fish.

As expected, differences were noted in the catch encounters and mortalities observed between the boats in the study. This group of boats likely represents the overall fleet in their different levels of experience and attitudes fishing Area 4. There will always be some boats with higher mortality, regardless of area, fishery or gear type. This can be influenced by any number of factors: fisher’s attitudes, mechanical equipment on the boat, or environmental factors related to the specific area being fished. It was reported that the net used by the Raven Explorer, who often fished away from the rest of the group, was torn up beyond the ability to effectively catch fish. This suggests that the conditions the net was fished in may have been more physically strenuous than the other nets. If this is so, perhaps the force(s) that tore up the net also put strain on fish caught in the net. The Raven Explorer had the highest coho mortality rate (10.3%) but also had the second lowest coho encounter rates (only 39 in 386 sets). The Sherry Shan had an even lower coho encounter rate (35 coho in 490 sets), but finished the study with no coho mortalities. Regardless of the reasoning, this was good for the study to show that the net is capable of low mortality, but that this impressive rate is not always universal between vessels.

Although initially many of the participants commented that the net mesh was too weak, in post-study interviews the overall consensus was that the net was a sufficient strength. It was just strong enough to hold most fish, though some larger or extremely lively fish broke through. Over time, it was realized that the advantages of this lighter strength twine far outweighed the disadvantages. All fish were easily removed from the net, either on board or when shaken in the water. For target species, this provided an excellent quality product with little bruising, scale loss, or net marks, and it placed less physical stress on the fish to be released. As seen in Table 5, fish had excellent recovery rates when put in revival tanks prior to release, which suggests that fish were neither highly traumatized nor injured in the catch and release process. As well, with the net being lighter, it was easier and faster to haul in times of trouble. Fishermen did not seem upset by short set restrictions, as it was comparatively effortless to retrieve the net.

Throughout the study comments were also made regarding the high number of fish dropping out of the net before reaching the boat, or as the net was pulled out of the water. This is perhaps the most disadvantageous quality of the tooth tangle net, particularly when the target species is sockeye. As sockeye do not have prominent teeth to catch in the net they must tangle by other means, most often by the maxillary or mandible (Table 9). Ideally, once encountered the fish will struggle and tangle itself in the net. However, without a good initial catch point, fish insufficiently tangled fall out of the net when it is pulled taut. One study participant commented that there were more dropouts observed when the net was being towed, and therefore it was better to leave a net to soak in one spot. Fishers suggested increasing the hang ratio from 2.2:1 to 3:1. Accordingly there would be an increased chance that the fish would wrap itself in the struggle with the net, and as such, not drop out as easily during net retrieval.

6.0 CONCLUSIONS

All three study objectives were met:

- The results prove that this net can successfully catch sockeye. The catch rates, during open fisheries with the gillnet fleet, were lower than those of traditional nets, but on days when fewer nets were in the water, the net had a higher CPUE than traditional nets (Table 1). With a few minor adjustments (ie deeper net and greater hang ratio) this net could possibly be as effective, or perhaps more effective, as a standard gillnet, particularly when considering aspects of responsible harvest.

- Coho mortality rates were an outstanding 2% for this study. Two of the five boats fished the entire study with no coho mortality. Almost all (98%) lethargic coho could be revived (Table 5).

- The third study objective was to monitor the condition of target fish. Those participants concerned with catching fish for a quality market were happy that eighty to ninety percent of all sockeye were brought on board alive. Furthermore, participants reported that fish showed few signs of bruising, scale loss or net marks. Industry buyers have spoken of increasing prices for "quality product," and the fish caught in the tooth tangle nets meet or exceed the required specifications.

Overall, the participants liked this net. It was light and easy to use and manipulate, and it was quick to release caught fish. As well, the fishery managers should be pleased with the results of the study. The tooth tangle net caught fair numbers of fish, but with far greater survival rates than traditional gillnets. It seems that this net, combined with a positive attitude on selective fishing and proper fish handling techniques, is a viable alternative to gillnetting in species sensitive areas and times.

7.0 RECOMMENDATIONS

Despite the low observed restricted species mortality, the commercial fleet may be reluctant to adopt the tooth tangle net as a primary fishing net because of the comparatively lower catch rates. However, this may be the selective tool that FOC is looking for to enable the gillnet fleet (or a portion thereof) to fish in areas and at times recently restricted because of high bycatch encounter rates. Further study should be done on this net to explore configurations that may enhance the catch efficiency of the net, as well to study more closely the resultant catch in different fisheries and areas.

The reason for the lower comparable catch rates when fishing with the fleet should be explored in more detail. Issues of fish behaviour changing in response to a larger fleet or the selective removal of sockeye of an optimum tangle size need to be quantified.

In future studies, more attention must be paid to fish that have died. Survival estimates could be made with greater confidence if information pertaining to release condition of all fish was also available. The data must clearly account for fish that are dead at release as well as on arrival, and make a clear distinction between fish released immediately and those not released.

Comments were made about smaller fish being gilled or caught in the net in such a way that gill function was compromised, however sufficient data was not collected to support this. It would be beneficial to more closely study the relationship between fish condition and fish size.

Test the net with increased hang ratio (perhaps 3:1), and possibly slightly deeper net. A 60 mesh depth test net is considerably shorter than a 60 mesh traditional net depth due to the smaller individual mesh size used in the tangle net.

Appendix A – Raw Data Summaries

Table A1. Observed Daily Catch by Vessel

Date	Vessel	# sets observed	Total Catch Sockeye	Pink	Chum	Coho	Chinook	Steelhead
06-Jul-01	Debbie Dee	14	60	0	0	0	2	0
	Harlynn	12	56	0	0	0	6	1
	Raven Explorer	18	199	0	0	0	2	0
	Sherry Shan	19	99	0	0	0	3	0
	Tricia Lynn	25	73	0	0	0	5	1
July 6 Total		88	487	0	0	0	18	2
07-Jul-01	Debbie Dee	23	426	0	0	1	30	6
	Harlynn	13	381	1	0	0	19	2
	Raven Explorer	19	345	0	0	0	6	2
	Sherry Shan	18	380	0	0	0	17	0
	Tricia Lynn	28	201	1	0	0	18	2
July 7 Total		101	1,733	2	0	1	90	12
09-Jul-01	Debbie Dee	15	99	0	1	0	4	1
	Harlynn	14	74	0	0	0	0	2
	Raven Explorer	18	202	0	0	0	2	0
	Sherry Shan	15	93	0	0	0	2	0
	Tricia Lynn	21	77	0	0	0	10	1
July 9 Total		83	545	0	1	0	18	4
10-Jul-01	Debbie Dee	12	84	1	0	0	6	0
	Harlynn	13	61	0	0	0	6	2
	Raven Explorer	14	196	0	0	0	4	0
	Sherry Shan	13	46	1	0	0	8	0
	Tricia Lynn	13	67	1	0	0	5	0
July 10 Total		65	454	3	0	0	29	2
11-Jul-01	Debbie Dee	22	912	3	1	1	15	3
	Harlynn	14	532	3	0	0	2	0
	Raven Explorer	14	401	2	1	0	3	0
	Sherry Shan	19	695	5	0	0	12	0
	Tricia Lynn	23	342	0	0	0	14	0
July 11 Total		92	2,882	13	2	1	46	3
12-Jul-01	Debbie Dee	12	157	0	0	0	0	0
	Harlynn	15	131	0	0	0	1	0
	Raven Explorer	7	58	1	0	0	0	0
	Sherry Shan	6	20	1	0	0	3	0
	Tricia Lynn	11	66	0	0	0	4	0
July 12 Total		51	432	2	0	0	8	0
13-Jul-01	Debbie Dee	10	125	1	0	0	0	2
	Harlynn	1	1	0	0	0	0	0
	Sherry Shan	15	57	0	0	0	1	0
	Tricia Lynn	14	38	1	0	0	0	0
July 13 Total		40	221	2	0	0	1	2

Table A1. Observed Daily Catch by Vessel continued

Date	Vessel	# sets observed	Total Catch Sockeye	Pink	Chum	Coho	Chinook	Steelhead
14-Jul-01	Debbie Dee	14	443	0	0	0	2	0
	Harlynn	11	296	1	2	0	1	2
	Raven Explorer	15	434	3	0	0	1	1
	Sherry Shan	20	548	3	0	0	2	0
	Tricia Lynn	27	167	1	0	0	1	0
July 14 Total		87	1,888	8	2	0	7	3
15-Jul-01	Debbie Dee	9	111	7	0	1	1	0
	Harlynn	7	61	0	1	0	1	0
	Raven Explorer	13	281	0	1	0	0	1
	Sherry Shan	18	288	1	0	0	1	0
	Tricia Lynn	22	361	2	0	0	0	1
July 15 Total		69	1,102	10	2	1	3	2
16-Jul-01	Debbie Dee	5	174	0	0	0	0	0
	Harlynn	13	194	2	0	0	1	0
	Raven Explorer	15	275	6	1	0	0	0
	Sherry Shan	7	57	0	0	0	1	1
	Tricia Lynn	8	56	0	0	0	0	0
July 16 Total		48	756	8	1	0	2	1
17-Jul-01	Debbie Dee	11	476	4	2	1	4	0
	Harlynn	9	271	1	1	0	2	0
	Raven Explorer	11	538	4	0	0	1	1
	Sherry Shan	13	576	10	0	0	2	1
	Tricia Lynn	23	503	2	0	0	2	2
July 17 Total		67	2,364	21	3	1	11	4
18-Jul-01	Debbie Dee	14	247	8	0	0	7	1
	Harlynn	11	170	2	0	0	0	0
	Raven Explorer	8	337	5	0	0	2	0
	Sherry Shan	15	173	5	0	0	2	2
	Tricia Lynn	23	129	3	0	0	0	0
July 18 Total		71	1,056	23	0	0	11	3
19-Jul-01	Debbie Dee	19	667	17	0	0	15	1
	Harlynn	11	707	6	0	0	7	0
	Raven Explorer	8	665	1	0	0	0	0
	Sherry Shan	10	961	5	0	0	2	0
	Tricia Lynn	21	522	8	1	0	9	0
July 19 Total		69	3,522	37	1	0	33	1
21-Jul-01	Debbie Dee	23	240	0	0	0	8	0
	Harlynn	19	358	2	1	1	4	1
	Raven Explorer	22	330	5	0	0	10	1
	Sherry Shan	20	284	7	0	0	4	1
	Tricia Lynn	33	190	3	0	3	6	0
July 21 Total		117	1,402	17	1	4	32	3
23-Jul-01	Debbie Dee	24	143	15	0	2	2	1
	Harlynn	22	84	7	0	2	1	3
	Sherry Shan	24	95	3	0	0	4	1
	Tricia Lynn	28	129	5	0	4	6	3
July 23 Total		98	451	30	0	8	13	8

Table A1. Observed Daily Catch by Vessel continued

Date	Vessel	# sets observed	Total Catch Sockeye	Pink	Chum	Coho	Chinook	Steelhead
24-Jul-01	Debbie Dee	19	208	27	2	1	2	1
	Harlynn	20	194	13	0	7	1	1
	Sherry Shan	21	209	29	0	5	12	2
	Tricia Lynn	22	117	6	0	2	5	2
July 24 Total		82	728	75	2	15	20	6
25-Jul-01	Debbie Dee	21	802	48	0	5	34	16
	Harlynn	17	393	29	0	2	1	0
	Sherry Shan	19	647	43	0	5	5	1
	Tricia Lynn	30	425	23	0	6	5	3
July 25 Total		87	2,267	143	0	18	45	20
27-Jul-01	Debbie Dee	24	516	11	1	1	0	1
	Harlynn	20	299	25	0	2	0	1
	Raven Explorer	9	265	25	1	1	3	0
	Sherry Shan	21	542	28	0	1	0	2
	Tricia Lynn	27	256	4	1	4	3	0
July 27 Total		101	1,878	93	3	9	6	4
28-Jul-01	Debbie Dee	27	857	15	1	9	1	3
	Harlynn	20	717	49	0	5	2	0
	Raven Explorer	19	574	51	0	0	2	1
	Sherry Shan	17	841	16	0	4	1	3
	Tricia Lynn	10	49	0	0	0	0	0
July 28 Total		93	3,038	131	1	18	6	7
29-Jul-01	Debbie Dee	16	286	13	1	2	0	0
	Harlynn	20	290	27	0	1	3	2
	Raven Explorer	11	126	18	0	0	0	4
	Sherry Shan	14	143	23	0	0	1	1
	Tricia Lynn	30	223	8	0	3	0	0
July 29 Total		91	1,068	89	1	6	4	7
30-Jul-01	Debbie Dee	21	227	17	1	1	1	1
	Harlynn	21	131	38	1	1	0	2
	Raven Explorer	21	260	54	3	0	0	4
	Sherry Shan	23	124	27	0	2	0	0
	Tricia Lynn	29	183	19	0	4	2	0
July 30 Total		115	925	155	5	8	3	7
31-Jul-01	Tricia Lynn	27	359	34	2	3	1	3
July 31 Total		27	359	34	2	3	1	3
01-Aug-01	Debbie Dee	27	210	33	0	2	2	0
	Harlynn	19	121	12	0	1	0	0
	Raven Explorer	16	70	13	1	0	0	1
	Sherry Shan	25	207	15	1	1	0	0
	Tricia Lynn	11	39	3	0	0	0	1
August 1 Total		98	647	76	2	4	2	2

Table A1. Observed Daily Catch by Vessel continued

Date	Vessel	# sets observed	Total Catch					
			Sockeye	Pink	Chum	Coho	Chinook	Steelhead
03-Aug-01	Debbie Dee	18	32	30	1	3	1	0
	Harlynn	18	42	28	1	0	0	0
	Raven Explorer	17	50	56	0	4	2	2
	Sherry Shan	25	116	40	1	3	0	1
	Tricia Lynn	20	46	34	1	8	0	0
August 3 Total		98	286	188	4	18	3	3
06-Aug-01	Debbie Dee	24	116	54	0	12	0	4
	Harlynn	24	204	74	0	8	0	1
	Raven Explorer	24	148	89	5	1	0	0
	Sherry Shan	22	240	61	0	5	1	1
	Tricia Lynn	32	47	29	2	16	1	3
August 6 Total		126	755	307	7	42	2	9
07-Aug-01	Raven Explorer	22	364	73	2	20	0	1
August 7 Total		22	364	73	2	20	0	1
08-Aug-01	Debbie Dee	27	404	316	2	26	0	3
	Harlynn	22	299	221	1	12	0	0
	Raven Explorer	23	312	127	3	3	0	1
	Sherry Shan	22	447	195	6	4	0	2
	Tricia Lynn	35	228	92	0	33	0	6
August 8 Total		129	1,690	951	12	78	0	12
09-Aug-01	Debbie Dee	28	270	203	2	19	1	10
	Harlynn	20	211	140	3	8	0	5
	Raven Explorer	16	118	110	1	4	0	2
	Sherry Shan	19	247	118	2	2	0	0
	Tricia Lynn	33	321	96	1	12	0	6
August 9 Total		116	1,167	667	9	45	1	23
13-Aug-01	Debbie Dee	11	35	45	2	2	0	2
	Harlynn	11	20	43	0	1	0	0
	Raven Explorer	11	63	136	4	3	0	5
	Sherry Shan	8	6	14	0	0	0	0
	Tricia Lynn	8	4	6	0	0	0	0
August 13 Total		49	128	244	6	6	0	7
15-Aug-01	Debbie Dee	18	42	39	4	0	0	6
	Harlynn	19	42	52	2	0	0	0
	Raven Explorer	14	18	63	1	3	0	2
	Sherry Shan	13	74	40	3	1	0	0
	Tricia Lynn	26	51	76	3	4	0	2
August 15 Total		90	227	270	13	8	0	10
19-Aug-01	Debbie Dee	1	2	14	2	4	0	0
	Raven Explorer	1	0	4	0	0	0	0
	Sherry Shan	9	12	158	1	2	0	2
	Tricia Lynn	15	7	13	0	13	0	4
August 19 Total		26	21	189	3	19	0	6
23-Aug-01	Harlynn	16	23	205	0	16	0	1
	Tricia Lynn	35	23	196	0	47	0	3
August 23 Total		51	46	401	0	63	0	4
Grand Total		2,547	34,889	4,262	85	396	415	181

Table A2. Comparison of Area 4 Daily Sockeye Catch

Date	Average Daily Sockeye Catch		
	Tooth Tangle Nets	Traditional Nets Entire Area 4	Traditional Nets River/Gap/Slough
6-Jul	97.4	117.2	120.2
9-Jul	109.0	100.0	185.7
10-Jul	90.8	110.8	87.2
12-Jul	86.4	116.6	179.6
13-Jul	44.2	80.4	35.4
15-Jul	220.4	159.0	232.2
16-Jul	151.2	172.0	211.0
18-Jul	211.2	235.0	283.3
21-Jul	280.4	305.0	396.2
23-Jul	90.2	184.0	178.7
24-Jul	145.6	207.0	215.4
27-Jul	375.6	237.0	350.9
29-Jul	213.6	236.0	324.2
30-Jul	185.0	196.0	268.1
1-Aug	129.4	131.0	163.2
3-Aug	57.2	70.0	74.5
6-Aug	151.0	123.0	148.8

Appendix B – Data Forms

Figure 1. Set Log Form

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Set Log Form (one per set)
Tooth Tangle Net Study 2001

Date (dd/mm/yy)	Set #	Vessel + CFV	Observer	Area	Sub Area	Location Description	Time Net Set (24:00)	Time Net Hauled (24:00)	Soak Time (min)	Net length (fathoms)

CAPTURE CONDITION: **AFTER RECOVERY BOX:**

BY-CATCH	# Captured					Total	Net Morts					Seal Morts					Procedural Morts					Prev. Caught Morts				
SPECIES	1	2	3	4	5	All	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
Coho																										
Chinook																										
Steelhead																										

CAPTURE CONDITION: **MORT CLASSIFICATION:**

TARGET	1
Sockeye	
Chum	
Chinook	
Pink	

FISH RETAINED:

Sockeye	Chum	Pink	Chinook	Other:

Comments: ______________________________

Weather Conditions:______________________
Water Clarity:__________________Water Temp:__________°C
Wave Action: __________________River level: low mod high
Tide: low flood high ebb

Figure 2. Tally Sheet

Catch Tally Sheet (one per set)
Tooth Tangle Net Study 2001

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Date	Set #	Vessel + CFV	Observer	Are a	Sub Area	Location Description	Time Net Set (24:00)	Time Net Hauled (24:00)	Soak Time (min)	Net length (fathoms)

Fish Capture Condition

		1	2	3	4	5 Net	5 Seal	5 Proc.	5 Prev.Capt	Total Sampled	Total Caught	Sample Description
Sockeye	Tally											
	Total											
Chum	Tally											
	Total											
Pink	Tally											
	Total											
Coho	Tally											
	Total											
Chinook	Tally											
	Total											
Steelhead	Tally											
	Total											

TANGLE NET REPORT

2002

2002 TANGLE (LIVE CAPTURE) NET

SELECTIVE FISHING PROJECT

FEBRUARY 2003

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2002 TANGLE (LIVE CAPTURE) NET

SELECTIVE FISHING PROJECT

FEBRUARY 2003

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And
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1.0 INTRODUCTION

In British Columbia three types of commercial salmon fishing gear are permitted, seine, troll and gillnet. Salmon fishery managers are challenged with protecting weak salmon stocks while allowing mixed stock fisheries. Historically, time, area and gear restrictions have been employed to limit the harvest of non-target species. Revival boxes were mandated in BC commercial salmon fisheries to improve fish handling practices and increase the chances of survival for fish released. If the risk of catching fish from weak stocks is too high, and fish capture and/or handling methods do not allow for a high survival rate of released fish, then fishery managers must restrict fishing opportunities. The development of more selective fishing practices can provide fishers with additional fishing opportunity without jeopardizing weak stocks.

Selective fishing can be accomplished either by avoiding encounters of non-target species or by being able to capture and release non-target species in good condition with a high probability of survival. Studies have shown that the immediate survival of chinook captured in a gillnet may be quite high, greater than 95%, but the post release survival drops significantly to only about 50% (Vander Haegen et al 2002)

During the 2002 salmon fishing season, a selective fisheries project was undertaken by Fred and Linda Hawkshaw, owners of the commercial fishing vessel *Tricia Lynn*, to evaluate the feasibility of using a tangle net to capture target species and release non-target species in good, live condition. The net was to be fished in both deeper, open waters and in protected waters to determine the versatility of the net and whether drop-outs are of concern. This follows a similar project undertaken by Mr. and Mrs. Hawkshaw in 2001 (J.O. Thomas 2002).

Tangle nets are made of multifilament web of smaller mesh size than a conventional gillnet. This prevents adult fish from entering the net and becoming caught around the gills or body. Instead, fish are typically caught by the teeth, maxillary or jaw, allowing non target species to be released in good physical condition. Mr. and Mrs. Hawkshaw have successfully been using this net for the past seven years under scientific permit to supply live salmon to their markets.

Archipelago Marine Research Ltd. was engaged to process, compile and present the information collected from this project. This project was not intended to provide data for strict statistical analysis but rather to demonstrate the obvious advantages and/or disadvantages with respect to selective fishing with a tangle net as compared to a traditional gillnet. The information provided by this project will assist Fisheries and Oceans Canada (DFO) in the evaluation of this type of gear. Mr. and Mrs. Hawkshaw hope that DFO will sanction the use of the tangle net in the 2003 salmon fishing season.

2.0 METHODS

The *Tricia Lynn* participated in commercial gillnet sockeye openings between June 11 and August 8, 2002 using a tangle net. At the end of the season, between August 15 and September 5, 2002, the *Tricia Lynn* was authorized to fish with a tangle net during commercial closures under a scientific permit. Pinks were the only target species permitted to be retained during commercial closures. All fishing took place in the North Coast of British Columbia near the Nass River, Pacific Fishery Management Area (PFMA) 3 and near the Skeena River, PFMA 4 (Figure 1). No observer was on board during the project due to financial constraints. Instead, catch information was collected and recorded by Fred and Linda Hawkshaw.

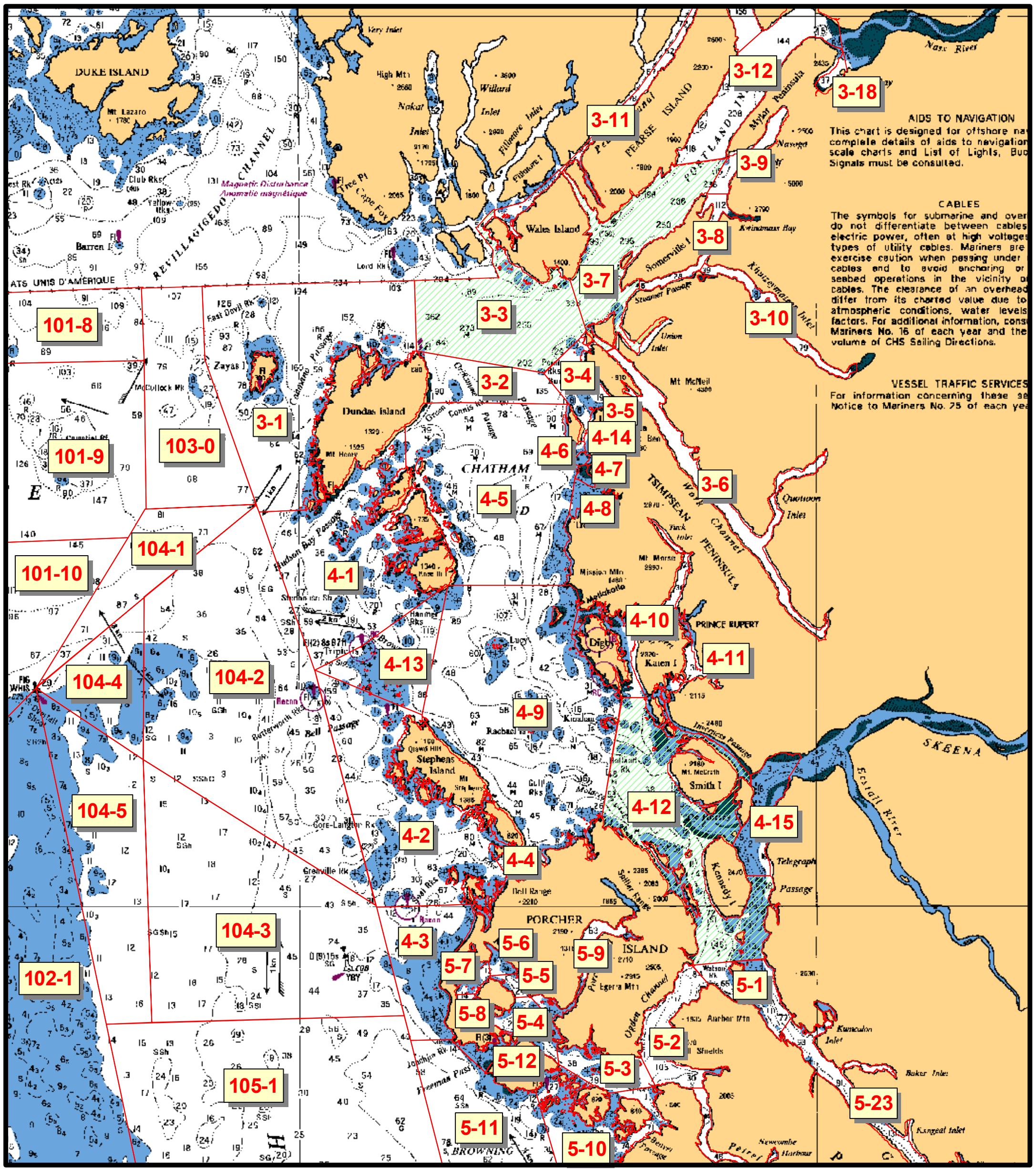


Figure 1. Tangle net fishing locations.

The tangle net used was constructed of 4.0 inch mesh consisting of four strand, 1.5mm monofilament twine, UR-32 in colour. Nets were 100 fathoms in length, hung at a ratio of 2.2:1. Nets of 60 meshes and 90 meshes deep were used. All corks were red in colour. Soak times, the time between the first cork in the water and the last cork out, were approximately 30 minutes or less. The following table summarizes the dates fishing took place and the net specifications used each day.

Table 1. Summary of days fished and tangle net dimensions

Opening Date	Opening Time	PFMA	Target Stock	Net Length (fathoms)	No. Meshes Deep
June 11	06:00 to 22:00	3	Nass Sockeye	200	90
June 12	06:00 to 22:00	3	Nass Sockeye	200	90
June 17	06:00 to 22:00	3	Nass Sockeye	200	90
June 18	06:00 to 22:00	3	Nass Sockeye	200	90
June 24	06:00 to 22:00	3	Nass Sockeye	200	90
June 25	06:00 to 22:00	3	Nass Sockeye	200	90
July 1	06:00 to 22:00	4	Skeena Sockeye	200	90&60
July 18	06:00 to 22:00	4	Skeena Sockeye	200	60
July 22	06:00 to 21:00	4	Skeena Sockeye	100	60
July 23	06:00 to 21:00	4	Skeena Sockeye	100	60
July 29	06:00 to 21:00	4	Skeena Sockeye	100	60
July 30	06:00 to 21:00	4	Skeena Sockeye	100	60
August 1	06:00 to 21:00	4	Skeena Sockeye	100	60
August 2	06:00 to 21:00	4	Skeena Sockeye	100	60
August 5	06:00 to 21:00	4	Skeena Sockeye	100	60
August 8	06:00 to 21:00	4	Skeena Sockeye	100	60
August 15	N/A	4	Pink	50-100	60
August 18	N/A	4	Pink	50-100	60
August 24	N/A	4	Pink	50-100	60
August 30	N/A	4	Pink	50-100	60
September 5	N/A	4	Pink	50-100	60

3.0 DISCUSSION OF RESULTS

3.1 CATCH PERFORMANCE

The catch data for the tangle net are provided in Appendix I and summarized in Table 2.

Table 2. Summary of total tangle net encounters

Species	Pieces
Target Salmon	
Sockeye	1356
Pink	1497
Non-target Salmon	
Coho	57
Chum	16
Chinook	17
Steelhead	39
Atlantic	0
Non-salmon	
Sculpin	1
Poacher	1
Dolly Varden	5
Dogfish	1
Herring	2
Shad	1
Birds	**0**
Harbour Porpoise	**1**

For the 16 days of fishing during commercial openings, gillnet data was obtained for comparison from DFO's Fishery Operations System (Patten 2003). The Fishery Operations System (FOS) database stores all of the commercial catch reported by fishers. The catch data was converted to catch per unit effort (CPUE) by dividing the number of fish caught by the hours fished. The hours fished includes the soak time, net deployment and retrieval, and time spent searching for fish. The CPUE of the tangle net was compared to that of the commercial gillnet fleet fishing the same Pacific Fishery Management Sub-area as the *Tricia Lynn*. The CPUE comparisons for each salmon species, including steelhead were plotted separately in Figures 2 to 7. All other non-salmon species caught were pooled together and plotted in Figure 8.

There are many factors affecting the CPUE of an individual vessel such as the fishing location, fishing experience of the skipper, and the proportion of the soak time to the total hours fished. Despite these variables, the CPUE plots can be used to identify general trend similarities or differences between the two gear types.

Figure 2. Sockeye

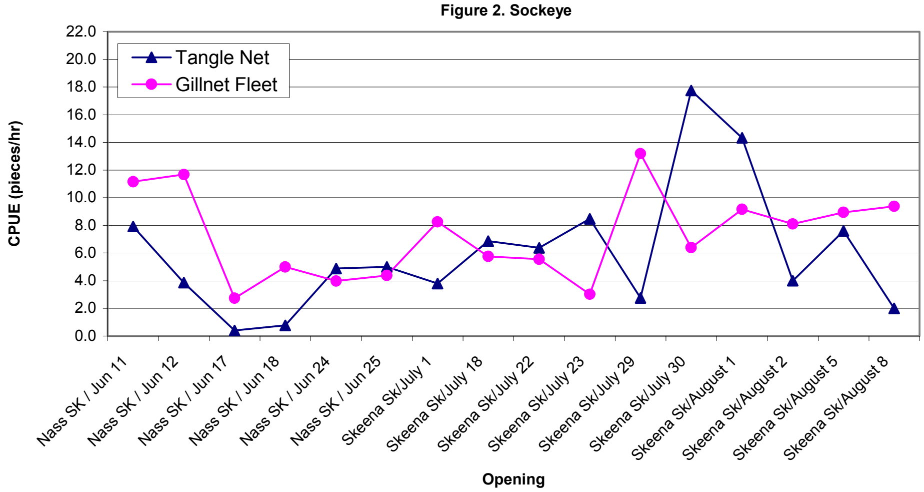
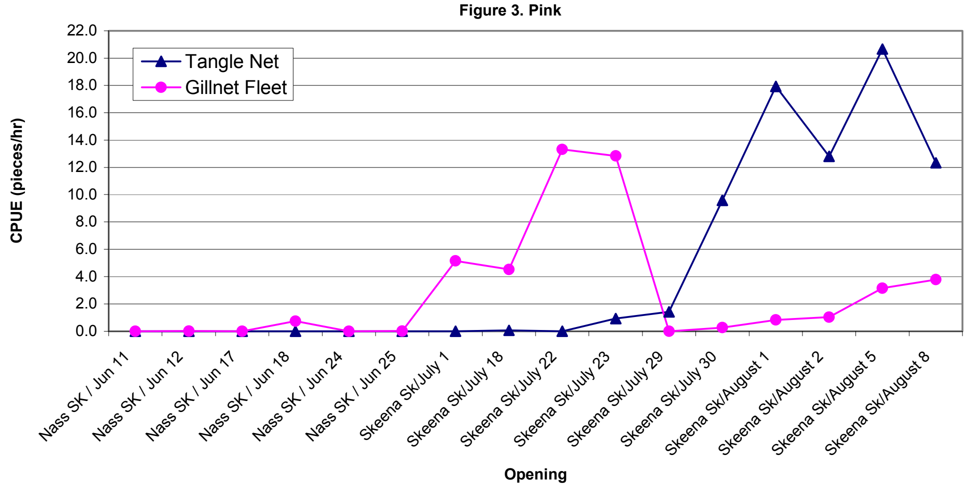


Figure 3. Pink



Comparing the target species catch of sockeye (Figure 2) and pink (Figure 3) to the commercial fleet, the tangle net performed similar to the gillnet. The sockeye CPUE line for the tangle net "criss crosses" the CPUE line for the gillnet fleet, indicating similar productivity. The pink CPUE doesn't follow as closely, with the gillnet catch rate significantly exceeding the tangle net between July 1 and July 23. However, the tangle net significantly outperformed the gillnet fleet July 30 to August 8. These differences could be due to the productivity at different fishing locations within the same sub-area.

Figures 4 through 8 compare the catch of non-target salmon and non-salmon species, from the tangle net and the gillnet fleet. The rate of coho (Figure 4) caught was very similar to the gillnet fleet until July 29, when the tangle net catch rate exceeded the commercial fleet. The coho catch rates appear to be closely linked to the pink catch rates. For both the commercial fleet and the tangle net, high encounters of coho corresponded to high encounters of pinks.

Figure 4. Coho

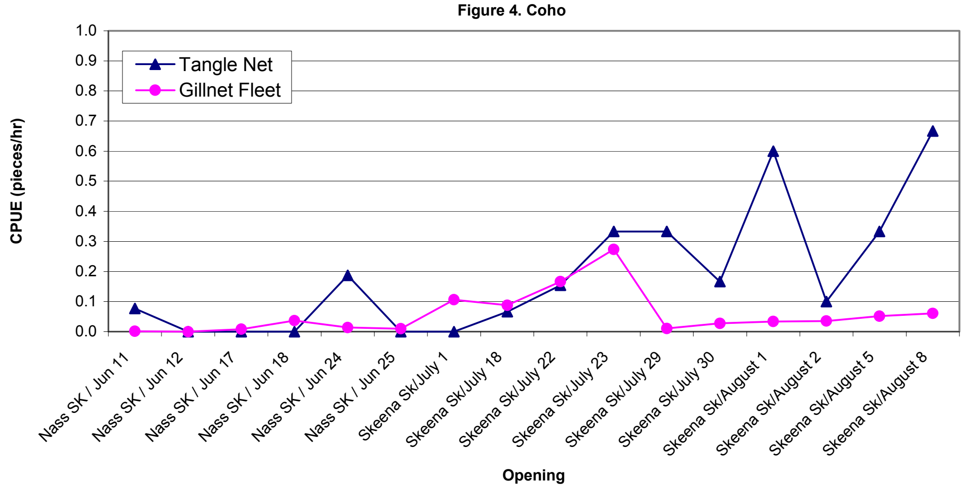


Figure 5. Chum

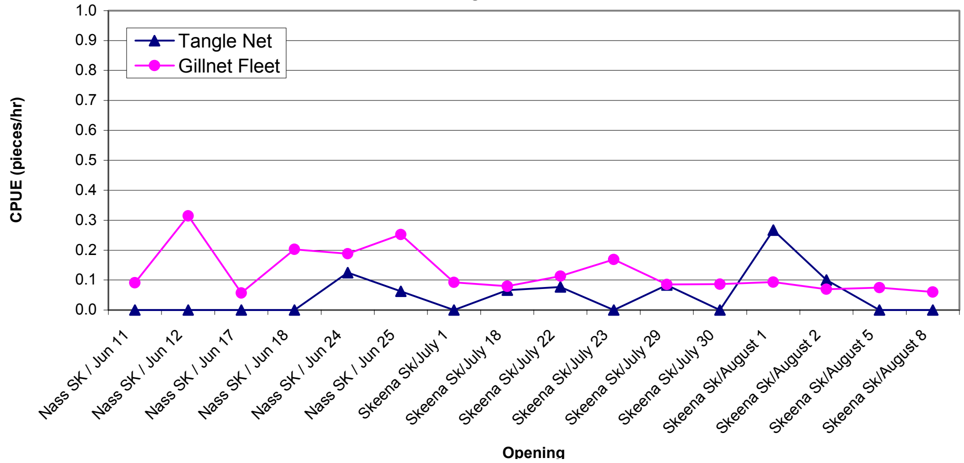


Figure 6. Chinook

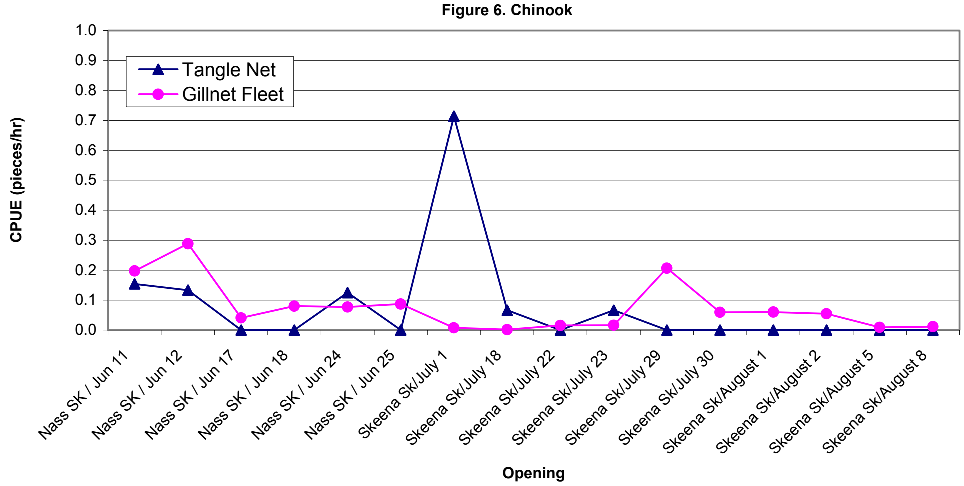


Figure 7. Steelhead

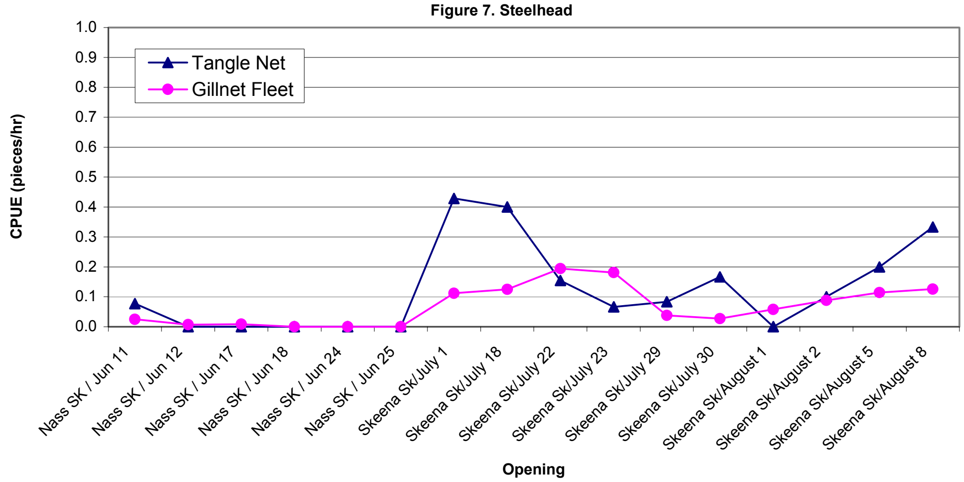
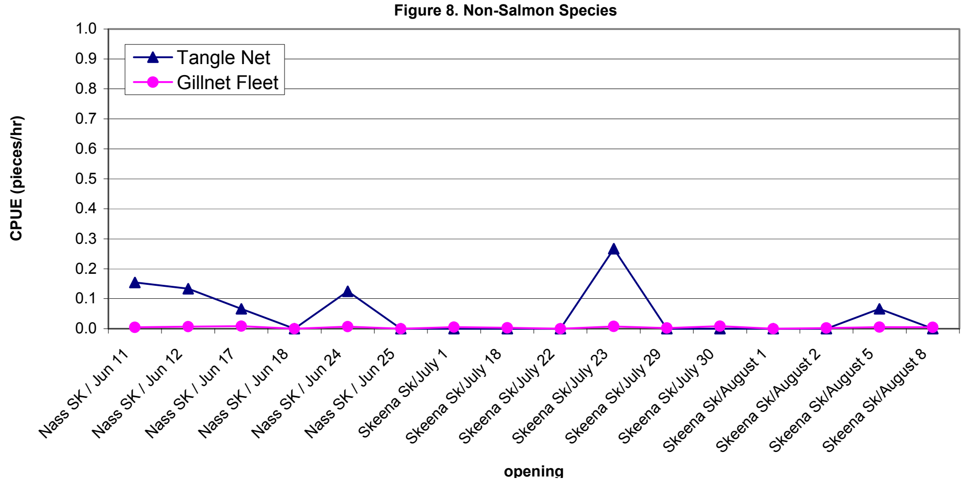


Figure 8. Non-Salmon Species



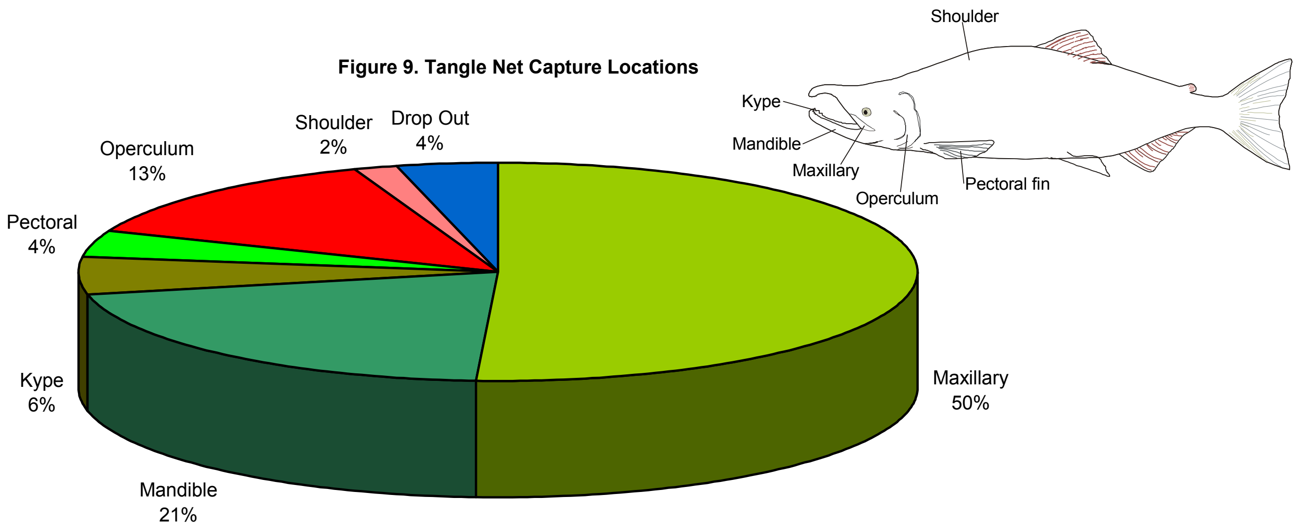
The tangle net consistently captured slightly fewer chum than gillnets (Figure 5). Catch rates of chinook (Figure 6) and steelhead (Figure 7) were very similar to the gillnets with the exception of the spike in encounters of both species in the tangle net on July 1. Six non-salmon species were encountered with the tangle net, sculpin, poacher, dolly varden, spiny dogfish, herring and shad. Eleven non-salmon fish were caught and released in total. As compared to the gillnet, encounters of non-salmon species (Figure 8) were slightly higher for the tangle net. This is consistent with other similar studies (Vander Haegen et. al. 2002) and is likely a function of the smaller mesh size. It should be noted that the gillnet comparison data was reported by fishers who have only recently been required to report their bycatch species in logbooks. For this reason, many fishers likely haven't made reporting non-salmon species a primary focus. In general, tangle net catch rates of non-target species, both salmon and non-salmon, were similar to the gillnet fleet at less than 0.5 fish per species, per hour.

No birds and one harbour porpoise (released alive) were encountered during this project. No birds have been encountered in the seven years of using the tangle net (Hawkshaw pers. com.). Mr. Hawkshaw attributes this mainly to the brightly coloured corks used. Based on his observations, birds seem to be attracted to white corks, perhaps because they resemble gulls from a distance. Conversely, birds seem to be deterred by brightly coloured corks, like red and pink, and stay clear of the net.

3.2 Capture Locations

During commercial fishery closures between August 18 and September 5, more detailed information was collected about how each fish was captured by the net. The capture location data (Appendix 2) was summarized and is presented in Figure 9. Over 77% of non-target salmon were captured by the mouth, either the maxillary, mandible or kype. In most cases, these capture locations allow the fish to continue to breathe freely without injury to the gills or body.

Figure 9. Tangle Net Capture Locations



Figures 10 to 12 show capture locations on pink and sockeye. The bodies of the fish are in good condition with no markings or scale loss. Larger fish are commonly caught by the lower jaw and pectoral fin (Figure 10). Some fish are caught as daintily as by a few of teeth (Figure 11). This is in contrast to how a gillnet functions where the majority of fish are captured by the operculum or wedged further behind the operculum at the shoulder or dorsal fin. These gillnet capture locations can result in significant injury to the fish, both internally and externally as the fish struggles to try and free itself. Figure 13 shows a sockeye that previously escaped a gillnet. There is a considerable mark on the outside of the fish around the belly accompanied by scale loss. When this fish was processed (Figure 14) several bruised and broken ribs were evident. Another example of external injuries is on the female steelhead in Figure 15, previously caught in a gillnet with obvious bruising on the shoulder and back..

Figure 10. Large male pink caught by lower jaw and pectoral fin.

Figure 11. Female pink caught by front teeth on lower jaw.

Figure 12. Sockeye caught by upper teeth and lower jaw

Figure 13. Sockeye, previously gillnet caught, with external marking on belly.

Figure 14. Sockeye, previously gillnet caught, with bruised and broken ribs next to spine.

Figure 15. Female steelhead, previously gillnet caught, with wounds across back.

Mr. Hawkshaw also noticed a difference in the behaviour of tangle net caught fish from gillnet caught fish. Fish in a tangle net are retrieved in a calmer state. Fish caught in a gillnet are lively and struggle to get out of the net. Some (Vander Haegen et al. 2002 and Hawkshaw 2002) have hypothesized an explanation for this. Fish wedged around the body, as in a gillnet, may have a flight response to try and get away from the net. In the process, they often sustain injuries as a result of being squeezed between the meshes. Even though appearing lively upon handling, these fish may be close to physiological exhaustion, unable to escape predators upon release or regain enough strength to reach the spawning grounds. Fish caught by the mouth, as in a tangle net, do not seem to panic and perhaps undergo a kind of auto-shutdown response. They have not

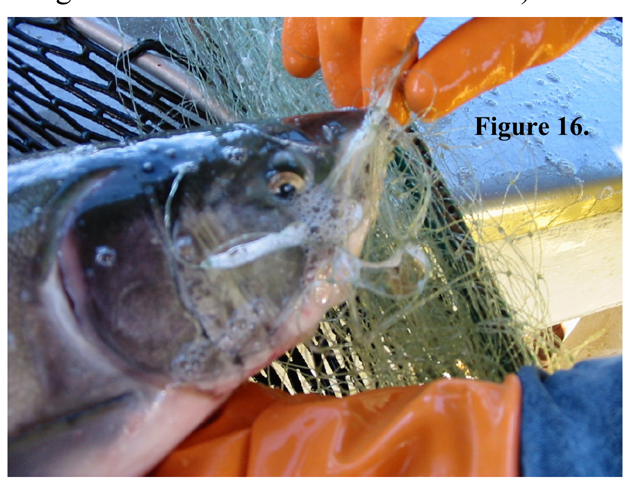


Figure 16.

expended as much energy and are not as exhausted. This, however, does not mean that they are not under some stress, as indicated by the tangle net caught sockeye in Figure 16, still alive but foaming around the face.

These observations have implications for the evaluation of fish condition. Typically there are five categories for evaluating the condition of a fish; 1. vigorous and not bleeding, 2. vigorous and bleeding, 3. lethargic and not bleeding, 4. lethargic and bleeding, and 5. dead. A vigorous fish is generally considered to be in better condition than a lethargic fish. However, given the observations of tangle net caught fish, the opposite may be true, a vigorous fish may be in worse condition than a lethargic fish.

3.3 COHO MORTALITIES

A total of 36 coho were encountered with the tangle net during the commercial openings. Four coho could not be revived for a total mortality of 11%. Two of the four coho that died were previously net caught and were likely already in a weakened condition; therefore, contributing to a higher mortality than what the Hawkshaws have experienced in the past of under 10% (J.O. Thomas 2002). The coho that were released live were all in good condition.

Mr. and Mrs. Hawkshaw typically keep their target sockeye live for up to 48 hours and pinks live for up to two weeks prior to processing. They experience fish mortalities of only around 5% to 10% on these fish. This supports the conclusion that these fish are in good condition after being caught and gives some indication that the longer term survival of fish after release would also be quite good.

3.4 FISHING HIGHLIGHTS FROM FRED HAWKSHAW

Mr. Hawkshaw provided some notes for this report regarding his experience fishing the tangle net in 2002. His experiences are summarized in the following points below:

- In Area 3, a 90 mesh net was sufficient as very few fish were encountered near the lead line.
- The net performed well in open water even when weather and sea conditions were unfavourable. Only about 5% live dropouts per day were occurring and were not considered a concern.
- In excess of 95% of the sockeye were delivered live for processing.
- It was an advantage to have the full length 200 fathom net cut into two equal portions (of 100 fathoms each) so that a shorter length net could be set and retrieved quicker. This allowed for more timely retrieval of fish from the net resulting in better quality fish for market and better condition of non-target species for release. In some cases only 50 – 100 fathoms of net were deployed depending on the number of fish caught in the previous set and the number seen "hitting" the net. In this way, the net could be set as if "spin casting a lure".
- Fish of all sizes were captured with the tangle net. This reduces the size selectivity of only the mid to large size fish from the gene pool as occurs with a traditional gillnet.
- A net with 3.75 inch mesh consisting of three strand, 1.5mm monofilament hung on a 2.3:1 ratio may be better suited for targeting pinks. It might reduce the chances of smaller fish getting too far into the net, especially the smaller coho that are commonly encountered with pinks.

4.0 CONCLUSIONS

It is apparent from the information collected from this project that the tangle net is effective at catching salmon. Where this net excels is in how fish are captured. Over 77% of the fish were captured by the mouth and are less likely to sustain injuries or exhaust themselves as a result of struggling to get free of the net. This enables the fisher to harvest excellent quality fish for market and release non-target species in good, live condition.

It is also clear that fish handling practices, including net deployment and retrieval behaviour plays a key role in the resulting condition of each fish taken from the net. The Hawkshaw's are motivated to bring in fish of high quality because they are advocates of selective fishing practices and because they are rewarded financially for delivering quality fish to their markets.

The net performed well in both open and protected waters with only about 5% live drop outs. No birds and one harbour porpoise (released alive) were encountered during the project.

Consideration should be given for incorporating the tangle net into the gillnet fishery. It could provide fishery managers with a tool to allow gillnet fisheries to occur without jeopardizing stocks of concern. With the potential for higher prices awarded to tangle net caught fish, the pace of the gillnet fishery could be slowed, and tighter restrictions placed on fish handling practices and soak times, while providing fishers with more fishing opportunities throughout the season. By allowing the tangle net into the gillnet fishery, at least for a trial season, more data could be collected for further evaluation.

5.0 REFERENCES

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APPENDICES

Appendix I. Tangle net catch data - June 11, 2002 to September 5, 2002

Location	Date	PFMA	Sub-Area	Sets	Hours	Sockeye	Coho	Pink	Chum	Chinook	Steelhead	Atlantic	Birds	Mammals	Sculpin	Poacher	Dolly Varden	Dogfish	Herring	Shad
Nass River	6/11/2002	3	7	11	13	103	1	0	0	2	1	0	0	0	1	1	0	0	0	0
Nass River	6/12/2002	3	3	6	7.5	29	0	0	0	1	0	0	0	0	0	0	1	0	0	0
Nass River	6/17/2002	3	3	11	15	6	0	0	0	0	0	0	0	0	0	0	0	1	0	0
Nass River	6/18/2002	3	3	7	6.5	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Nass River	6/24/2002	3	3	16	16	78	3	0	2	2	0	0	0	0	0	0	0	0	2	0
Nass River	6/25/2002	3	3	10	16	80	0	0	1	0	0	0	0	0	0	0	0	0	0	0
Subtotal Area 3 - Comm. Openings				**61**	**74**	**301**	**4**	**0**	**3**	**5**	**1**	**0**	**0**	**0**	**1**	**1**	**1**	**1**	**2**	**0**
Skeena River	7/1/2002	4	12	13	14	53	0	0	0	10	6	0	0	0	0	0	0	0	0	0
Skeena River	7/18/2002	4	12	15	15	103	1	1	1	1	6	0	0	0	0	0	0	0	0	0
Skeena River	7/22/2002	4	12	20	13	83	2	0	1	0	2	0	0	0	0	0	0	0	0	0
Skeena River	7/23/2002	4	12	20	15	127	5	14	0	1	1	0	0	0	0	0	4	0	0	0
Skeena River	7/29/2002	4	12	10	12	33	4	17	1	0	1	0	0	0	0	0	0	0	0	0
Skeena River	7/30/2002	4	12	20	12	213	2	115	0	0	2	0	0	1	0	0	0	0	0	0
Skeena River	8/1/2002	4	12	20	15	215	9	269	4	0	0	0	0	0	0	0	0	0	0	0
Skeena River	8/2/2002	4	12	13	10	40	1	128	1	0	1	0	0	0	0	0	0	0	0	0
Skeena River	8/5/2002	4	12	21	15	114	5	310	0	0	3	0	0	0	0	0	0	0	0	1
Skeena River	8/8/2002	4	12	6	3	6	2	37	0	0	1	0	0	0	0	0	0	0	0	0
Subtotal Area 4 - Comm. Openings				**158**	**124**	**987**	**31**	**891**	**8**	**12**	**23**	**0**	**0**	**1**	**0**	**0**	**4**	**0**	**0**	**1**
Skeena River	8/15/2002	4	12	22	10.5	47	2	238	0	0	11	0	0	0	0	0	0	0	0	0
Skeena River	8/18/2002	4	12	27	10.5	11	4	248	3	0	1	0	0	0	0	0	0	0	0	0
Skeena River	8/24/2002	4	12	17	7.5	0	5	51	0	0	3	0	0	0	0	0	0	0	0	0
Skeena River	8/30/2002	4	12	13	6	3	2	47	1	0	0	0	0	0	0	0	0	0	0	0
Skeena River	9/5/2002	4	12	16	5.5	7	9	22	1	0	0	0	0	0	0	0	0	0	0	0
Subtotal Area 4 - Comm. Closures				**95**	**40**	**68**	**22**	**606**	**5**	**0**	**15**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Total				**314**	**238**	**1356**	**57**	**1497**	**16**	**17**	**39**	**0**	**0**	**1**	**1**	**1**	**5**	**1**	**2**	**1**

Appendix 2. Tangle net capture locations – August 18, 24, 30 and September 5, 2002

Capture Location	Sockeye	Steelhead	Coho	Chum	Total	Percent
Maxillary	13	2	12		27	50.9
Mandible	2	1	3	5	11	20.8
Kype			3		3	5.7
Pectoral	1		1		2	3.8
Operculum	4		3		7	13.2
Shoulder	1				1	1.9
Drop Out		2			2	3.8
Total	21	5	22	5	53	100

SUBMISSION TO WILD SALMON POLICY CONSULTATIONS FEBRUARY 2005

Please provide your written submissions by February 18, 2005 by email, fax or mail.
Email: wsp@pac.dfo-mpo.gc.ca
Fax: (604) 666-3295

Mail Address:
Wild Salmon Policy Consultations
Policy and Economic Analysis Branch
Fisheries and Oceans Canada
200-401 Burrard St.
Vancouver, BC V6C 3S4

Strategy 1- Standardized Monitoring of Wild Salmon Status

- What advice do you have about the delineation of CUs and the protection of genetic diversity?
  Response:

BC has lost more than one genetically distinct stocks of wild salmon over the years and it is an imperative that this no longer be allowed to happen. Nature has designed wild salmon to respond to differing climate issues, diseases, water Ph levels and rearing strategies and thus, while on the surface most "species" appear similar, by "stock", in fact each has different needs that have been developed and designed over millennia. A good case in point would be sockeye, a species that has evolved largely specific to each watershed. The reasons for this may not be that simple to us, but for whatever reason, Nature may have designed sockeye around the earth's constantly changing geologic structure. Where in one stream system that specific stock may not have immediate access to a lake for successful rearing and natural stock enhancement, a nearby system that has such a lake in it, may, by virtue of an earthquake one day cut off access to that stock and the system then might offer what to that point in time had only been a small in-river stock of sockeye, could then suddenly grow to take over from where the now no longer accessible river system's stock that had now been cut off and we would then still have a viable run of sockeye into and emerging from the same lake source, albeit from a "new" stream source.

While some species of wild salmon are more able to adapt to choosing alternate systems such as pinks and chums, depending on seasonal or climactic changes, diseases, changing Ph factors, human impact on the earth and riparian zones demand we not afford to delete any of our salmon stocks simply because they cannot tolerate previous harvest rates now diminished as a result of our human intrusion into affecting or impacting on their fresh water eco-system. Most of our wild salmon have the ability to use a multiple of year classes as a strategy to ensure success for their future with the exception of our Pink salmon. This species uses its ability to produce massive volumes of off-spring as the key to its survival, plus an inherent ability to stray to alternate systems should the immediate need arise.

The Dept of Fisheries intended to establish terms of reference points or goals to meet in regards to selective or responsible fishing as a management tool to avoid reducing the viability of the fishery in regards to target species/stocks; to date this has had little in the way of positive response from fishers, in particular the gill-net fleet. The Dept's response to this has been to curtail access at best and to "request" at worst that fishers comply. The effect has been terrible for the viability of those who support responsible fishing and is putting the rebuilding of the stocks targeted for rebuilding at long-term cost to the fishery – for no good reason. As access to target volumes diminishes to protect and rebuild failing stocks, a direct result of non-compliance with selective fishing, the viability of the remaining fishers also diminishes. As the gill-net sector refuses to accept the need for changes in the harvest/after-harvest sectors (processing), the response to selective fishing has also diminished and it is this intolerance to responding to the need for change and personal responsible behavior that is conflicting with the Dept's need to ensure both sustainability and viability for the future – if a commercial/commercially viable fishery is still envisioned for the future.

- What criteria should go into identifying the lower and upper benchmarks of biological status?

Response:

Given that it is very difficult to identify one "stock" against another within any given species without a physical marking or characteristic such as a clipped adipose fin, and unless/until the Dept can use DNA typing to establish finite times of harvest restraint, coupled with the fact that we can no longer afford to lose any more stocks of wild salmon, I would have to suggest there is but one choice; live harvesting coupled with DNA sampling or risk further collapse to the economic future of the fishery. Where the issue is around a ***species*** in a given system, then it behooves the Dept to put more teeth into selective fishing and more support behind those willing to comply with responsible behavior, in concert with policies that support alternate gear types and formats in order to affect a fisher's ability to fall in line with full selective fishing behavior. Since few other than a biologist or genetic scientist would have the knowledge to interpret how many individuals it will take to successfully sustain a population of fish, people like me would not be qualified to comment further on this issue, save to say that since the Dept has always maintained a healthy approach to limiting the amount of genetic intrusion hatcheries could subject our wild species/stocks to, there must be a base-line understanding of how few or how many fish it requires to successfully sustain a given population of fish; that part of the wild population not affected genetically by the intrusion of artificial enhancement. My biggest concern stems not from the Dept's ability to know when enough is enough, but far more from those who have managed to remain at the helm of controlling how, when and for whose benefit we fish and the deception of being forced into keeping with out-dated gear formats and types simply to suit those who see no future in change.

- How can monitoring of biological status be done effectively and how could First Nations and local organizations become involved?

Response:

Upriver First Nations have already shown their willingness to get involved with monitoring and other issues that our wild salmon face, but, like responsible fishers out here on the coast, they seem to be hindered by lack of or weak Government Policy provisions to support honest responsible behavior; be that in fishing, logging or farming. Not that long ago, the Dept made a serious attempt to bring a process to the North Coast that could offer resolution to the ongoing conflicts that define the gill-net fishery. Last year the Dept suggested it was redesigning the Advisory Board that has for so long been at the heart of the conflicts and the failure of our resources and values, both in our communities and people/infrastructure related so inextricably to it. To date neither this attempt at change nor the Dept's efforts have ever resulted in change, in fact, the Skeena Watershed Committee, of which a close Native friend of mine and I were once a part of, were handily removed, just like the Skeena Watershed Committee itself, by the same people who still control this Board to this very day, some 12-15 years later. While we were still a part of this Committee, I certainly felt that the upriver Natives, of all the people thereon, were being the most pro-active in supporting and seeking changes in the way they harvested or interacted with the fish as they sought there food allocations. From my personal experiences on that Committee, I feel quite comfortable in stating that had the same people who are crushing the industry today, been themselves crushed back then, both that Committee and the fishery today would still be a viable, healthy and complimentary part of our present and future. Why and/or how the Dept has tolerated these peoples negative impact on: (a) the upriver Natives, the Sports fishery upriver, our communities both upriver and here along the coast is simply beyond my comprehension. From Alert bay to the Nass, from the coast to the interior, Native Communities have suffered hugely at the hands of these people and the Dept's failure to deal with the issue, why that is tolerated by the Canadian Public can only said to be the enigma of the century.

That our wild salmon in BC and so many of our coastal communities continue to have almost no value any more is a tragic statement of the controlling impact the canning industry, the Union and ill-thought out Advisory Boards has had and continues to have on this fishery. To that end, I would suggest it has been reasonable to understand why Ottawa has cut support and economic/social interest in the wild salmon net fishery, both North and South. Until the industry figures out it has a responsibility to all Canadians alike to challenge the currently suppressed and artificially low prices paid for wild BC salmon, it will be difficult for Ottawa to ask the Canadian Public for more funding to support what? If we are asking the Native peoples to become more involved in tackling the issues that wild salmon face in their fresh water domain, someone should better figure out a way to deal with the people on the Advisory Boards who are crushing both selective fishing, which is supposed to be the key to sustaining our access and future and come to terms with the responsible solutions to rebuilding the viability for fishers in this industry once again, for both Native peoples and non-native peoples equally and alike.

Trying to explain why it is important for the Interior Native peoples to support maintaining and sustaining the watershed zones that are vital to our wild salmon will currently only have meaning to those who still see a value in harvesting them for food. Someone in the Dept needs to explain to both me and the natives, not to forget the entire Canadian Public, coast to coast why wild salmon of all species have been allowed to fall so low in social and economic values? Imagine if you can, a Native elder who for his/her entire life and generations before them, knew, with every bone and fiber of their being that wild salmon had always been the one key element to their very survival for thousands of years and yet today, simply because the people who still control the Advisory Boards could care less about anyone else's values, never mind needs and then explain to me why or how any Native person is going to sort through the morass of conflicting signals to understand why he/she should be worried anymore about wild salmon? Imagine how difficult it must be for the old folks to come to terms with today's message that is lying to us all that our wild salmon have no value anymore and yet for thousands of years, without them there would be no coastal indigenous peoples here?

Imagine if you can, not even our community Civic leaders are allowed to penetrate the dark halls of these Advisory Boards which are ruining our collective lives and future, how unbelievably ridiculous is that? And the Dept asks how and who would be likely to *want* be involved? We had the right steering committee with the Skeena Watershed Committee; had we not had the same people who today are still actively in control of suppressing change in our fishery today, there might not be a need to look for a new group today with new energy.

- Have we missed any action steps in our proposed standardized monitoring of wild salmon status?

Response:

I have only one answer and one simple, fair and reasonable solution, for a responsible change and **real** new beginning: **allow honesty and respect for all stakeholders to actively become a fundamental and functional, integral part of the Advisory Board Process/participants and real, positive changes to flow into and out of the Advisory Boards for the betterment of all stakeholders, fishers and communities - coastal and interior alike – that the well-being that once was can flow forth once again.**

Strategy 2- Assessment of Habitat Status

- What suggestions do you have for appropriate benchmarks and indicators of habitat quality and quantity?

Response:

If our BC wild salmon has the same value to the Canadian society and economy it had 100 years ago to Canada/BC, then it is fair and reasonable to suggest that the same habitat and quality of benchmarks that we had then should apply to today, is it not? Sadly this is no longer possible, issues like the weather/climate change and unsuspected events that are occurring as a result like the Pine Beatle outbreak that could spell the end of the BC Pine forests throughout the interior is destined to have a massive impact on the quality and future of entire river systems like the Fraser River. A recent study in Alaska is showing, among other things:
http://www.adn.com/alaska/story/5909359p-5816486c.html
A U.S. Geological Survey cited by the district's report suggests that Cook Inlet Basin streams may experience a water temperature change of 5.4 degrees Fahrenheit in coming years, a change that could lead to increases in fish disease.

The USGS study based its conclusions on a model using air temperature to predict water temperature and accounted for climate warming.

Phosphorus, while crucial for aquatic life, is a contaminant at high levels.

"Significant concentrations can result in dramatic decreases in dissolved oxygen, which is essential for the survival of all fish," the district said.

Given that no one here has the power to alter the course of nature as we speak, the best we can hope for is Government responsibility to tackle these kinds of issues at higher levels than we can muster. Having said that, the only thing I can think of that will work with any attempts to establish terms of reference or bench-marks for ascertaining the most effective parameters for habitat quality would have to be to stop the direction of the current fishery and move radically towards a fishery that is limited to focusing solely on maximizing values – all values - by maximizing the time of access expressed over far greater harvest periods with fewer fish being harvested per diem to maximize managements effectiveness in having the greatest opportunity to put the best of our stocks on the grounds for the future while still rebuilding the viability of the fishery. As opposed to today's/yesterdays expectations of access to maximum fish, all stocks and species, which we now know is not at all a sustainable approach any more, fishers expectations must be reversed to a focus on maximizing **their** sustainability and future by working implicitly with the Dept and all stakeholders to address known ways and exploring new ways and means to extract the most from the least fish, which can only have the positive affect of protecting all stakeholders future and rebuilding that centuries old fundamental wisdom that our wild salmon still have the same worth and values they had ten thousand years ago and it all boils down to this industry learning the real meaning of respect, both self and for all others inclusive; something the current Advisory Board is incapable of.

- How can interested individuals and organizations be effectively involved in the assessment and monitoring of habitat status within CUs?

Response:

It's wonderful that some people have the ability to respect the simple fact that our wild salmon truly do have huge value to our environment and our society. What makes this fact all the more staggering is the fact that some folks do so even as the very industry that should be showing the same degree of respect isn't?

My wife and family and I have a ten year PIP/DFO award for our credibility and respect for and in working with the future of our wild salmon as Public volunteers. That some people have the courage and self-respect to undertake such endeavors speaks volumes as to the Public belief that our salmon are worth looking after, but, faced with increasing odds against any efforts to sustain our wild salmon by the net industry, demands the question firstly *why*, then *who* and then *how* will anyone have the strength of will and character to maintain that essential level of belief and trust, that what they are about to undertake will have any use if those who are abusing the resource at sea fail to be brought to the table of respect?

Pretending that by some miracle the Dept will have the courage to allow the Canadian Public and/or any-all responsible and concerned people to challenge those who currently reside at the Advisory Board Process, seems out of the question; which in turn begs the question: If the Public is not allowed to have a say in the future of this resource and the fishery it supports, then is it not fair to question why anyone would take the Dept seriously? If we are allowed to challenge the negative impact the Advisory Board people are having both at sea and upriver, and this action is allowed to flow into support for active participation by people inland to over-see the sanctity of the fresh water habitat, I believe people will have just cause and good reason to get involved.

With so much negative attitudes towards this once vital and precious resource today,(please, a nickel a pound for a wild pink salmon?) it is hard to imagine how even the few who really do care could sustain that energy for long enough to see anything positive come out of their efforts, paid or otherwise, trust me, we've long been there. That some folks manage to maintain the energy level required to keep a stiff upper lip in the face of huge and overwhelming odds is a miracle, but we need more than a miracle today to pull this into the future. How a group of determined people can still carry on when a company dumps toxic pollution into a stream time after time their working on to rebuild, how some people can carry on with selective fishing efforts when the Dept breaks down the whole system by not *enforcing compliance* of any sort, how some people can work so hard to clean up a stream after logging negatively impacts it, how fish can survive as they are forced to pass upriver through raw municipal effluent, how we still have any harvestable degree of resources today after the level of abuse too many have suffered is all nothing short of a miracle. For the future, we need more than small miracles, we need those who are willing to tackle the impossible to be given **all** the support **all** levels of Government can muster.

- Have we missed any action steps necessary to the assessment of habitat status?

Response:

When many sockeye failed to show up on the spawning grounds this year, the best defense the Dept could muster was warm water. While the Depts scientists may not think the Public needs to have more credible answers, without them how do they expect the Public to support the Dept, and this resource? Above I've included some findings (URL LINK)that are going to be part of the future, like it or not. As opposed to having all these conflicts and poor answers flying around and our wild salmon and our commercial fisheries taking the brunt of it all, why is the Dept not sharing with the Public some very credible knowledge that they, the public can push Politicians the world around to address these increasing threats?

How big an impact is the Pine beetle going to eventually have? I don't believe we've even seen the tip of the "ice-berg" yet. How huge is the impact going to be after all these dead and dying trees are removed? How much silt, how big will the negative impact of increased Phosphorous resulting from this increased silt load be in regards to the stress factor, how much higher will the water temperatures go, how severe will the disease increase be as all these and other toxins that are going to come from this event to drive down the fishes natural immune system?

Our first response to this event should be to get seedlings restarted along all the affected stream-sides; to get shade and sediment blocks rebuilding as soon as possible. For decades to come there will be no trees to naturally die and fall into the streams to provide pools for fry growth, nutrients for the invertebrate and plankton growth to feed our following generations of salmon fry. Like Wash and Ore, our streams could become straight through-flumes for the water run-off to roar off out to sea, leaving our fry regeneration nothing for protection from rain burst events and spring freshet events. If we do not get people actively involved now in reseeding these vast moonscapes of desertification, how fast will the water temperatures and Ph become fully lethal to fish? Bad enough that these great forests are being removed like an army barber cropping the hair off a new recruit, for snow melt and rain events to flush massive amounts of silt into our water ways, but that to do so they are building roads all over the country which will provide even more siltification routes into our rivers and streams.

Strategy 3- Inclusion of Ecosystem Values and Monitoring

- What are your suggestions for a procedure to develop an ecosystem assessment framework and who should be involved in this procedure?

Response:

Firstly, both the Prov. and the Federal Governments scientists will have to be on the front lines in this effort, the job is going to be massive, unlike any before, anywhere - unless all we're interested in is the new Canadian "Sahara" Desert.

- What do you understand the term "ecosystem values" to mean and how should they be measured?

Response:

Good question and a deep question but one that deserves a great deal of science, a huge deal of new science. Until this Beetle event occurred, most of our waterways were reasonably consistent with both the past and what we still have lots of in BC, but tragically, this will very soon no longer be the case. While we'll still have many of the past's pristine examples to look at, this new event is so huge, so vast, nothing we have today or from the past will help measure what the new values will be. It is illogical and unreasonable to think that there is some magic way we will be able to define what the future of the Fraser system will look like in ten years, this event is so vast by any measure, whole new ideas and science will have to be developed in order to salvage even a remote semblance of the past. With quick action to get at the job, and it's going to have to involve perhaps thousands, maybe even tens of thousands of people working in what was once this vast forested area; if there is any hope of saving the Fraser River wild salmon populations, even a far bigger effort will be required if there is to be any semblance of even a small commercial harvest for the very far foreseeable future.

Strategy 4 - Integrated Strategic Planning

- How can the range of interests be brought together to collectively develop integrated (habitat enhancement, fisheries, marine area) plans that reflect salmon conservation needs?

Response: Firstly, the Dept will have to enable new people involved in the Advisory Board process who will tolerate a diversity of interests, ideas, thoughts and a willingness to engage a collaborative plan by all stakeholders to effect real salmon conservation. The Dept tried and failed to bring this concept about in the mid-nineties called the Skeena Watershed Committee. This great idea went sour because a few in the commercial sector were unwilling to make any compromises and in fact, went out of their way to ensure this idea was destined to. Having said that, how to change this self-centered issue is the sixty-four thousand dollar question, one I believe only honesty within the Dept itself can address. Finding a new solution is going to require the Dept have a better look at who is at the helm of the process that they've given free reign to that continues to keep division their goal – their own Advisory Board and it's Process. I listened to a bit of CBC at noon on an interview with Brian Riddel and Arne Narcisse got on. Even he has concerns about how to get fishers and Native communities on the coast to understand the gravity of the situation. I know I'm beating about here, but if this question were allowed to be addressed by *honest*, not self-centered people, there are solutions, but the Dept has to engage honest and willing people first. The Dept insists their Advisory Board Process is fully Democratic. That the same people who are there today are the same people who were there a decade and more ago and that they managed to get themselves voted in; yes, that is supposedly a definition of democracy. The simple facts are nothing could be further from the truth and reality***; this is a Canadian Public resource, not as the Dept insists, the exclusive property of the commercial sector to abuse and use as only it sees fit.***

- Stated another way, what organizational structure could be developed to achieve effective long term planning?

Response: It is as if you read my mind from your last question. I could hardly doubt many people would love to be involved in the future of the BC Wild Salmon, but first we need to remove those at the helm of the Advisory Board Level who would deny that spirit of Public involvement and support. Getting anyone from the commercial sector onboard with the real future, a truly sustainable and viable future for all stakeholders as their objective will require a change of attitude and real desire on the Dept's part to want to develop a process that could come without yester-years baggage. There can be no future, no compromise, no co-operation between the commercial sector and any other user/true owner group. The Dept has built division into the process in a poor attempt at what it likes to believe is "Democracy". *This resource is a Public resource*, a Canadian resource, not the property exclusive of the commercial fishery. The Dept continues to deny the Canadian Public any access to the decision making process in a "closed-door" Advisory Process. If the Dept is truly interested in a real Democratic Process, and is truly serious about the future and sustainability of this resource, they need to take a better look at who they have given so much power to that is denying any hope of a future. To achieve the goals as stated in the Wild Salmon Policy, or at least in so far as the Canadian Public believes it's getting, we need a process that cannot allow these same people to continue in control.

In a letter to the Editor, Daily News, January 26, 2005 regarding the new Wild Salmon Policy, the Minister states and I quote; "No matter how strong our commitment to it's implementation, success in salmon conservation will depend on constructive cooperation among all interested groups and individuals."

His next statement that insists the conflict and competition that have often characterized salmon conservation must give way to collaboration and a shared commitment to achieving the goal of this policy has the keys to our collective future…unfortunately the current and past Advisory Board Process is and remains so flawed with the same old people who have no intention of respecting anyone else's position or needs period, there is no hope period of bringing responsible people to this table or into any new process to address the Ministers stated concerns and solutions. The Province of BC has just put up $5,000,000 to a group selected to define the issues and hopefully – for $5,000,000 - find solutions. For free I could and would offer the solution but since no one not "elected" to the Advisory Board is allowed to speak up, of what use my wasted breath?

The wild salmon commercial net sector has been at the literal mercy of the whims and needs of the canning industry, insatiable demands for unsustainable and high risk to the resource volumes. That the head of the process that is supposed to work with or "Advise" the Dept and industry to build, not crush a viable and sustainable Public resource and future can be seen by the Dept as a democratic process is in the truest sense of the word, an enigma of incredible proportions, a conundrum beyond credible belief. IF the Dept is sincere about making this new Policy work, sincere about the future of BC's wild salmon and it's genetic integrity and supportive of a viable commercial fishery here in BC, then first and foremost the solution is simple, remove the arbitrary powers from this farce of a "democratic" process and begin with something that respectfully reflects honesty and a willingness to work together with all stakeholders for the benefit of all Canadians alike and we will have a future.

- What comments do you have about the adequacy of the planning process described in Action Step 4.1?

Response: I'd be needlessly repeating myself to write it all over again, but maybe that's what it will take before the Dept will admit, the process that should have by now accepted the need for change, simply said - will not. Normally I get told I am too long-winded and people lose touch with my thoughts. To avoid that, in this case, it may well be best to leave this one as it is……….if there is anyone in the Dept who is willing to take charge of their responsibilities and admit, we are stuck with a process so fatally flawed, and people in charge of it so self-centered, working with it as our "Organizational Structure" will deny any hope of a future, period, end of comment.

- What comments do you have about the adequacy of the interim planning process described in Action Step 4.2? Response - ?

- What would constitute exceptional circumstances under which the Minister of the Department of Fisheries and Oceans might decide to limit activities to avoid losses of wild salmon?

Response: It could be fairly said that this is a poorly worded question. Limiting access to protect or rebuild stocks of salmon has been and remains the sole method the Dept uses. Because industry has essentially flatly refused to adopt better gear formats or types and new attitudes regarding behavior and personal responsibility, being allowed by the Dept to hide or disguise their responsibilities behind a flawed "revival-box" system that was supposed to take the place of personal responsibility, rather than avoiding losses of wild salmon, just the reverse has occurred.

Not only have we lost wild salmon, but we've lost tens of millions of wild salmon throughout the nineties here on the Skeena and the effects still linger on to this day like the very worst of a terrible hang-over. When the Dept asked fishers to accept the need for better gear and behavior, instead of agreeing, fishers turned their backs on the whole process and the Dept in turn turned their backs on the industry by shutting the fishery down completely, the last resort left to ensure protection for weak stocks. In future I would suggest there are new ideas, new formats of gear and far better attitude possibilities that would, **if** accepted by the Advisory Board people who to date have refused to accept anything new, that could lead to "losing" less fish, both target and non-target stocks/species while sustaining the viability of fishers and the fishery.

To this point in time the Dept has resorted to the "stick" method for addressing responsibility by punishing the whole "class" instead of just the offenders. Is the Dept unaware that a carrot idea could have far greater benefits and positive impact? Those who believe non-compliance is the best way to make easy money at the expense of the rest can sit at the back of the class with their dunce-caps on until they "get" it. The current fishery is one that is fatally flawed and pre-set to fail. The current fishery is based on a policy of either all fish or no one fishes, good behavior or not. What incentive is there to comply when there is no support for creating an environment or atmosphere of willingness to comply?

- What information would you need in order to understand such a decision?

Response: The Dept seems determined not to build an atmosphere of tolerance; they do not seem willing to embrace fisher responsibility, choosing rather to threaten closures instead of fostering an atmosphere of wanting to comply…why? I can understand the need to restrict the fishery if there are no other solutions to getting a particular stock or weak specie past the fishery, what I cannot understand and cannot support is the idea that all fishers are to blame for non-compliance with ways and means to mitigate or work around social and economic closures that should be unnecessary most of the time? While the Skeena sockeye run here for four months, we are down to fishing 7 days a year now, 7 -16 hour days a year. There is no threat to the Skeena sockeye which run upriver in August or Sept, but rather than engage responsible fishers by enabling them to access these stocks, no, the Dept would rather impose a gong-show derby fishery in the midst of the two weak stocks of sockeye, Coho and steelhead and disregard the values fishers in compliance could earn by not fishing in a frenzy of poor prices for a couple a days a year and expand their efforts out across the full spectrum of the entire season.

Strategy 5 - Annual Program Delivery

- How frequently should the performance of the Wild Salmon Policy be evaluated and who should conduct the review?

Response: Since the average cycle of wild salmon revolves around a four year term, then it should be at least appropriate to expect a Public review no more, no less than every four years. *Who should conduct it*? Wow, that you even ask the question could be the start of something new, something positive for a welcome and long overdue change. Is there any doubt that any review must be peer-reviewed by the Canadian Public? I remind you again, this resource is a Public resource, a Canadian heritage and social/economic future and the sooner the Dept comes to terms with that the better all around. To have any semblance of credibility any review process cannot have any persons who are involved directly or indirectly with the fishery (processing/buying), first and foremost. The problems we face today should have been mitigated years ago had we been allowed to have an honest and open to the public Advisory Board Process. That the industry has failed today is a direct reflection of this failure on the Dept's part to acknowledge that to this point in time, there has been no open access process and no public input period.

- How should the strategic and annual plans be communicated?

Response: Given, currently we are ruled by an autocratic Advisory Process, any information should be passed out directly to individuals, not through this Board. Allowing this Board to filter out what it does or doesn't like will only further exacerbate the problems. The media is a public communication format and this also should be used to communicate information that the Canadian Public can remain informed as to what is happening with both it's fishery and it's resources, unlike anything we have today where a closed door-tight-fisted reign of control is held exclusively for and by a very few self-centered people.

General

- What is a reasonable time frame for full implementation of this policy?

Response: Given it's so long over-due, as soon ***as the review has been completed***, to show sincerity, as immediately soon after that date as possible.

- Considering the wild salmon policy as a whole is there something that needs to be added to the policy or reassessed?

Response: There is nothing wrong with the concept, nothing wrong with the intent, the greatest threat to failure here is as I've stated above so many times now, the Dept, no one else, has the ability or power, must; I say again, *must* rethink what an Advisory Board means, what real democracy means and the intent of real democracy. The people who reside on the Board now have no say in the future, they've shown they are incapable of sharing the trust so vital to the future of this resource and fishery, in particular as it relates to matters of responsibility – personal responsibility and responsible fishing behavior or collaboration with all stakeholder parties.

Humans supposedly have the intelligence to know they should learn from past mistakes. The Dept learned nothing when it "changed" or restructured the Advisory Boards, nothing. They admitted there were problems with the old process and attempted to change it. When the East Coast cod fishery collapsed, would it be fair to suggest that quite possibly the wrong people, just like here now, were at the helm when their ship sank? That our salmon haven't completely collapsed as yet is little short of a miracle, nothing more, nothing less and certainly no help from the people on the Advisory Boards.

It's not a bad thing to admit sometimes mistakes get made is it? If a mistake is made and an attempt is made to correct it and that fails as well, then it's time to look at the why. If I had a hope, it would be that the Federal Government seriously considers sharing the responsibility of re-building the future of this resource and fishery with the Government of the Province of BC; after all, the people of BC have a stake in the values of this resource as well.

I don't know what was spent on trying to make the Skeena Watershed Process work, I don't know how many hundreds of millions of dollars have been lost since fishers, with the support of these Advisory Boards refused to accept the need for selective or responsible fishing was introduced, how many people, upriver and here on the coast who have suffered needlessly because of this, but this Board refuses to let the past go and work with/accept the need for change. It may be seen by the Dept as acceptable that we still have generally viable populations of wild salmon left, but that has come at massive hurt and suffering to those who have and would have accepted the need for change; what has been gained, can the massive losses and social/economic hurt ever be justified?

The wild salmon Policy must remain focused on the value and more today, the real potential that is so missing from today's net fishery. This precious resource has supported countless generations of people for countless thousands of years and that alone, if nothing else, qualifies this fishery as extremely important to the North Coast, its people, fishers, related and unrelated business/social infrastructure and communities. That one self-centered little group of people, hidden behind their "elected" exclusive doors of private control have the power to continue abusing so many countless people is beyond human belief and leaves any honest, any caring person, with a very bad taste for the Dept's idea of "democracy", a viable and sustainable fishery and collaboration in a very Public resource.

That we have a hope of a new beginning in this Wild Salmon Policy is a sign the Government is at least willing to have another look at the significance, both socially and economically this resource and the fisheries it supports *could* contribute to our society, given an honest chance and that is the best beginning of all; for this my wife and I wish to thank you.

Sincerely, Fred and Linda Hawkshaw,

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Unaccounted mortality in salmon fisheries: non-retention in gillnets and effects on estimates of spawners

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Summary

1. Effective and sustainable natural resource management is enhanced when the consequences of exploitative practices are fully understood and acknowledged. Commercial fisheries devote considerable resources to maximize the harvest of target species and minimize interference with non-target stocks. Appropriately, bycatch and discard of non-target stocks are recognized as critical economic and conservation concerns. Few studies, however, have examined non-retention mortality in target stocks. Non-retention, where fish are engaged by fishing gear but not landed, is rarely quantified and the effects on stocks are unknown. Mortality due to non-retention may have important effects on the dynamics of exploited populations.

2. We surveyed spawning populations of sockeye salmon *Oncorhynchus nerka* that had traversed commercial fisheries in Bristol Bay, Alaska, to estimate the incidence of non-retention in gillnets and the severity of injuries associated with entanglement. To better understand how gillnet injury affects spawning success, we tagged and monitored stream-spawning fish and applied a maximum likelihood model to mark–recapture data.

3. A substantial portion (11–29%) of spawning sockeye salmon exhibited clear signs of past entanglement with commercial gillnets. Survival among such fish was significantly reduced. More than half of the fish that reach natal spawning grounds with fishery-related injuries fail to reproduce. This suggests that estimates of spawning stocks are inflated by 5–15% at minimum.

4. *Synthesis and applications*. Our analyses indicate that non-retention in gillnet fisheries is an important and under-appreciated consequence of the exploitation of salmon. Stock estimates for exploited populations that do not account for non-retention mortality overestimate the number of reproductively viable fish. Unaccounted mortality and interannual variation in the magnitude of this mortality may prevent accurate estimates of viable spawners, confound our understanding of the relationship between stock size and recruitment, impede optimal management and obscure the ecosystem impacts of migratory stocks in coastal watersheds. Given the magnitude of non-retention in this fishery, explicit consideration of non-retention mortality may be warranted across a wide range of exploited populations.

Key-words: delayed mortality, ecosystem engineers, fishery-induced injury, mark–recapture analysis, natural resource management, Pacific salmon, population dynamics, stock-recruitment estimation

Introduction

Fishery-related injury in target stocks is rarely quantified but may be an important source of mortality in heavily exploited populations (Alverson 1997; Hall, Alverson & Metuzals 2000). Both immediate and delayed mortality caused by encounters with commercial gear is often high (Chopin & Arimoto 1995). While bycatch, discard and release of non-target species is often considered (Harrington, Myers & Rosenberg 2005), damage sustained by target stocks is often ignored. Certain gear types have low retention rates, enabling a portion of fish that encounter gear to disentangle or escape, often leading to delayed mortality. Such delayed mortality may have important consequences for fisheries management and the sustainability

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of exploited populations, especially where these stocks are managed for explicit targets and fishing effort relative to stock size is variable.

Many Pacific salmon gillnet fisheries are managed according to escapement targets. These are terminal fisheries, which harvest salmon on their return migration to freshwater and are regulated to ensure that sufficient numbers of adults evade the fishery and spawn. While most fish intercepted by the fishery are harvested, many disentangle from nets and continue their migration to natal spawning areas. Many of these fish sustain serious injuries. Although counted as part of the aggregate escapement of viable spawners, fish damaged in the fishery experience physical trauma, physiological stress, exhaustion and increased susceptibility to disease (Ricker 1976; Davis 2002). These fish may die prior to spawning or have reduced spawning success. Such losses have a direct bearing on estimates of spawning adults. If a significant portion of the enumerated escapement fails to spawn, escapement estimates will not accurately reflect the effective population of viable spawners. This will also confound analyses of the relationship between spawning stock size and future recruitment to the population. Where delayed mortality affects a constant percentage of escaped stocks, this loss may be implicit in the stock-recruit function. In most fisheries, however, fishing effort is variable between years, dependent on the size and timing of the salmon run. The failure to account for inter-annual variability in fishery-related injury to spawning stocks may generate significant errors in stock assessment.

Survival for fish entangled by gillnets is the lowest for all gear types (ASFEC 1995). With regard to commercial salmon fisheries, there are no current estimates of gillnet-related injury in exploited populations nor has there been extensive research to determine the consequence of these injuries on spawning success among escaped fish. Studies of mortality associated with non-retention in salmonids have largely focused on catch-and-release sport fisheries (Vincent-Lang, Alexandersdottir & McBride 1993; Booth *et al.* 1995) or commercial fisheries using troll and seine gear (Parker, Black & Larkin 1959; Thomas & Associates Ltd 1997). The few existing studies that address non-retention mortality in gillnet fisheries either examine the issue in an experimental context (Thompson, Hunter & Patten 1971; Thompson & Hunter 1973), document outdated harvest regimes such as high seas fisheries (French *et al.* 1970; Ricker 1976), evaluate selective fisheries practices where entangled fish are deliberately released and revived (Buchanan *et al.* 2002; Vander Haegen *et al.* 2004) or exclude severely damaged fish from analysis (Thompson & Burgner 1952; Hartt 1963).

The Bristol Bay sockeye salmon *Oncorhynchus nerka* fishery is managed to achieve constant annual escapement. Our study was designed to quantify the impact of gillnet injury on escaped stocks, given the current operation of the fishery. We estimated the incidence and severity of injuries in fish returning to natal streams and the effect of such injuries on pre-spawning mortality. The findings suggest that gillnet injuries are common and, in many cases, inhibit spawning. The effects of such unaccounted mortality may have important implications for the designation of optimal escapement targets in exploited populations, the estimation of spawner-recruit relationships, the understanding of evolutionary processes driven by fishery selection and the characterization of the ecosystem effects of spawning activity in coastal watersheds.

Materials and Methods

ESTIMATION OF THE INCIDENCE OF GILLNET INJURY

Analyses were conducted in the Wood River system in south-west Alaska (see Map Appendix S1, Supporting Information). The Wood River system is the primary watershed in the Nushagak district of the Bristol Bay fishery, supporting one of the world's largest stocks of commercially exploited sockeye salmon (Hilborn *et al.* 2003). Throughout the Wood River system, sockeye salmon gather within a 100 m range of their natal stream for a period of 1 month following migration through the fishery, entering spawning streams at maturation (Hendry, Berg & Quinn 1999). This behaviour allowed us to sample discrete populations immediately prior to their entry to spawning grounds. At Pick Creek, the site of our mark–recapture study, we used beach seines to sample 200–500 fish each year for three consecutive years (2005–2007) to determine the incidence and severity of gillnet injuries in the pre-spawning population of sockeye salmon that had successfully transited the fishery. In 2006 and 2007, we expanded sampling to include 10 populations throughout the Wood River system. All sampling occurred within a 2-week period (12–24 July). We sampled streams in accordance with historical peak spawning date (University of Washington, unpublished data), immediately prior to expected stream entry.

CLASSIFICATION OF GILLNET INJURY

All sockeye salmon were examined for fishery-related injury. Clear net marks, abrasions, contusions or scale loss spanning the circumference of the fish were considered evidence of gillnet entanglement. Gillnet marked fish were grouped according to the severity of the injury: (i) minor injuries included any evidence of gillnet entanglement, including net marks and/or scale loss; (ii) moderate injuries included open wounds and/or skin loss on 5–20% of the surface area of the fish; and (iii) severe injuries included large open wounds, fractured jaws or gill plates, and/or skin loss on > 20% of the surface area of the fish (Fig. 1).

STREAM RESIDENCE AS AN INDICATOR OF PRE-SPAWNING MORTALITY

Our analysis sought to determine whether gillnet injury resulting from non-retention in commercial fisheries prevents injured fish from spawning. We examined a stream-spawning population of salmon, using stream residence as a proxy for successful reproduction. Direct observation of spawning activity was not possible given the spatial extent of the survey. Egg retention estimates were compromised by scavenging gulls *Larus glaucescens*. Therefore, a mark–recapture study was conducted at Pick Creek (59°33′00″N, 159°04′18″W) to determine relative differences in survival and stream residence between fish with and without fishery-related injuries. A second-order stream, Pick Creek originates in a series of spring-fed ponds and flows 2 km before entering Lake Nerka. The stream averages 33 cm deep and 7·8 m wide (Hendry 1998) with high water clarity and relatively constant discharge (Hendry *et al.* 1999). Spawning occurs at high densities throughout the lower 2 km of the stream, with an average of

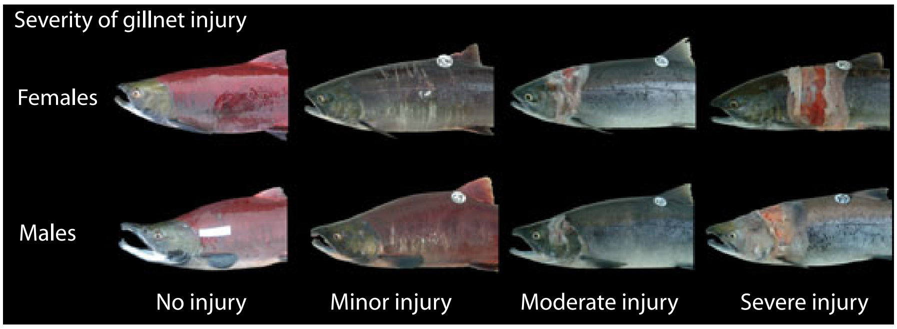

Fig. 1. Photographs of relative severity of gillnet injury. Note that coloration is dark (red) and scales are absorbed in fish without injury. Fish have less coloration (red → blush → silver) and retain scales as severity of injury increases. Morphological traits associated with sexual maturity in males (dorsal–ventral expansion and extended kype) are less pronounced among fish with injury. These trends suggest gillnet injury may retard or inhibit sexual maturation.

8000–10 000 adult spawners (Rogers & Schindler 2008) and a spawning season of *c.* 40 days. Due to the presumption that mortality of severely injured fish would increase as a function of distance travelled from the fishery, we sought to sample a population that represented the average distance from commercial fishery to natal stream for Bristol Bay stocks. Throughout Alaska, sockeye salmon stocks migrate a mean distance of 103 ± 70 km (n = 32) to an elevation 72 ± 104 m (n = 32). The average Bristol Bay sockeye migrates 94 km to 28 m (Burgner 1991). With a freshwater migration of 98 km to an elevation of 22 m (Hendry & Berg 1999), the Pick Creek population is representative of the post-fishery migration in Bristol Bay.

Pre-spawning mortality was assumed to occur where fish failed to demonstrate sufficient stream residence to allow spawning opportunities. Although sockeye salmon enter spawning areas at reproductive maturity, several days in-stream precede successful spawning at high density sites. The reproductive lifespan (stream entry to senescence) of Pick Creek fish is 17–20 days (Hendry *et al.* 1999). All sockeye salmon perish soon after spawning. Typically fish hold in tight schools during their first days of stream residence and disperse to colonize spawning habitat within a week of stream entry. Subsequent studies in Pick Creek indicate females secure territory and spawn towards the end of the first week of in-stream residence (mean days post-entry = 8·05 ± 5·56) and defend their redd site until senescence, typically maintaining a consistent presence for a week or more (mean days post-spawning = 6·93 ± 2·37; M. Baker, unpublished data). While movement does not preclude reproductive success in males, males establish dominance hierarchies on small spatial scales (Quinn, Adkison, & Ward 1996) and typically demonstrate strong site fidelity following a period of initial exploration (Foote 1990; Rich *et al.* 2006). Competitive advantage among males is driven by prior residence (Foote 1990) and, as males remain reproductively active until death, extended stream residence confers greater reproductive opportunities. Given these conditions, we determined any fish that failed to demonstrate a minimum stream residence of 3 days failed to spawn (sensitivity to this threshold value shown in Table 1).

MARK–RECAPTURE SAMPLING AND IN-STREAM OBSERVATION

From 15 to 17 July 2005, we sampled and tagged pre-spawning adult sockeye salmon at the mouth of Pick Creek. Fish were captured using a beach seine. A sample of 100 gillnet-marked fish was tagged, including 50 with minor injuries, 30 with moderate injuries and 20 with severe injuries (42 males and 58 females). This distribution of severity of injury reflects a representative sampling of the injured population of fish at Pick Creek (n = 1863). A sample of 100 uninjured fish (50 males and 50 females) was also tagged as a control group. Each fish was anaesthetized with tricaine methanesulphonate (MS-222; Western Chemical, Inc., Ferndale, WA), tagged with an external uniquely coded 3-cm Petersen disc tag (Floy Tag Co., Seattle, WA), rejuvenated in cold water and released (Fig. 2). This method of tagging corresponds to a well-established procedure that neither accelerates mortality nor has lasting effects on fish behaviour (Quinn & Foote 1994). Presence and severity of fishery-related injury and presence of fungal infection (*Saprolegnia* spp.) was assessed at this stage. Photographs of all injured fish were reviewed at the conclusion of sampling to re-evaluate classification and ensure standard ranking over time.

Visual stream surveys of Pick Creek were conducted every other day throughout the lifespan of all tagged fish (17 July to 25 August). Surveys recorded the presence, absence and mortality of tagged fish. For analysis, each 2 day period was considered a sampling event.

NONPARAMETRIC ESTIMATOR FOR STREAM RESIDENCE TIME

Survival between sampling occasions and stream residence for each category of gillnet injury were estimated through a nonparametric estimator using a maximum likelihood approach. This allowed us to separately estimate survival and account for failures to detect fish during stream surveys. A model developed by Lady & Skalski (1998) was adapted and used to estimate stream residence, following approaches developed by Cormack (1964) and elaborated by Burnham *et al.* (1987), whereby conditional survival probabilities are estimated from one sampling event to the next based on release–recapture data for marked individuals.

Maximum likelihood estimation (MLE) was used to derive survival and detection probabilities, using the following function:

$$L(S,P,\lambda|a,c) \propto \left(\prod_{i=1}^{K-2} S_i^{v_i}\right)\left(\prod_{i=2}^{K-1} P_i^{a_i}(1-P_i)^{V_{i-1}-a_i}\right)\left(\prod_{i=1}^{K-1} \chi_i^{c_i}\right)\lambda^{v_{K-1}}$$

where K is the number of sampling occasions; S_i is the probability that an individual alive at sampling occasion i will be alive at sampling occasion i + 1; P_i is the probability that an individual alive at sampling occasion i will be detected; λ is the product of final survival and detection probabilities ($S_{K-1}P_K$); a_i is the number of marked individuals detected at sampling occasion i; c_i is

Table 1. Estimated stream residence time and pre-spawning mortality according to severity of gillnet injury and presence of *Saprolegnia* spp. infection

	Tagged fish (*n*)	Pre-spawning mortality: Threshold for successful spawning (minimum: 3 days; range: 1–9 days)		Stream residence time (days): Maximum likelihood estimates		Individual mark–recapture histories	
				All fish	Fish observed in stream	All fish	Fish observed in stream
Gillnet injury							
Uninjured	100	6%	(2–25%)	10·78	11·01	14·4 ± 8·3	14·7 ± 8·1
Gillnet injured	100	51%	(42–71%)	4·54	7·82	6·1 ± 7·8	10·5 ± 7·6
Minor	50	16%	(8–44%)	8·14	8·85	10·9 ± 8·0	11·9 ± 7·6
Moderate	30	80%	(67–93%)	1·37	4·11	1·7 ± 3·7	5·2 ± 4·8
Severe	20	95%	(90–100%)	–	–	0·4 ± 1·4	0·4 ± 1·4
Fungal infection (*Saprolegnia* spp.)							
No infection	157	11%	(4–35%)	9·84	10·30	12·8 ± 8·4	13·4 ± 8·1
Fungal infection	43	93%	(86–95%)	0·53	3·83	0·7 ± 2·5	5·2 ± 5·1

Stream residence was calculated for each category of gillnet injury through maximum likelihood estimation methods as a function of survival probabilities between 2-day sampling periods. Stream residence was also estimated on the basis of individual mark–recapture histories (± SD). Pre-spawning mortality was assumed in fish that failed to demonstrate in-stream survival over a minimum of two sampling periods (3 days). Sensitivity to this threshold stream residence is shown as a range of estimated pre-spawning mortality given threshold values of 1–9 days.

Fig. 2. Fish with Petersen disc tag (photograph: Michael Webster).

the number of marked individuals detected for the last time at sampling occasion i; v_i is the number of marked individuals known to be alive at sampling occasion $i + 1$; χ_i is the probability that an individual alive at sampling occasion i will not be detected again ($\chi_i = c_i/a_i$). R is the number of individuals tagged at the initial sampling occasion.
where

$$v_i = R - \sum_{j=1}^{i} c_j$$

The maximum likelihood estimators for survival parameters (and their variances and covariances) are derived by Burnham *et al.* (1987) and reformulated by Lady & Skalski (1998):

$$\hat{S}_1 = \frac{a_2 v_2}{R(a_2 - c_2)}$$

$$\hat{S}_i = \frac{a_{i+1}(a_i - c_i)v_{i+1}}{a_i v_i (a_{i+1} - c_{i+1})} \quad \text{for} \quad i = 2, \ldots, K-2$$

Using these survival probabilities, Lady & Skalski (1998) developed the following estimator of stream residence time (T), operating on assumptions that: (i) the distribution of deaths between sampling periods is uniform and (ii) all individuals die prior to the final sampling occasion.

$$\hat{T} = \frac{1}{2}\sum_{i=1}^{K-2}\left\{(t_i + t_{i+1})(1 - \hat{S}_i)\prod_{j=1}^{i=1}\hat{S}_j\right\} + \frac{1}{2}(t_{K-1} + t_K)\prod_{j=1}^{K-2}\hat{S}_j$$

where t_i is the time of the ith sampling occasion relative to the initial sampling occasion, $t_1 = 0$.

Although technically developed to derive estimates of stream residence time, this model was applied to data on a beach spawning population (Quinn & Foote 1994), where fish were marked and recaptured at the same location. In our study, fish were tagged at the stream mouth and surveys were conducted within the main stem of the stream. We therefore modified the model to estimate separate probabilities for: (i) whether or not a fish entered the stream and (ii) its survival and detection within the stream.

In our analysis, the first period describes the probability of stream entry or the interval between when a fish was marked (tagged at the stream mouth) and its first recapture (first in-stream observation). This is defined as the joint probability of survival and stream entry.

The second period describes survival after stream entry, which we characterize as stream residence. Stream residence was estimated only for fish that were observed in the stream and initiated at the first in-stream observation. For integration with the model above, we arranged the data such that the first in-stream observation (stream entry) for a given individual is considered the first sampling occasion (release) for that individual, regardless of calendar date. All subsequent sampling occasions for that individual are relative to that first in-stream observation, in effect, modelling stream residence as a first-order approximation by entry date rather than calendar date. Calendar date of spawning had no influence on the senescence schedule of fish (Appendix S2).

Results

INCIDENCE AND SEVERITY OF GILLNET INJURY

Fishery-related injuries due to gillnet entanglement were evident in 11% of fish sampled at Pick Creek in 2005. Subsequent sampling in 2006 and 2007 recorded gillnet injury rates of 29% and 18% respectively. Fungal infection was strongly associated with the severity of gillnet injury. No infection was observed in uninjured fish in 2005. Nearly half (43%) of gillnet-injured fish were infected, with rates of 6%, 76% and 100% for fish with minor, moderate and severe injuries respectively. Similar patterns were noted in 2006 and 2007.

In multi-year sampling at 10 streams, the incidence of gillnet injury ranged between 4–37% (mean = 18 ± 13·1%) in 2006 and 7–29% (mean = 14 ± 6·5%) in 2007 (Fig. 3). Among injured fish, both sexes exhibited 68% minor injury, 23% moderate injury and 9% severe injury in 2006 and 80% minor injury, 18% moderate injury and 2% severe injury in 2007. Fungal infection was associated with severity of gillnet injury (2 × 3 contingency tables: 2006: $\chi^2_2 = 748{\cdot}20$, $P < 0{\cdot}001$; 2007: $\chi^2_2 = 91{\cdot}90$, $P < 0{\cdot}001$). Infection rates for fish with minor, moderate and severe injuries were 9%, 41% and 77% (2006) and 5%, 33% and 62% (2007) respectively. Although excluded from our mark–recapture analyses, 2% of sockeye salmon sampled across 10 streams in both 2006 and 2007 also exhibited damage from boat propellers.

STREAM ENTRY AND IN-STREAM OBSERVATIONS

Fish must enter and maintain residence in the stream to successfully spawn. We tested the independence of severity of injury and whether or not fish entered the stream and found significant differences between groups ($\chi^2_3 = 117{\cdot}79$, $P < 0{\cdot}001$). Virtually all (98%) uninjured fish and most (92%) fish with minor injuries entered the stream in contrast to 33% of fish with moderate injuries and 10% of fish with severe injuries. The presence of fungal infection was also a strong indicator of whether fish entered the stream ($\chi^2_1 = 130{\cdot}94$, $P < 0{\cdot}001$). Nearly all (96%) fish without fungal infection were observed in-stream in contrast to a minority (14%) with infection. Whether or not a fish was observed in-stream was independent of sex in the control group ($\chi^2_1 = 2{\cdot}04$, $P = 0{\cdot}153$).

Differences were also noted in the date of stream entry. Most control fish entered the stream 4 days after tagging. Fish with minor injuries held off the mouth more than twice as long. Both the mean ($t_{2,59} = 4{\cdot}21$, $P < 0{\cdot}001$) and variance ($F_{2,97,45} = 0{\cdot}327$, $P < 0{\cdot}001$) in stream entry date were distinguishable from control fish. There was no detectable difference ($t_{2,90} = 0{\cdot}60$, $P = 0{\cdot}549$) in mean stream entry date between control males (mean days to stream entry = 4·4 ± 4·8) and control females (3·8 ± 3·9). Similarly, no detectable difference was found ($t_{2,43} = 0{\cdot}22$, $P = 0{\cdot}829$) between males with minor injury (mean days to stream entry = 9·4 ± 7·8) and females with minor injury (9·0 ± 7·6). Few fish with moderate-to-severe injury entered the stream, which prevented accurate estimates.

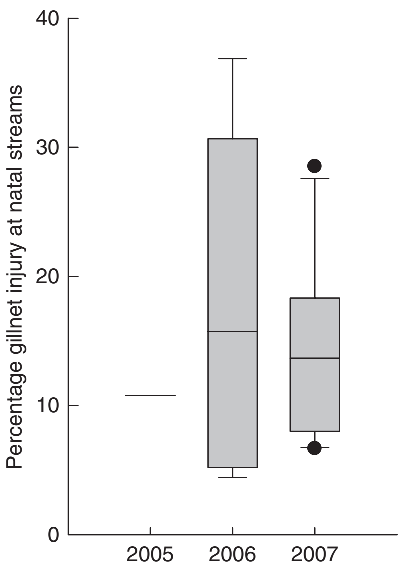

Fig. 3. Incidence of gillnet injury averaged across 10 streams in the Wood River system (2005–2007). Only one site was sampled in 2005 (Pick Creek).

SURVIVAL AND STREAM RESIDENCE TIME

Survival and detection probabilities

Using the maximum likelihood estimates of survival between sampling occasions, we calculated cumulative in-stream survival across sampling intervals as a function of entry date (Fig. 4). In-stream survival declined precipitously for fish with moderate to severe gillnet injury. Trends were even more pronounced for comparisons of fish with and without fungal infection. On any given sampling occasion, the probability of detecting a control fish known to have entered the stream was estimated at 0·718, taken as an average of MLE estimates over 20 sampling events. No differences were noted between males (0·700) and females (0·698). To enable estimation of detection probabilities independent of survival we also employed the Manly & Parr (1968) approach and recorded a detection probability of 0·702.

Stream residence by entry date

Maximum likelihood estimates of stream residence time ($\hat{T}$) were calculated as a function of survival probabilities between 2-day sampling periods. Gillnet injury had a direct bearing on stream residence time. We assumed fish that were never observed in the stream, never entered the stream. Among fish that entered the stream, uninjured fish had a mean stream residence of 11·01 (95% CI = 9·44–12·58) days in contrast to 8·85 (95% CI = 5·85–11·84) days for fish with minor injury and 4·11 (95% CI = 2·28–5·95) days for fish with moderate injury. Too few fish with severe injury entered the stream to estimate stream residence. Stream residence was also estimated as a

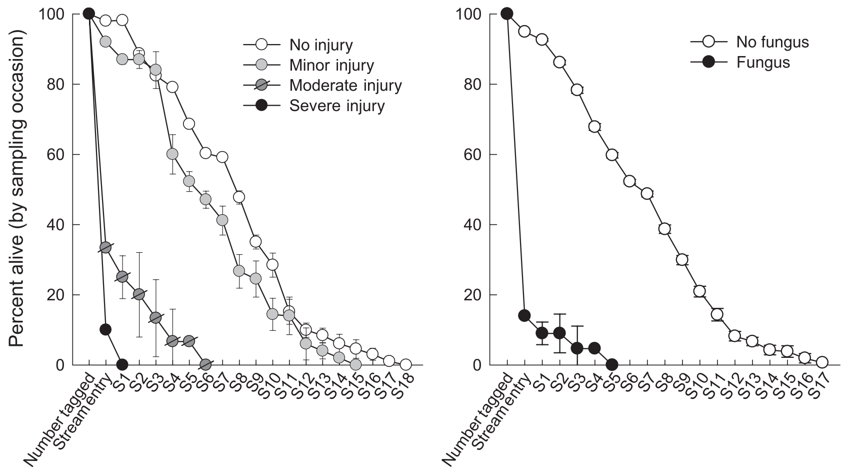

Fig. 4. Plots of in-stream survival according to severity of injury and presence of fungal infection. These estimates standardize by stream entry date, such that the plots illustrate total in-stream survival regardless of the timing of stream entry. The first interval reflects the number of fish tagged and released. The second interval is the percentage estimated to have entered the stream according to in-stream observations. Subsequent intervals (S1–S18) are calculated as the product of the number alive at the previous period and our MLE estimate for survival between the previous and the current period (95% confidence intervals are contained within error bars). Fish not observed in the stream were presumed dead.

function of all fish in each category (regardless of whether fish entered the stream) by integrating maximum likelihood estimates of stream residence for fish observed in the stream with estimates of zero for those never observed.

Longevity and stream residence by calendar date

Due to standardization by stream entry date, our maximum likelihood estimates do not provide estimates of survival for individual fish in real time nor allow us to characterize the number of fish in-stream at any given time. To analyse differences by calendar date, we estimated longevity for individual fish on the basis of the last observation for that individual. We estimated stream residence as the difference between the first and last in-stream observations. These methods confirmed the results achieved through maximum likelihood methods (Table 1).

Longevity (survival in days post-tagging) was greatly reduced ($t_{2,146} = 15{\cdot}03$, $P < 0{\cdot}001$) among moderately and severely injured fish relative to control fish. Interestingly, fish with minor injuries lived somewhat longer than the uninjured fish ($t_{2,78} = 1{\cdot}36$, $P = 0{\cdot}179$; Fig. 5a), but exhibited reduced stream residence ($t_{2,94} = 2{\cdot}02$, $P = 0{\cdot}046$), due to later stream entry (Fig. 5c). Pair-wise comparisons of stream residence between categories of gillnet injury confirmed significant differences between all groups ($P < 0{\cdot}050$) except between those with moderate and severe injuries (ANOVA, *post hoc* Tukey HSD: $P = 0{\cdot}912$). Distinct patterns in longevity were also noted as a function of fungal infection. Fish without fungal infections lived more than 15 times longer ($t_{2,173} = 16{\cdot}95$, $P < 0{\cdot}001$; Fig. 5b) and, among fish observed in-stream, spent more than twice as long in-stream ($t_{2,6} = 3{\cdot}80$, $P = 0{\cdot}005$; Fig. 5d). The longevity of control females (mean = $19{\cdot}6 \pm 7{\cdot}7$, $n = 50$) was significantly longer ($t_{2,94} = 2{\cdot}50$, $P = 0{\cdot}014$) than control males (mean = $15{\cdot}3 \pm 9{\cdot}2$, $n = 49$) and among those that entered the stream, females demonstrated longer stream residence ($t_{2,95} = 2{\cdot}65$, $P = 0{\cdot}009$). Overall, however, males and females displayed similar patterns of decline in stream residence as a function of severity of gillnet injury (Fig. 6).

PRE-SPAWNING MORTALITY

The average stream residence for Pick Creek fish not killed through predation is 10–25 days (Hendry *et al.* 1999). We adopted a conservative estimate of pre-spawning mortality, assuming fish that failed to demonstrate in-stream survival for a minimum of 3 days failed to spawn. Using maximum likelihood estimates, pre-spawning mortality was calculated as a function of fish known alive at the second sampling occasion (v_1). According to our model, stream entry is considered the release date for each individual. Subsequent in-stream observations are in reference to this standardized release. Thus the percentage known alive at the second sampling occasion (v_1), includes all fish that survive a minimum of two sampling intervals (3 days) from stream entry. Given this criteria, the majority (51%) of fish with gillnet injuries were predicted to fail to spawn in contrast to 6% of control fish. Nearly all fish (93%) with fungal infection at the time of tagging failed to spawn (Table 1).

To account for predation effects, we surveyed all carcasses to determine the cause of death. Brown bears *Ursus arctos* are a major source of in-stream predation and pre-spawning mortality on sockeye salmon in south-west Alaska (Shuman 1950; Gard 1971) and are known to preferentially select fish in better condition in environments that facilitate foraging (Gende, Quinn & Willson 2001). We noted higher predation on control fish. Among fish with known fates ($n = 76$), bear predation was observed for 31% of uninjured males ($n = 17$) in contrast to 17% of gillnet-injured males ($n = 7$) and in 11% of uninjured females ($n = 39$) in contrast to 8% of gillnet-injured females ($n = 13$). While a significant portion of pre-spawning

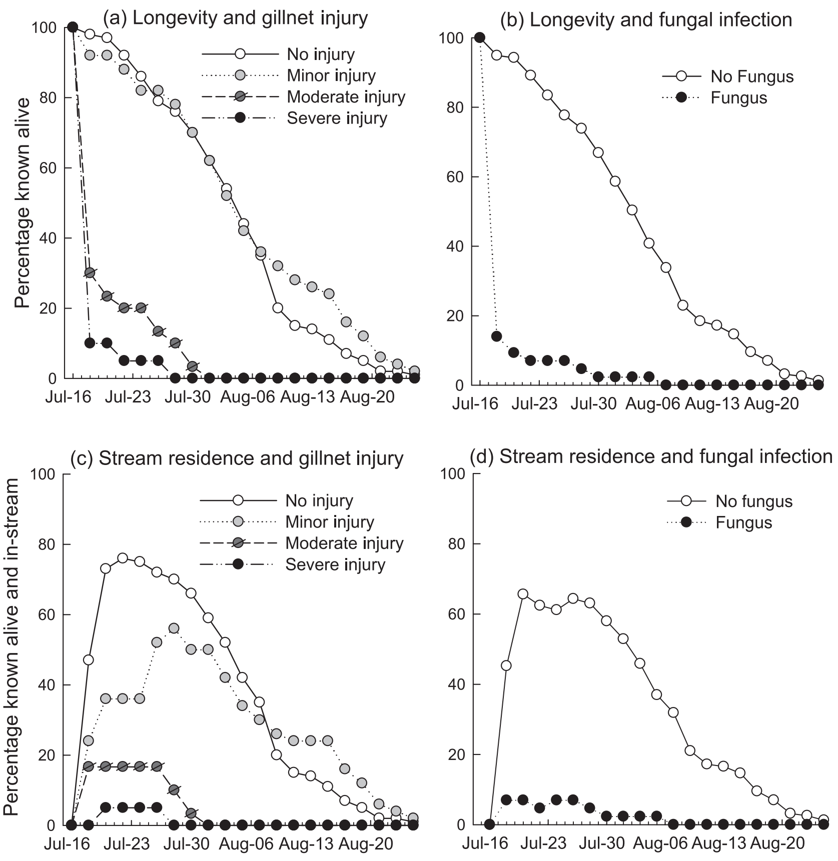

Fig. 5. (a–d) Longevity (post-tagging survival) and stream residence time according to severity of injury and presence of fungal infection. These estimates illustrate survival and stream residence by calendar date. Longevity estimates include fish known alive at any given sampling occasion. Stream residence estimates include fish known alive and known to have entered the stream.

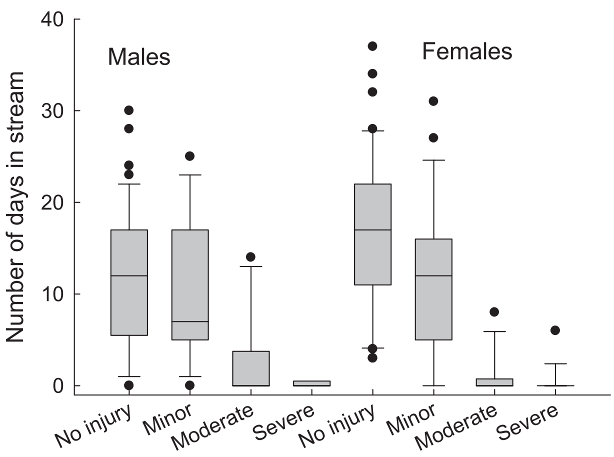

Fig. 6. Box plots of stream residence time according to sex and severity of gillnet injury.

mortality in our control group may be attributable to bear predation, it is unlikely that predation alone accounts for the high rates of pre-spawning mortality in fish injured through non-retention in gillnets.

MODEL PERFORMANCE AND ASSUMPTIONS

To analyse model performance, we utilized the release–recapture software SURPH 2·1 (Survival Under Proportional Hazards. 2002). To determine whether survival and detection are the same across treatment groups, we applied TEST 1 developed by Burnham *et al.* (1987) and confirmed that survival parameters differ between fish with and without evident gillnet injury (χ^2_{39} = 117·73, P = 0·000). To determine whether sex impacts survival or detection, we compared males and females within the control group and found no significant differences (χ^2_{39} = 34·23, P = 0·687). Because our analysis standardized survival estimates according to stream entry date, we tested whether detection probabilities hold constant across sampling occasions to ensure different conditions at different sampling occasions would not bias this approach. Specifically we analysed mark–recapture data by calendar date and compared the relative performance of: (i) a model assuming unique detection parameters for each sampling period and (ii) a model assuming a common detection parameter across sampling periods. On the basis of the Akaike Information Criterion (Akaike 1973), we found the model with common detection parameters provided the best fit to the data (Table 2).

Discussion

IMPLICATIONS FOR NON-RETENTION AND DELAYED MORTALITY IN EXPLOITED STOCKS

Our results suggest that disentanglement from gillnets is a regular occurrence in commercial fisheries in Bristol Bay, Alaska. As a consequence, fishery-related injuries are common in spawning stocks of sockeye salmon. Mark–recapture results

Table 2. SURPH model comparison for unique vs. common detection parameters applied across sampling occasions

Model	No. parameters	Ln likelihood	AIC
Unique detection parameters for each sampling occasion	39	−852·618	1783·24
Common detection parameters for every sampling occasion	21	−786·366	1614·73

This analysis confirms our assumption that in-stream detection remained constant throughout the sampling period. It suggests that standardizing individual capture histories by stream entry date (rather than calendar date) did not bias survival estimates. AIC, Akaike Information Criterion.

demonstrate that survival on the spawning grounds is markedly reduced among gillnet-injured fish and inversely correlated with the severity of injury. Conservative estimates suggest that more than half of the fish that reach natal spawning grounds after contracting injuries in the fishery fail to reproduce. The incidence and severity of gillnet injury also appear to vary between years, probably as a function of fishing intensity and run size. Due to constant escapement targets, larger runs will experience higher rates of exploitation. During smaller runs managers implement more closures, which inadvertently improves the relative condition of the escaped stocks. Differences in the size of returning fish may also influence retention, given a relatively constant range of mesh sizes used in the fishery. For these reasons, distinguishing between total escapement (all fish that migrate past escapement towers) and effective escapement (fish that survive the migration and spawn) should be considered.

There are also broader ecological implications to decreased spawning activity in coastal watersheds. Recent attention has focused on the consequences to habitat and community structure related to the overexploitation of ecosystem engineers by commercial fisheries (Coleman & Williams 2002). Habitat modification by spawning salmon alters community organization in stream ecosystems and strongly influences the downstream flux of nutrients and resource subsidies (Moore, Schindler & Scheuerell 2004). Non-retention mortality in spawning stocks will reduce these effects relative to expectations based on escapement counts.

POTENTIAL FOR UNDERESTIMATING INCIDENCE OF GILLNET INJURY

Our estimates of the incidence of gillnet injury are almost certainly lower than actual rates of non-retention in escaped stocks of spawning salmon. To assess fish from discrete populations and minimize the inclusion of strays or migrants, our sampling was conducted at natal streams immediately prior to stream entry, roughly 2 weeks after stocks had migrated through the fishery and were enumerated at escapement counting towers. During this period, many injured fish probably do not survive the challenges associated with migration, osmoregulation, sexual maturation and maintenance metabolism. Experimental studies of maturing sockeye salmon disentangled from gillnets found that 80% died within 1 week (Thompson *et al.* 1971; Thompson & Hunter 1973). Our estimates of the incidence of non-retention fail to account for fish that survive long enough to migrate past escapement towers but perish before our sampling occurs at natal streams. It is therefore reasonable to assume our estimate of 11–29% gillnet injury is conservative. Actual rates of injury in escaped stocks may be considerably higher (for further research, see Appendix S3).

PRE-SPAWNING MORTALITY AND PROXIMATE MECHANISMS

It is clear that virtually all fish with moderate to severe gillnet injury fail to spawn. In the case of fish with minor injuries, the delay in stream entry, abbreviated stream residence and the inhibition of morphological traits associated with sexual maturation (Fig. 1) suggest that even minor injuries retard maturation and reduce reproductive fitness. This delay in maturity may explain why fish with minor injuries live longer than uninjured fish despite reduced stream residence. Pre-spawning mortality was highly correlated with and was likely facilitated by fungal infection, caused by *Saprolegnia* spp., a facultative parasite common in freshwater ecosystems. *Saprolegnia* spp. causes tissue damage, loss of epithelial integrity and osmoregulatory failure (Bruno & Wood 1999). It is associated with damaged epidermal tissue (Hatai & Hoshiai 1994; Pickering 1994), suggesting fish with gillnet injuries are particularly susceptible to such infections. Fish with severe infections generally fail to recover (Pickering & Willoughby 1982). Of 43 fish with fungal infection at the time of our tagging, only one successfully spawned. Many injured fish without *Saprolegnia* spp. at tagging presumably developed infections subsequently. Due to the close correlation between fungal infection and pre-spawning mortality, *Saprolegnia* spp. is likely to be the proximate cause of pre-spawning mortality in gillnet injured fish.

BROADER APPLICATION OF NON-RETENTION MORTALITY AND SUSTAINABLE FISHERIES MANAGEMENT

Commercial gillnet fisheries harvest Pacific salmon on their return migration and are managed to ensure sufficient numbers of adults spawn and perpetuate discrete stocks. Complicating management, many salmon enumerated in escapement counts suffer injuries in the fishery and fail to spawn. Estimates of spawning potential based on such escapement counts fail to consider this loss. Our study indicates that gillnet injury affects a minimum of 11–29% of escaped fish. Roughly half of the injured fish fail to spawn. Even minor injuries may lead to adverse consequences, such as delayed maturation. The number of viable spawners in escapement counts may be overestimated by 5–15%, with repercussions for stock-recruitment analyses (Fig. 7). Currently, non-retention and delayed mortality are neither measured nor explicitly incorporated into stock assessment. The magnitude and inter-annual variation of non-retention in spawning stocks suggest that this source of

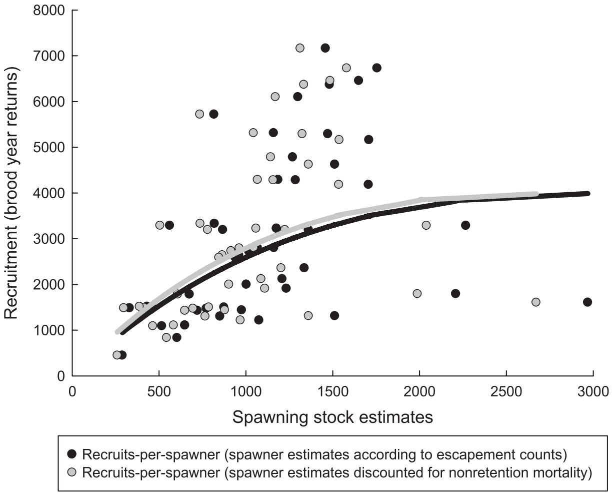

Fig. 7. Plots and Ricker (1954) model fit to spawner-recruit data in Wood River stocks (1956–2001). Failure to account for non-retention mortality in escaped stocks of salmonids will inflate estimates of viable spawners and underestimate recruits-per-spawner. We plot the stock recruitment relationship with spawning stock as enumerated at escapement towers (●) and discounted (−10%) for non-retention mortality (◎) Mean recruits per spawner are 2·81 (escapement estimates) in contrast to 3·21 (discounted estimates). While a constant discount rate illustrates a significant difference in estimated productivity, accounting for interannual variance in non-retention (as a function of fishing intensity and size of returning fish) would be more informative to management and may improve our understanding of the relationship between spawning stock size and recruitment.

mortality is not adequately considered under current management assumptions. This additional unaccounted source of fishing mortality has not prevented sustainability in the Bristol Bay fishery due to a precautionary approach to management. It does, however, suggest that the productivity of these stocks has been systematically underestimated and indicates a means to improve efficiency if retention can be increased or mortality due to non-retention reduced. Management agencies across a wide range of commercial fisheries should carefully consider the potential for non-retention mortality in target stocks and instances where such mortality can be estimated and/or minimized.

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Supporting Information

Additional supporting information may be found in the online version of this article.

Appendix S1. Map of the Nushagak fishing district and Wood River system, Bristol Bay, Alaska

Appendix S2. Influence of spawning date on the senescence schedule of salmon

Appendix S3. Our results in the context of past research

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LETTER FROM MINISTER OF FISHERIES AND OCEAN

LIVE-HARVEST PROCESSING

Minister of fill; * Ministre des
Fisheries and Oceans Peches et des Oceans

Ottawa, Canada K1AOE6

A$! 3 0 2003

Mr. Fred Hawkshaw
Ms. Linda Hawkshaw
421 6th Avenue East
Prince Rupert, British Columbia
V8J 1W6

Dear Mr. and Ms. Hawkshaw:

Thank you for your e-mail of March 11, 2003, expressing your interest in the live-harvest and the live-harvest processing of salmon in the North Coast Area of British Columbia.

Fisheries Management staff with Fisheries and Oceans Canada (DFO) in the Pacific Region advise me that, as a gillnet fisher specializing in selective sockeye salmon fishing, you promote a high-end salmon product that finds a ready market in direct sales to restaurants. I also understand that while industry mortality averages 65%, your selective methods result in a mortality rate of only 5%. I would like to congratulate you. I believe you have found a system and a direction that other selective fishers will surely follow.

You express concerns about matters of marketing and processing that are not part of my department's mandate. I suggest you contact the British Columbia Ministry of Agriculture, Food, and Fisheries for assistance in these matters. If you have further questions about selective fisheries, please do not hesitate to contact Mr. Jim Steward, a Resource Manager for North Coast Area, at (250)627-3421.

Thank for bringing these issues to my attention.

Yours truly,

Robert G. Thibault

LETTER WITH DFO

NON-RETENTION

Dear Mr. Hawkshaw:

Thank you for your correspondence of July 20, 2010, wherein you discuss chum in Area 3 and the Skeena sockeye return. I would like to take this opportunity to clarify our management response to poor chum returns and Skeena sockeye.

The chum returns in Area 3 have trended down during the past decade, and have caused us some concern. In 2004, chum non-retention was implemented in most seine fisheries in Area 3. For gill nets, a different approach seemed warranted, due to the high mortality of chum released from a gill net, which is calculated at 60%. So in 2005, instead of implementing non-retention for gill nets, we implemented a 0.5 nautical mile ribbon boundary around the Pearce Island shore, with no gill net fishing shoreward of this boundary, to protect chums migrating into inner Area 3 along this shoreline. By 2008, we had a ribbon boundary of 1.0 nautical mile around Wales Island, and 0.5 nautical miles around Pearce Island. Seines still had a non-retention provision. For gill nets, we requested them release all live chum to the water with the least possible harm. In this fashion, we were allowing gill net vessels to keep dead chum, while asking them to return live chums to the water.

By mid-2009, we realized that our strategy was not working well, and in the areas that gill net vessels were allowed to keep chums, at times they were targeting them, which was not our intent. So, we implemented non-retention in 3-12. By 2010, we expanded this to non-retention and non-possession of chum in 3-12 to start the season. Due to the large catch of chum in the remainder of the area, once again it was evident that gill net vessels were targeting chums where they were allowed to keep them, so we implemented a total closure of retention and possession of chums within the gill net fleet. It is hoped that this restriction will lead to the rebuilding of these valuable fish stocks in the coming years.

In regard to Skeena sockeye, the Pacific Salmon Treaty imposes restrictions on Alaskan catches of sockeye in District 104, commonly known as Noyes Island. Catches and fishery performance is reviewed every year post-season in the regular Pacific Salmon Commission process. During the fishing season, our staff are in close communication with Alaskan managers and get all needed catch and abundance information in a timely manner.

Thank you again for expressing your interest and concern regarding these important issues. I am confident that, working together, chum and sockeye stocks will be returned to their normally healthy status.

Sincerely,

David Einarson

Area Chief, Resource Management — *Chef de Secteur, Gestion des Pêches*
North Coast Area — *Secteur de la côte nord*
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From: Fred Hawkshaw [redacted]
Sent: July 20, 2010 9:55 AM
To: Einarson, David
Cc: Macgillivray, Paul; Rupert Howes - MSC; Phelan, Deborah; Karl English, M.Sc. -PSF; Don Kowal -PSC; XNCR, Min; Don Roberts; Cullen, Nathan - M.P.; Brian Riddell; Brad Ack; Art.Tautz@gov.bc.ca; Farlinger, Susan; Peacock, David

Subject: Where is the truth?
Importance: High

Mr. Dave Einarsen, Director North Coast;

Dear Sir;

It has come to my attention that all is not as it seems. For years now the Dep't has remained silent on seine kill on Nass chum (and any other non-target species), choosing instead to lay all the blame on the gill net fishery. Don't get me wrong, I have no like for the conventional gill type net either but that can be no justification for deliberately crippling our North Coast small-boat net fishery when there is no evidence to show the Area "A" seine fleet is not equally as guilty in killing weak stocks of Nass chum.

Here's what I do know: one seine caught 700 chum last week in Area 3. In the event more than 4 seines participated in the Area 3 fishery last week, anything more than the 4 vessels sharing our concerns for non-target species, we can safely assume we're talking about thousands of dead chum discarded just by seine alone. Could the numbers be into the tens of thousands for just one opening? How many did the gill net fishery up there kill by comparison? It matters not how many, that more than what isn't possible to control were knowingly killed is far too many for a certified sustainable fishery! That we have such simple solutions to correct this behavior that doesn't require punishing the wrong people as a bad management habit, leaves honest people aghast.

I was told this vessel along with 3 other seine vessels are most likely the only vessels honestly sharing my wife and I's concern regarding non-compliance and the totally unnecessary kill on non-target stocks of salmon and steelhead. What I don't know is how many seine vessels fished in Area 3 last week because I didn't ask- shock does that to one. It was explained to me in detail how these particular seines go about doing their utmost best to minimize the percentage of non-target fish encounters they harm or kill. Obviously they, like us, do so at great personal expense and loss with no compensation or acknowledgement from DFO Management. My wife and I, as your Dept is well aware, share these values and practice the best responsible fishing practices we can given we are locked into a derby fishery, the same as these responsible seine operators. I have known for years the issue with huge seine by-catch kill but it was always word of mouth from our caring guardians, people you would not likely take their concerns from seriously and people we don't feel justified in exposing to your office which could lead to their being punished for speaking out. Why did the Dept choose to punish only the gill net fishery last year knowing seine by-catch kill is no better and likely far worse by numbers than the gill net fishery? The crime is, DFO has chosen to use majority non-compliance in one single fishery only to punish the wrong people and do nothing to protect our wild salmon stocks and the fisheries that depend on their well-being- when will this open abuse cease? Your Dept gifted the Area "A" seine fleet with almost 100% of the Nass and Skeena pinks and all the coho last year based on nothing more than a concern the gill net fishery could not be trusted to live up to full compliance on non-target species. I take no issue with punishing the right people but I do take it very seriously and personally that your Dept would cause the actions of others, over many years, as justifiable reason to punish us. You wrote me once and told me you could not create a fishery for "Linda and Fred"- I still have that letter to remind me how foolish we've been to trust responsible fishing would be rewarded by the Prince Rupert Office. If not for responsible fishers, be they seine or gill net, who then can you create a fishery for if responsible fishing practices are key to generating a sustainable resource given your efforts thus far have failed everyone including our chum and sockeye, so completely and so miserably?

On one other note, is there some political mechanism being used to ensure only so many Skeena sockeye cross the A/B line? Does it not seem a bit out of the ordinary that we would experience a sudden burst of sockeye into the Skeena last week and then as suddenly barely enough to keep escapement up with the very tangible threat we may not fish again this year? Was it not in 2006 that so many sockeye were present for the gill net fishery that year in fact using our small mesh net my wife and I were overwhelmed with fish on a daily basis? The fish we caught last week in the Skeena appeared to be the same fish- mostly male and small, small enough we could pull many straight through the 4" mesh and most were caught by the body, what one would expect in the conventional mesh sizes of 30 years ago and fish of that mesh size 30 years ago, aka the manner in which the conventional gill net works. Had we been using a conventional gill net mesh size we would have caught barely half what we did. My point is, why has the Skeena failed to produce a vibrant return on this cycle year? If as your biology Dept claims it has nothing to do with size selective fishing practices, what else could it be if not sanctioned Alaskan seine intervention through area misreporting?

How much Skeena sockeye have the Alaskan seines taken already this year? Does DFO know? Does the PSC have any concrete idea? If not why not, given the devastating harm being done to our career and that of so many others who depend on the Skeena sockeye?

We would appreciate feedback on this letter please. I would like to share your response with others who share our growing concerns, in particular the MSC. If it seems unreasonable that I question how many Skeena sockeye have been taken by Alaskan seines this year, in another letter I will be explaining on what I base my concerns.

Sincerely, Fred and Linda Hawkshaw

LETTER WITH SUE FARLINGER

----- Original Message -----
From: Fred Hawkshaw
To: Susan.Farlinger, Director Pacific Region
Sent: Saturday, August 21, 2010 1:53 PM
Subject: Why, not how (we know how) did fishing responsibly become the wrong choice?

#1- Area 12 (Upper Johnston Strait)
Seines extended one additional day until Friday, August 20. Fishing times will remain open from 06:00 hours until 21:00 hours daily in ...

#2- Further to FN667, due to commercial seine fleet interference with test fishing assessments in the test fishing zone in Subarea 12-3, the daily Area B fishing time that will be permitted in Subarea 12-3 has been changed to 09:00 hours to 21:00 hours daily. -- When a seine test fishing vessel is arriving to a designated test fishing location to make a set and while making the set, vessels must provide priority access to
this seine test vessel. Fishing at this location can occur once the seine test vessel rings are up. For further details, refer to Appendix D of the Area B and Area H Fraser Sockeye ITQ Fishery 2010 Guidelines provided in the Area B license package. If there is poor compliance identified on the grounds additional closures will be implemented within the test fishing area.

Dear Sue;

As much as it troubles me to continually write you and little that seems on the positive side, faced as you are with a new job and all it came with, what can people who care do to stop the majority abuse without management support? "Request" management doesn't work, has never worked since the concept was first initiated with the seines on Chinook in the mid-1980's yet management continues trying to make a silk purse out of the proverbial sow's ear? As I understand it, DFO has implemented an IQ fishery for the seines in Area "B"? Forgive me if I have it wrong but isn't the claimed intent of IQ's to enable enforcement management the ability to apply correction to the individual? Of what use an individual share if the majority still hold the right to shut a fishery down? Enforcement explained it this way to me: throughout Society in general there is always a certain percentage that simply don't accept rules, they make their own. Generally speaking the majority abide by the rules unless there is no risk of punishment for cheating. In almost all situations there is a certain percentage that simply accept authority and the rules as they are. The breakdown is thus: non-compliant- 10-15%; majority- 70% +/-; and the compliant- 10-15%.

When "request" is used to manage issues within a fishery, it is expected there will be a 15% component that enforcement will have to deal with. The hope is the 70% will see no incentive to follow the 15% cheaters, motivated if you will presumably by the consequences of getting caught. (Some folks will always speed when driving. Others normally wouldn't take the risk. Try doing the speed limit on the freeway - you'll get run down before you get very far and that's what happens when enforcement isn't able to control the 15% who will speed regardless of the risk.) What we have in our net fisheries is a parallel to the speeding issue on the freeway; trying to do the speed limit and drive responsibly is very risky, no less than the "benefits" of fishing responsibly in a fishery completely out of control.

Theoretically enforcement should only have to deal with the 15%, which in theory should leave the majority in good shape to enjoy maximum benefit with minimal non-target kill risk to management. Here's reality: when enforcement has no tools with which to keep the 15% non-compliant in control, there is an immediate benefit gap that the majority will soon see as an open door for them to also reap the benefits of non-compliance. This leaves the 15% who largely abide by the rules without question, the sole source for punishment. DFO sees compliant fishing as the minority as being foolish.

No, neither Area licensing nor the derby or current IQ management is the answer. Had Policy been such that enforcement had the means to immediately jump on non-compliance before it spread, we would not be in this predicament today. Today there would be no need for allowing discarding to cover up a failure to clean up the fishery, individual accountability would do the job quite nicely, the proverbial carrot leading the majorities choices. The INTENT behind IQ's and Area Licensing had valid credibility but it appears those ideals have been run off the tracks. An Inquiry was set up to sort through the issues with the Fraser sockeye and fishery management. In the attached article from CBC we learn the panel chosen to bring out the issues has been disbanded. These were Canada's top scientists. If their credibility is no longer valid or acceptable, and we're no closer today than we were 25 years ago to enjoying the rewards of a responsible fishery, on what is the MSC basing their right to declare BC's sockeye fisheries and management sustainable?

DFO set up the Advisory system to provide the majority with the ability to make decisons that would benefit all equally, as equally as a derby fishery can deliver anyway. The problem is, in the case of our seine and gill net fisheries the majority have found it more beneficial to disregard the rules and it's the benefits derived from that have driven majority non-compliance from what began as minority non-compliance. Those who choose to abide by the rules are the only ones who are bearing the full brunt of punishment and the DFO ensures this through Area Licensing. No good business person would deliberately ruin his/her source of supply but in the salmon net fishery, the incentive is to destroy the resource before someone else might. The only way to get ahead in commercial fishing today is to kill more fish than everyone else, including any non-target species that might one day provide someone else with the ability to become successful so there's no chance anyone else can succeed which would make them a competitor- and do so for the cheapest values possible.

This is a Public resource and the fishery a Public access priviledge. In the drug trade it is important to get rid of your competitors and they do so by killing them off. In this fishery competition isn't killed off literally, just driven out of the fishery by badly managed greed. It's been made a fault, a sign of weakness to want to share equally with everyone through responsible fishing and gear. Why has DFO set up the salmon fishery to discourage responsible fishing to such a degree, fishing responsibly is a clear liability? Why did DFO not open the fishery (above) at the regularily scheduled time for those giving the test vessels their necessary time and open the fishery for those who were the problem at the later time? Fishers are not paid to be police. After all, the Area "B" seine fishery is a quota fishery so why should it matter that some who made bad choices may find themselves pinched for time as a direct result of their own actions? By punishing everyone all that will be achieved is to put everyone in a push for time which is going to have even greater negative consequences for non-target species? Why put compliant fishers in a difficult position, having to make choices they wouldn't otherwise do for no other reason than they are imprisoned to the punishment circle by DFO's unwillingness to open the door to encouraging compliant behavior as the reward for leading the way forward?

Sincerely, Fred and Linda Hawkshaw

EVOLUTIONARY CONSEQUENCES OF FISHING AND THEIR IMPLICATIONS FOR SALMON

Evolutionary Applications ISSN 1752-4571

SYNTHESIS

Evolutionary consequences of fishing and their implications for salmon

Jeffrey J. Hard,[1] Mart R. Gross,[2] Mikko Heino,[3,4,5] Ray Hilborn,[6] Robert G. Kope,[1] Richard Law[7] and John D. Reynolds[8]

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Keywords
adaptation, fitness, heritability, life history, reaction norm, selection, size-selective mortality, sustainable fisheries.

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Abstract

We review the evidence for fisheries-induced evolution in anadromous salmonids. Salmon are exposed to a variety of fishing gears and intensities as immature or maturing individuals. We evaluate the evidence that fishing is causing evolutionary changes to traits including body size, migration timing and age of maturation, and we discuss the implications for fisheries and conservation. Few studies have fully evaluated the ingredients of fisheries-induced evolution: selection intensity, genetic variability, correlation among traits under selection, and response to selection. Most studies are limited in their ability to separate genetic responses from phenotypic plasticity, and environmental change complicates interpretation. However, strong evidence for selection intensity and for genetic variability in salmon fitness traits indicates that fishing can cause detectable evolution within ten or fewer generations. Evolutionary issues are therefore meaningful considerations in salmon fishery management. Evolutionary biologists have rarely been involved in the development of salmon fishing policy, yet evolutionary biology is relevant to the long-term success of fisheries. Future management might consider fishing policy to (i) allow experimental testing of evolutionary responses to exploitation and (ii) improve the long-term sustainability of the fishery by mitigating unfavorable evolutionary responses to fishing. We provide suggestions for how this might be done.

Introduction

Anadromous salmonids (Table 1) migrate through freshwater and marine habitats, where they grow to maturity before homing to natal rivers for reproduction (Quinn 2005). Their high nutritional quality and relative ease of capture have subjected them to substantial human exploitation, through commercial, recreational and aboriginal fisheries. Demographic and stock-recruitment relationships for salmon are often used by fisheries managers to set exploitation levels with the objective of a maximum sustainable yield (Ricker 1958, 1969; Walters and Martell 2004). But rarely are the evolutionary responses of salmon considered in the setting of exploitation levels or in the methods and timing of capture. Even though no single study has yet conclusively demonstrated fisheries-induced evolutionary changes in exploited fish in the wild, theoretical and empirical evidence for fisheries-induced selection pressures is strong (e.g. Ricker 1981; Heino 1998; Law 2000; Carlson et al. 2007), and there is a growing body of evidence suggesting that evolutionary changes in fish life histories may already be widespread (e.g. Ricker

Table 1. Prominent life history traits of the primary salmonids considered in this paper for evidence of fisheries-induced evolution. Most anadromous forms that spend more than a single season at sea are vulnerable to extensive fishing.

Species (common names)	Scientific name	Migration	Reproduction	Age structure
Atlantic salmon	*Salmo salar*	Anadromous	Iteroparous	Variable (MSW)
Sea trout/brown trout	*Salmo trutta*	Anadromous/FW resident	Iteroparous	Variable (MSW)
Chinook salmon	*Oncorhynchus tshawytscha*	Anadromous	Semelparous	Variable (MSW)
Chum salmon	*Oncorhynchus keta*	Anadromous	Semelparous	Variable (MSW)
Coho salmon	*Oncorhynchus kisutch*	Anadromous	Semelparous	Simple (~16 months at sea)
Pink salmon	*Oncorhynchus gorbuscha*	Anadromous	Semelparous	Fixed (2 years)
Sockeye salmon	*Oncorhynchus nerka*	Anadromous/FW resident*	Semelparous	Variable (MSW)
Cutthroat trout	*Oncorhynchus clarki*	Anadromous/FW resident†	Iteroparous	Variable
Steelhead/rainbow trout	*Oncorhynchus mykiss*	Anadromous/FW resident	Iteroparous	Variable (MSW)
Brook charr	*Salvelinus fontinalis*	Anadromous/FW resident	Iteroparous	Variable
Lake whitefish	*Coregonus clupeaformis*	FW resident	Iteroparous	Variable
European grayling	*Thymallus thymallus*	FW resident	Iteroparous	Variable

FW, freshwater; MSW, multi-sea winter.
*Freshwater resident form = kokanee.
†All but the coastal subspecies exhibit the freshwater resident form only.

1981; Law 2000; Kuparinen and Merilä 2007; Edeline et al. 2007; International Council for the Exploration of the Sea (ICES) 2007; Swain et al. 2007). Moreover, evolutionary changes in fish life histories could affect viability and future yield in the fisheries, which is the opposite of that desired in management (Heino 1998; Law 2000; Conover and Munch 2002; de Roos et al., 2006).

Concerns about the potential evolutionary effects of salmon fishing are now a century old, but relatively few studies of these effects are available, and none of these investigations provides direct evidence for fisheries-induced evolution (Table 2). Stone (1880, 1882) and Rutter (1904) appear to have been the first to speculate in the literature that salmon fisheries might enhance the representation of smaller, younger male breeders and that removal of larger adults could lead to reductions in adult size as well as yield. Smith (1920) was concerned that removal of immature salmon in ocean fisheries would reduce future yields, presumably through earlier maturation, but Miller (1957) argued that the high plasticity of salmonid growth and maturation would render inert any selection imposed by fishing.

In the intervening century, such general concerns have persisted (Birkeland and Dayton 2005; Law 2007; Fenberg and Roy 2008; Hutchings and Fraser 2008), but salmon fishery management seldom incorporates evolutionary considerations in practice. In this review, we discuss what is known about the evolutionary consequences of fishing for salmon and address three central questions: First, what are the likely genetic consequences for salmon exposed to fishing, and what is the evidence? Second, do these consequences matter, when considered with other factors influencing viability? Finally, what is the lesson for management – how hazardous is it to ignore evolutionary considerations in salmon fishery management?

Fishing as an agent of change for salmonid life histories

Fishing practice

Salmon are extensively exploited by fisheries. For some populations, commercial and recreational fishing for anadromous salmon kills over 80–90% of individuals (Hankin and Healey 1986; Walters 1986; Heard 1991; Hilborn and Walters 1992; Pacific Salmon Commission (PSC) 2007). Historically, anadromous salmon were intercepted in high-seas fisheries as well as in coastal and riverine fisheries both in the Pacific and in the Atlantic. High-seas salmon fisheries in the Pacific have been prohibited since the 1990s and have been strongly restricted in the Atlantic; salmon are also by-catch in other fisheries. In high-seas fisheries, both immature and maturing individuals were killed, whereas terminal fisheries in estuaries and freshwater killed maturing individuals during their spawning migrations.

In recent decades, catches of Atlantic salmon have continued to decline, reaching their lowest levels in history. Productivity in nearly all populations is limited by high rates of marine mortality (International Council for the Exploration of the Sea (ICES) 2006). For Pacific salmon, catches have generally increased since the 1980s around the northern Pacific rim, with the exception of stocks in western Alaska (declining since the 1990s) and in southern British Columbia (declining since the 1980s) and farther south (declining since the 1930s). Increases in catch have been influenced by increasing hatchery production

Table 2. Summary of studies that have evaluated trends in size and life history of exploited salmonid populations potentially affected by fishing. Putative factors are the primary ones identified by the authors. Nearly all studies evaluated phenotypic trends or estimated norms of reaction, and therefore the primary causal factors for these patterns could not be ascertained. The table does not include modeling investigations of fishing-induced evolution specific to salmonids, such as Hard (2004); Hard (in press) for Chinook salmon or Thériault et al. (in press) for brook charr.

Species	Traits examined	Location (period)	Putative factors	Evidence for potential evolutionary response	References
Atlantic salmon	Body weight, run timing	Ireland (1926–1999)	F, E	↓ In weight, delay in run timing	Quinn et al. (2006)
	Body weight	Wales, UK (1907–1977)	F, E	↓ In weight, ↓ in MSW adults, ↑ incidence of grilse	Gee and Milner (1980)
	Body weight, age	Quebec, Canada (1859–1983)	F	↓ In weight, ↑ in age at maturation, ↓ in iteroparity	Bielak and Power (1986)
	Body weight, age	Maritime provinces, Canada (1954–1973)	F	Pop. variation in age & weight neg. correlated with fishing rate	Schaffer and Elson (1975)
	Body weight	North Sea – Norway and Scotland (1965–1993)	E	↓ In weight	Friedland et al. (2000)
	Age at maturation	Maritime provinces, Canada (1965–1972)	F	Changes in age at maturation, ↓ in MSW adults, ↑ incidence of grilse	Ritter and Newbould (1977); Paloheimo and Elson (1974); Ritter et al. (1986)
	Age at maturation	Scotland, UK (1872–1993)	E	Variable trends in incidence of grilse	Summers (1995)
	Body weight, age	Norway and NW Russia (1980–1994)	F	Variable trends in weight & size at age, ↓ in spawner age	Jensen et al. (1999)
	Allele frequency	Spain (1988–2000)	F	Generally stable frequency of common *MEP-2** allele	Consuegra et al. (2005)
	Body weight	Spain (1988–2000)	F	Trend toward ↓ spawner body weight	Consuegra et al. (2005)
	Age at maturation	Spain (1988–2000)	F	Trend toward ↓ sea age of spawners	Consuegra et al. (2005)
	Run timing	Spain (1945–2000)	F	Delays in median timing of capture	García de Leániz et al. (1992, 2001); Consuegra et al. (2005)
	Body length and weight	Spain (1945–2000)	F	↓ In weight & length of harvested fish	García de Leániz et al. (1992, 2001)
	Degree of iteroparity	Spain (1945–2000)	F	↓ Longevity, ↓ frequency of iteroparity	García de Leániz et al. (1992, 2001); Consuegra et al. (2005)
	Age at maturation	Spain (1945–2000)	F	↑ In smolt age, ↓ in sea age, ↑ frequency of grilse	García de Leániz et al. (1992, 2001)
	Age at maturation	Quebec, Canada (1967–1984)	F	↑ Frequency of mature male residents	Caswell et al. (1984); Montgomery et al. (1986)

Table 2. Continued

Species	Traits examined	Location (period)	Putative factors	Evidence for potential evolutionary response	References
Chinook salmon	Body weight	British Columbia, Canada (1951–1975)	F	↓ In mean weight (24 of 24 groups)	Ricker (1981)
	Body weight	British Columbia, Canada (1951–1991)	F, E	Variable trends in mean weight, with some ↓ showing reversals	Ricker (1995)
	Body weight	West coast N. America (1975–1993)	E	Variable trends in mean weight, with ↓ predominant	Bigler et al. (1996)
	Body length	West coast N. America (1979–1993)	E	↓ In mean weight	Bigler et al. (1996)
	Age at maturation	West coast N. America (1975–1993)	E	Variable trends in mean age, with ↓ predominant	Bigler et al. (1996)
	Spawn timing	Puget Sound, WA, USA (1960–2000)	H, E	Significant advances in spawn timing	Quinn et al. (2002)
	Body length and weight	British Columbia, Canada (1951–1981)	E	Predominantly negative trends in size, depending on period	Healey (1986)
	Body length	Yukon River, AK (1970–2004)	F or E	↓ Trends in relative abundance of large spawners (4 of 7 groups)	Hyer and Schleusner (2005)
Chum salmon	Body length	British Columbia, Canada (1951–1975)	F	↓ In mean weight (40 of 48 groups)	Ricker (1981)
	Body weight	British Columbia, Canada (1951–1991)	F, E	Weak, variable trends in mean weight (most groups)	Ricker (1995)
	Body weight	West coast N. America (1975–1993)	E	↓ In mean weight	Bigler et al. (1996)
	Body length	West coast N. America (1979–1993)	E	↓ In mean length	Bigler et al. (1996)
	Body length and weight	British Columbia, Canada (1951–1981)	E	Variable trends in size (mostly negative), depending on period	Healey (1986)
	Age at maturation	West coast N. America (1975–1993)	E	↑ In mean age	Bigler et al. (1996)
	Body length	Hokkaido, Japan (1992–1997) Kurile Islands, Russia	E, H	↓ In size at maturation & ↑ in age at maturation	Ishida et al. (1993, 1995); Kaeriyama and Katsuyama (2001); Eggers et al. (2005); Kaev (2000); Kaev and Romasenko (2003)
	Age at maturation, body length	Hokkaido, Japan (1962–1997)	E, H	↓ In size at maturation & ↑ in age at maturation	Morita et al. (2005); Morita and Fukuwaka (2006, 2007)
Coho salmon	Body weight	British Columbia, Canada (1951–1975)	F	↓ In mean weight in most areas	Ricker and Wickett (1980); Ricker (1981)
	Body weight	British Columbia, Canada (1951–1991)	E	↓ In mean weight (56 of 60 groups)	Ricker (1981)
	Body weight	British Columbia, Canada (1951–1991)	F, E	↓ In mean weight for most areas (except in north)	Ricker (1995)

Table 2. Continued

Species	Traits examined	Location (period)	Putative factors	Evidence for potential evolutionary response	References
	Body length and weight	British Columbia, Canada (1951–1981)	E	Variable trends in size (mostly negative), depending on period	Healey (1986)
	Body weight	West coast N. America (1975–1993)	E	↓ In mean weight	Bigler et al. (1996)
	Spawn timing	Puget Sound, WA, USA (1946–2000)	H, E	Significant advances in spawn timing	Quinn et al. (2002)
Pink salmon	Body weight	British Columbia, Canada (1951–1975)	F	↓ In mean weight (even- and odd-year lines; all groups)	Ricker (1981)
	Body weight	British Columbia, Canada (1951–1991)	F, E	↓ In mean weight of all groups (especially southern odd-year)	Ricker (1995)
	Body weight	British Columbia, Canada (1953–1988)	F	↓ In mean weight	Ricker et al. (1978), Ricker (1981)
	Body length and weight	British Columbia, Canada (1951–1981)	E	Variable trends in size (mostly negative), depending on period	Healey (1986)
	Body weight	West coast N. America (1975–1993)	E	↓ In mean weight	Bigler et al. (1996)
	Allele frequency	Kamchatka, Russia (1979–1981)	F	↑ In heterozygosity at *PGM* & proportion of early-maturing fish	Altukhov and Salmenkova (1991); Altukhov et al. (1991); Thorpe (2007)
Sockeye salmon	Body weight	West coast N. America (1975–1993)	E	↓ In mean weight	Bigler et al. (1996)
	Body weight	British Columbia, Canada (1951–1991)	E	↓ In mean weight (27 of 37 groups)	Ricker (1981)
	Body weight	British Columbia, Canada (1951–1991)	F, E	No sustained trend in mean weight	Ricker (1995)
	Body length	West coast N. America (1975–1993)	E	↓ In mean length (selected groups)	Bigler et al. (1996)
	Body length and weight	British Columbia, Canada (1951–1981)	E	Variable trends in size (mostly negative), depending on period	Healey (1986)
	Body length at age	Fraser River, BC, Canada (1952–1993)	E	↓ In body size correlated with sea surface temperature	Hinch et al. (1995); Cox and Hinch (1997)
	Body length at age	British Columbia, Canada; AK, USA (1967–1997)	E	↓ In body size correlated with ↑ abundance & SST	Pyper and Peterman (1999)
	Age at maturation	West coast N. America (1975–1993)	E	↑ In mean age (selected groups)	Bigler et al. (1996)
	Body girth	Bristol Bay, AK, USA (1994)	F	↓ In girth, scaling with harvest rate	Hamon et al. (2000)
	Run timing	Bristol Bay, AK, USA (1969–2003)	F	Advance in river entry timing for two fishing districts	Quinn et al. (2007)
	Allele frequency	Kamchatka, Russia (1930s–1980s)	F	↑ Proportion of heterozygous resident fish	Krogius (1979); Altukhov and Varnavskaya (1983); Altukhov and Salmenkova (1991)
	Age, growth rate	Kamchatka, Russia (1968)	F	↑ proportion of early-maturing resident fish	Nikulin (1970)
	Age, size, growth rate	Kamchatka, Russia (1935–1979)	F	↑ In proportion of early-maturing resident fish, ↓ in length	Krogius (1979); Varnavskaya and Varnavsky (1988); Altukhov (1994)
	Allele frequency	Kamchatka, Russia (1979–1981)	F	↑ In heterozygosity at *PGM* & proportion of early-maturing fish	Altukhov and Varnavskaya (1983); Thorpe (1993)
	Allele frequency	Kamchatka, Russia (1979–1981)	F	↑ In heterozygosity at *PGM, LDH, PX* & early-maturing males	Altukhov and Varnavskaya (1983)

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Table 2. Continued

Species	Traits examined	Location (period)	Putative factors	Evidence for potential evolutionary response	References
Brown trout	Body weight, age	Switzerland/France (1990s)	F	↑ Larger, older, Atlantic salmon and AB hybrids in catches	Mezzera and Largiadèr (2001)
Lake whitefish	Growth rate, age at maturation	Alberta, Canada (1941–1975); Lake Michigan (1932–1967); Germany (1947–1997)	F	↓ Growth rate, ↓ age at maturity	Handford et al. (1977); Taylor et al. (1992); Thomas and Eckmann (2007)
	Size at age, fecundity	NW Territories, Canada (1971–1978)	F	↑ Size at age and fecundity	Healey (1978, 1980)
Grayling	Age and size at maturation	Norway (1900s – most of 20th century)	F	↓ In weight, ↓ in age at maturation	Haugen and Vøllestad (2001)

E, environment (e.g. climate, ocean conditions); F, fishing selection; H, hatchery selection (e.g. domestication); MSW, multi sea winter; SST, sea surface temperature.

in many areas, and improving ocean conditions in the northern regions (Eggers et al. 2005). The recent declines in salmon numbers and concerns about loss of less productive populations have resulted in killing rates now more typically capped at 40–50%, although rates vary considerably among species and populations (Walters and Cahoon 1985; Walters and Martell 2004). Most Pacific salmon populations have experienced nearly a century of intensive fishing (Walters 1986; Walters and Martell 2004; Eggers et al. 2005; Hindar et al. 2007).

Salmon fisheries can be categorized by gear types such as hook and line (e.g. recreational fishing, commercial troll fishing), net (especially gillnet and purse seine), and trap technologies, and by the locations where gear intercepts fish on migration routes. These different gear types, and timing and location of use, exert different forms of selection. In general, hook and line salmon fisheries are size selective and timing is selective through regulation (Pacific Salmon Commission (PSC) 2004; Consuegra et al. 2005). Gillnet dimensions tend to be selective for body shape and migration timing (Todd and Larkin 1971; Hamley 1975; Millar and Fryer 1999; Hamon et al. 2000; Fujimori and Tokai 2001). Purse seines scoop up fish from aggregates and are thought to be less size selective (Pope et al. 1975; Ricker 1981) but could impose selection on migration timing and schooling behavior, particularly if the fishery employs specific time or area openings.

Traits under selection

Several salmonid traits are subject to direct or indirect effects of fishing. Two that have received considerable attention are body size and migration timing (Table 2). Fishing generally targets some aspect of body size, either through regulation or gear restriction. For example, gillnets target fish of particular girths but the degree of selectivity depends on population, sex, and state of maturation (Hamon et al. 2000; Fujimori and Tokai 2001; Quinn et al. 2001). Furthermore, size is correlated, genetically as well as phenotypically (Hard 2004), with other life history traits that influence salmon fitness. Even in the absence of direct selection on body size, changes in overall mortality level are driving selection on life history traits that involve trade-offs between performance in early and later life. This is most obvious for traits that relate to timing of major life history events such as smolting and maturation (Riddell 1986; Campbell et al. 2006; Thorpe 2007), but also applies to other traits such as growth and reproductive effort.

Although fishing mortality can account for only a fraction of total salmon mortality (Healey 1986; Riddell 1986; but see Heard 1991 for a counterexample), a sufficiently high fishing mortality can result in selection that has a substantial impact on fitness variation. It is sometimes argued that because most salmon die during the early stages of life, fishing mortality cannot have a decisive effect in shaping salmon life history. However, salmon approaching maturity are those that are most likely to pass their genes to future generations, and selective mortality among them is capable of generating substantial selection differentials as well as influencing population growth rate, particularly when fishing mortality is high. The decrease in population size through fishing mortality can indirectly select against sexually selected morphologies on the spawning grounds, including investment in male kypes and humps for fighting for access to females, and female body size for fighting for quality nest sites and for increasing survival through parental care (van den Berghe and Gross 1986, 1989; Fleming and Gross 1989). It can also bias the selective advantage of alternative life histories, for example favoring 'jack' or early maturing precocial males at the expense of later maturing 'hooknose' males (Gross 1996). Fishing with nets can directly target sexually selected characters when males with larger kypes have higher probabilities of entanglement (Hamley 1975).

In addition to selective effects within populations, differential selection on mixtures of populations with distinct characteristics can alter stock composition in fisheries. For example, spawning populations often differ in their migration timing through the fishery (Quinn et al. 2007), which might affect patterns of fisheries-induced selection on size, age, or morphology among populations.

Approaches to detecting fisheries-induced evolution

Regression analyses and reaction norms

Two approaches have been used to try to disentangle genetic effects of fishing from other factors influencing phenotypes, but with mixed success for salmonids: regression-based analyses (e.g. Ricker 1981, 1995; Rijnsdorp 1993; Morita et al. 2001) and analyses using probabilistic maturation reaction norms (Heino et al. 2002; reviewed in Dieckmann and Heino 2007; see Thériault et al. in press for an application of reaction norm methodology to migratory tendency). Both approaches have considerable appeal but their limitations arise from how they deal with genetic and environmental influences on phenotypic expression of growth, size, and maturation. Maturation reaction norms may offer a powerful tool for specific situations, although there is some debate as to how cleanly they separate genetic and environmental effects acting on maturation (see below). Regression analysis is a generic but often weaker approach. However, incorporating elements of quantitative genetics (see below) to regression-based analysis can improve its power (Swain et al. 2007).

Analyses of changes in maturation likelihood as influenced by size and age (e.g. Morita and Morita 2002; Morita and Fukuwaka 2006, 2007) have tried to separate the influence of phenotypic plasticity from those of environmental variation in size and age on maturation using probabilistic maturation reaction norms (PMRN). A PMRN describes probability of maturation as a function of age and size, and potentially other explanatory variables (Heino et al. 2002). The analysis of PMRNs can help to distinguish the influences of genetic components of variation from those of phenotypic plasticity on maturation, and thereby characterize the relationship between age, size and likelihood of maturation for different levels of exploitation (Dieckmann and Heino 2007). Indeed, the PMRN approach allows removal of the influences of demography and a major source of phenotypic plasticity from analyses of trends in maturation. However, as a purely phenotypic approach, it cannot be used to unambiguously demonstrate genetic change (Dieckmann and Heino 2007; Marshall and McAdam 2007; Wright 2007); the method can also be confounded by violations of assumptions about genetic control of maturation and growth that are difficult to test.

Quantitative genetic models of response to selection

A more direct approach to determining the direction and rate of evolutionary change under fishing is through quantitative genetic analysis of phenotypic evolution (Lande 1979; McGuigan 2006). Selection requires phenotypic variation and differential reproduction or survival. With sufficient knowledge of the population's relatedness structure, observed (i.e., phenotypic) patterns of mean trait values together with their variances and covariances can be used to estimate the genetic parameters that determine its responses to selection in a population. The framework for relating selection and its response in a particular trait relies on a simple empirical function that relates a population's short-term evolutionary response to the selection intensity and to the amount of genetic variation present. For a single trait, the 'breeders' equation' is given as

$$R = h^2 S$$

where R is the single-generation response to selection, h^2 is the trait heritability, and S is the selection differential (McGuigan 2006). R represents the change in the population's phenotypic mean for the trait from generation to generation, h^2 is the trait's heritability (i.e. the proportion of phenotypic variation that results from variation in expression of the trait's constituent genes), and S is the difference between the phenotypic mean before selection and that of potential breeders that survive selection within the same generation.

To fully characterize the evolutionary consequences of selection, a single-trait approach is insufficient because some traits are genetically linked and therefore can respond to selection even if not directly exposed to it. A multivariate, discrete-generation form of the breeders' equation takes these trait relationships into account (Lande 1979):

$$\Delta\mathbf{z} = \mathbf{G}\mathbf{P}^{-1}\mathbf{s}$$

where $\Delta\mathbf{z}$ is a vector of changes in the phenotypic means for all the traits under consideration, $\mathbf{G}$ is the genetic covariance matrix composed of the additive genetic covariances among the traits within an individual, $\mathbf{P}^{-1}$ is the inverse of the phenotypic covariance matrix, and $\mathbf{s}$ is the vector of selection differentials ($\mathbf{P}^{-1}\mathbf{s}$ is a vector describing the multivariate selection gradient β). Because this equation relates phenotypic changes to the selection applied through the genetic structure underlying those phenotypes, it (together with its age-structured analogs – see Law 1991a) provides a more complete characterization of short-term phenotypic response to selection imposed by fishing (Law 1991a; Policansky 1993a; Hard 2004; McGuigan 2006).

Fisheries-induced evolution in salmonids

The critical roles of growth and maturation

Most salmonids mature over a range of ages and sizes (Hendry and Stearns 2004; Quinn 2005; Table 1). Their propensity to mature depends on growth and physiological state at any of several potentially critical points in the life history, as dictated by their developmental programs. In anadromous salmon, reproductive investment appears to depend on energy availability; in coho salmon (*Oncorhynchus kisutch*), for example, ovary mass, egg size, and egg number are highly correlated with growth rate during the final spring and summer prior to ovulation (Campbell et al. 2006). A positive relationship between egg size and adult body size often varies with marine growth but not size at smoltification. Fish might be expected to grow at different rates when heavily fished, for behavioral, ecological or energetic reasons (such as a reduction in density resulting from fishing mortality, or an increase in relative predator abundance; e.g. Healey 1980; Trippel 1995; Salvanes and Baliño 1998), but changes in growth and maturation will also depend on their genetic architecture, as well as on how concurrent environmental changes affect the energetics of growth and the allocation of resources to reproductive effort. Thériault et al. (in press) show that migratory and reproductive patterns in anadromous brook charr (*Salvelinus fontinalis*) are likely to be influenced by mortality experienced at key points in the life cycle across the marine life-history transition. Fishing may therefore alter the size or age at which allocation of resources to gonads versus somatic tissues begins to shift. This, in turn, will affect the productivity of the population as well as the biomass available for harvest. Selection for faster growth might also affect rates of natural mortality by increasing foraging intensity and risk-taking behaviors (Lee 1912; Ricker 1969; Kristiansen and Svåsand 1998; Walker et al. 1998; Mangel and Stamps 2001).

The maturation process of anadromous salmonids is complex and protracted. Salmon initiate maturation well in advance of its phenotypic expression, apparently in response to physiological state or growth rate at a particular size or developmental stage (e.g. Thorpe 2007; Wright 2007). The consequences of selective fishing for growth and maturation may affect the onset of underlying developmental processes. Analysis of these effects using a PMRN typically invokes an assumption that maturation probability can be described by age and body size and therefore by average immature growth rate, but this assumes that the actual growth trajectory leading to a particular combination of age and size is unimportant. However, this is biologically implausible for most salmonids. In chum salmon (*Oncorhynchus keta* Walbaum), Morita and Fukuwaka (2006) found that probability of maturing was more closely linked to recent growth history than to body size (this example also shows how the PMRN approach can be extended with additional data). If the relationship between size and age is itself heritable, then the evolutionary consequences of fishing on size and age at maturation will depend on the shape of that relationship (Kuparinen and Merilä 2007). For example, if the reaction norm describing propensity to mature as a function of age (x) and size (y) is relatively flat (approaching size-constrained maturation, wherein fish tend to mature at the same size regardless of age), then fishing is expected to lead to faster growth and earlier maturation (Fig. 1A). By contrast, if this function is relatively steep (approaching age-constrained maturation, wherein fish mature at the same age irrespective of size, e.g. pink salmon, *O. gorbuscha*, and coho salmon, *O. kisutch*), then fishing could lead to slower growth and delay maturation (Fig. 1B). For age-structured salmonids, this relationship would be relatively flat, leading to a prediction that size-selective fishing will favor faster growth and younger adults. A more complex function (Perrin and Rubin 1990; Ernande et al. 2004) would have less predictable consequences.

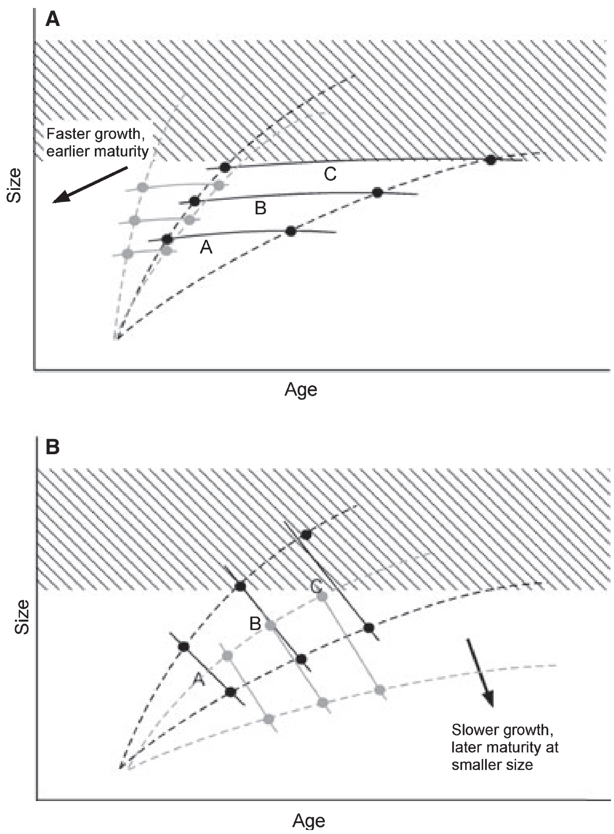

Figure 1 Hypothetical maturation reaction norms for size and age at maturation in salmonids under variable opportunities for growth. The dotted black curves depict hypothetical growth trajectories, from rapid (steep) to slow (shallow). In the strictest sense, reaction norms reflect phenotypic differences among distinct genotypes, although such functions are often used to evaluate patterns in other genetically differentiated groups. Here, A, B, C refer to distinct genotypes, families, or populations, with their maturation reaction norms indicated by the three solid curves in each pane. Solid black dots indicate the intersections of the growth trajectories and reaction norms for each group. (A) Maturation reaction norms corresponding to a primary influence of size on first maturation ('size-constrained maturation'). In this case the reaction norms are relatively flat, so that size selection imposed by fishing, indicated by the hatched area, is likely to increase growth rate and reduce size and age at first maturation in an exploited population. Possible responses in the reaction norms predicted by the arrow are given by the curves and dots in grey. This scenario appears consistent with the biology and phenotypic response of several species, such as Atlantic, Chinook, chum, and sockeye salmon, and steelhead and anadromous cutthroat trout (as well as some marine species such as cod and plaice). (B) Maturation reaction norms corresponding to a primary influence of age on first maturation ('age-constrained maturation'). In this case the reaction norms are more vertical, so that size selection imposed by fishing is likely to reduce growth rate, and perhaps increase age and reduce size at first maturation, in an exploited population. Possible responses in the reaction norms predicted by the arrow are given by the curves and dots in grey. This scenario is consistent with the biology of species with a constrained age structure, such as pink or coho salmon.

Ingredients of fisheries-induced evolution

Fishing as selection

The extent to which a population responds to fishery selection has some key prerequisites (Law 1991a; Hard 2004). First, fishing must be sufficiently strong to alter the distribution of phenotypes in the breeding population. Under constant fishing selectivity and genetic variability, higher fishing rates are more likely than lower rates to elicit an evolutionary response. If fishing selectivity is not sufficiently high to impose a detectable selection differential on size (or size at age), a short-term evolutionary response is less likely, although nonselective fishing mortality can still lead to evolution through changes in the maturation schedule (Policansky 1993a,b; Hard 2004). So too can accumulation of very small selection differentials that are repeated over the long time periods that fisheries can operate (tens or hundreds of years).

Fisheries that target maturing salmon concentrated near terminal areas are less likely to cause pronounced selection for age at maturation than those targeting immature fish migrating over ocean pathways, at least for semelparous populations or iteroparous populations with low rates of repeat spawning (Healey 1986). The primary reason for this is that fishing on semelparous individuals that have already made the physiological decision to mature will tend to have a reduced impact on age at maturation. Fisheries that target maturing fish expose all ages to the same mortality (subject to gear selectivity for size, etc.), while in fisheries that target immature fish, mortality is directly proportional to how long fish delay maturation once they become vulnerable to gear. Fisheries on immature individuals directly select for fish that mature earlier, or become vulnerable later, which might result in genetically based changes in reproductive output. Salmon fisheries in terminal areas, within rivers, or otherwise closely associated with aggregates of maturing fish are less apt to result in rapid evolutionary responses in age at maturation and correlated traits than those that are not (e.g. Kuparinen and Merilä 2007). Nevertheless, fishing on maturing individuals can alter other aspects of life history associated with size or age at maturation, including fecundity, egg size, redd size and depth, and nest defense (see van den Berghe and Gross 1989; Hamon et al. 2000; Hamon and Foote 2005).

Genetic variation in salmonid life history

Life history variation within and among populations of salmonids reflects both genetic and environmental sources of variation (Table 3; see also Carlson and Seamons in press). The genetic potential for key life history traits in salmon to respond to selection is high. However, few studies have examined specifically the genetic covariation

Table 3. Summary of heritability estimates for life history traits in anadromous salmonids likely to respond to fishing selection. With few exceptions, only studies involving narrow-sense estimates from correlation among relatives or response to selection in wild or hatchery-ranched, but not farmed, populations (i.e. considerable fraction of life cycle spent in wild and exposed to fishing mortality) are included. Data for only the species included in Table 2 are given here, and heritability estimates for disease resistance, juvenile behavior, and other traits are not included.

Species	Trait type	Description	Range of h^2	References
Atlantic salmon	Body size/morphology	Juvenile length	0.04–0.79	Bailey and Loudenslager (1986); Garant et al. (2003); Refstie and Steine (1978)
		Juvenile weight	0.10–0.89	Bailey and Loudenslager (1986); Jónasson et al. (1997)
		Immature length	0.57–0.73	Bailey and Loudenslager (1986)
		Immature weight	0.20–0.67	Bailey and Loudenslager (1986)
		Mature weight	0.20–0.36	Jónasson (1993); Jónasson and Gjedrem (1997); Jónasson et al. (1997)
	Survival	Marine survival	0.01–0.24	Jónasson et al. (1997)
Chinook salmon	Body size/morphology	Juvenile length	~0.0–1.0	Hard et al. (1999); Bryden and Heath (2000)
		Juvenile weight	0.99	Hard et al. (1999)
	Growth rate	Development rate	0.05–0.23	Kinnison et al. (1998)
	Age at maturation		0.30–0.57	Hankin et al. (1993); Hard (2004); Hard (1995)
	Survival	Marine survival	~0.0–0.12	Unwin et al. (2003)
	Migration or spawn timing	Maturation timing	0.23–1.0	Quinn et al. (2000); Hard (2004)
	Egg number		~0.0–0.76	Kinnison et al. (2001)
	Egg size		0.5–0.78	Kinnison et al. (2001)
Chum salmon	Body size/morphology	Juvenile length	0.13–0.86	Beacham (1990); Kanno (1990)
	Survival	Enbryo/alevin survival	~0.0	Beacham (1988)
Coho salmon	Body size/morphology	Juvenile length	~0.0–0.47	Murray et al. (1993)
		Juvenile weight	~0.0–0.62	Withler and Evelyn (1990); Murray et al. (1993)
		Immature length	0.32–0.69	Silverstein and Hershberger (1995)
		Immature weight	0.07–0.85	Silverstein and Hershberger (1995)
	Growth rate	Juvenile/immature	0.06–1.0	Sato (1980); Silverstein and Hershberger (1995); Vøllestad and Quinn (2003)
	Age at maturation	Male precocity	0.05–0.13	Silverstein and Hershberger (1992)
	Survival	Juvenile survival	~0.0–0.35	Beacham (1988); Murray et al. (1993)
Pink salmon	Body size/morphology	Mature length	~0.0–1.0	Smoker et al. (1994); Dickerson et al. (2005)
		Mature weight	~0.0–0.66	Smoker et al. (1994)
	Survival	Embryo survival	~0.0–0.21	Beacham (1988)
	Migration or spawn timing	Return timing	~0.0–1.0	Smoker et al. (1998); Dickerson et al. (2005)
		Spawn timing	0.06–0.54	Smoker et al. (1994)
	Egg number		~0.0	Funk et al. (2005)
	Egg size		0.22	Funk et al. (2005)
Sockeye salmon	Body size/morphology	Gill raker count	0.57	Foote et al. (1999)
Rainbow trout/steelhead	Body size/morphology	Immature length	0.11–0.58	McKay et al. (1986); Sylvén and Elvingson (1992); Thrower et al. (2004)
		Immature weight	0.13–0.65	McKay et al. (1986); Sylvén and Elvingson (1992); Thrower et al. (2004)
			0.12–0.73	McIntyre and Blanc (1973); McKay et al. (1986); Thrower et al. (2004)
	Growth rate	Proportion smolting	0.45–0.73	Thrower et al. (2004)
	Age at maturation	Early male maturation	0.02–1.0	Sylvén and Elvingson (1992); Thrower et al. (2004)

among salmonid life history traits, which can constrain or augment selection response; virtually all studies of fisheries selection to date have focused on single characters. More recent studies that have focused on the genetic architecture of salmonid life history include analyses of growth, size and maturation (e.g. Smoker et al. 1994; Quinn et al. 2000; Kinnison et al. 2001; Hard 2004; Thrower et al. 2004), juvenile body size and shape (Kanno 1990; Hard et al. 1999), and pathogen resistance (Withler and Evelyn 1990; Fjalestad et al. 1996; Guy et al. 2006; Hard et al. 2006). Genetic correlations are difficult to estimate with precision, especially without adequate breeding designs, and such estimates are not available for most exploited populations. Nevertheless, in general these analyses suggest that the indirect responses of traits to selection depend critically on their genetic and phenotypic covariances and that these will be difficult to predict solely from phenotypic information on the trait subject to direct selection (McGuigan 2006; Law 2007).

Few studies have provided estimates of selection differential imposed by fishing. Some of the best known estimates have been derived for body length in Atlantic cod, which varied from −1 to +2 cm for North Sea cod (Law and Rowell 1993) and from −4 to +4 cm for cod from Canadian catches (Sinclair et al. 2002). For Atlantic salmon, Hindar et al. (2007) provided estimates of selection differential on body weight for one-sea winter (1SW) grilse ranging from −0.08 to −0.52 kg, depending on the population and year. For Pacific salmon, Ricker (1981) estimated that the selection differential imposed by fishing on British Columbia coho salmon body weight between 1951 and 1975 varied from −0.50 to −0.73 kg. Hamon et al. (2000) estimated that the Bristol Bay (Alaska) gillnet fishery imposed selection differentials on body girth in sockeye salmon that ranged from −0.6 to −3.6 mm for females and −3.6 to +0.3 mm for males. Analyses by Washington Department of Fish and Wildlife (WDFW) biologists of coho salmon caught in gillnets in Washington state in recent years indicate that selection differentials on body length varied from −3.3 to +0.2 cm for females and −5.8 to +0.2 cm for males (C. Knudsen and C. Busack, WDFW, personal communication). Unfortunately, these estimates were not standardized, so direct comparisons are difficult, but from available information most selection differentials estimated for fishing appear to be in the range of ~0 to ±0.5 phenotypic standard deviations.

The combination of selection differentials with estimates of heritability for these traits indicates that responses in salmon size, growth, and maturation age to fishing-induced selection are likely to vary considerably among populations and over time. In most cases, these responses are expected to be modest over the short term (*ca*. 10 or fewer generations), although they could potentially be as large as −1 cm for length and −100 g for weight on an annual basis under stable environmental conditions. That said, the estimates of selection differentials tend to be similar to, but perhaps usually lower than, estimates of selection intensity imposed by natural and sexual selection in naturally reproducing salmon populations, which can sometimes exceed 0.5 standard deviations (van den Berghe and Gross 1989; Hamon and Foote 2005).

Only a few investigations have explored the consequences of such trait architecture under selection for viability. Hankin and Healey (1986) found that selective fisheries can decrease the mean age of Chinook salmon populations and increase the probability of significant population decline. The results of simulations of fisheries-induced evolution by Hard (2004) suggest that the selective exploitation of large Chinook salmon could lead to modest reductions in size-at-age within approximately five generations; further exploratory modeling (Hard et al., unpublished data) has shown that such responses can reduce abundance and catch and produce some maladaptive changes in life history that are likely to increase risk to population viability.

Evidence for fisheries-induced evolution in salmonids

The selectivity of fishing on many fitness traits in salmonids, coupled with the ample evidence of underlying genetic variation in these traits, indicates that rapid evolutionary responses to fishing are possible. Several studies over the past quarter century have explored the potential evolutionary effects of fishing on salmon (e.g. Ricker 1981, 1995; Hankin and Healey 1986; Healey 1986; Riddell 1986; Altukhov 1994; Hard 2004; Morita et al. 2005; Quinn et al. 2007). In a recent perspective, Jørgensen et al. (2007) identified 46 studies involving six traits in 18 fish species that implied fishing-induced evolution and estimated appreciable rates of evolutionary change. For salmon, these studies involved five species, and provided evidence for evolutionary rates from less than 20 to more than 30% over 24 years (on the order of 1% change annually). However, since the design of the study by Jørgensen et al. (2007) excluded research which did not suggest evolutionary change, the overall effects of fisheries-induced evolution are likely to be less than this.

Ricker's (1981, 1995) pioneering analysis of changes in mean weight of several Canadian species of Pacific salmon *Oncorhynchus* spp. (and in mean age for Chinook salmon, *O. tshawytscha*) caught between 1950 and 1993 raised concerns about future fishery yields. Ricker (1995) concluded that the effects of size-selective fishing were complex and difficult to disentangle from other factors affecting survival and growth in age-structured species, but that fisheries-induced genetic changes were likely, especially in pink and coho salmon (Ricker et al. 1978; Ricker and Wickett 1980). In a separate study, terminal fisheries with minimum size limits did not lead to changes in mean length in many populations of Pacific salmon in Canada, and observed changes were probably not genetic but due to environmental variation (Healey 1986; see also Riddell 1986). Summers (1995) and Friedland et al. (2000) observed changes in life history for Atlantic salmon consistent with temporal variation in marine environmental conditions. In an Asian fishery, chum salmon exhibited a decrease in the mean size at age of mature individuals, and an increase in the age at maturation, after the fishery switched from a high-seas gill-net fishery to a terminal set-net fishery (Morita et al. 2005).

Healey (1986) concluded that observed declines in the size of Pacific salmon previously attributed to selective fisheries probably also reflect changes in climate affecting marine growth and productivity of salmon, and he and Riddell (1986) identified several factors that tend to limit detection of an evolutionary response to fishing. First, the data may be inadequate or of low quality. The characteristics of many fisheries and of much of the associated catch data, such as those considered by Ricker (1981, 1995), do not lend themselves well to genetic analysis because of variable stock composition of the catch, because the data suitable for monitoring are limited, and because selection differentials are not easily quantified. Second, the environmental contribution to variation in size and age is likely to be large. Third, the genetic structure of size, age and correlated traits can constrain response to selection. Fourth, the consequences of tetraploid ancestry in salmonids for genetic variation and evolutionary dynamics are still not well understood. Fifth, response to selection can be complex for age-structured species due to variation in selection differentials for fish maturing at different ages, and specifically tailored life history models are required to adequately capture the evolutionary dynamics of salmonids (whether iteroparous or semelparous). Finally, countervailing selection in the wild (e.g. natural and sexual selection on spawners) might oppose fishing selection (Healey 1986; Riddell 1986; Carlson et al. 2007).

Hamon et al. (2000) found that selectivity in gillnet fisheries can impose strong selection on adult body morphology (girth). The magnitude and direction of this may vary as well (Miller and Kapuscinski 1994). In the Yukon River, Alaska, which historically produced appreciable numbers of large, old Chinook salmon, the numbers of very large (≥90 cm) fish have been declining in recent decades (Hyer and Schleusner 2005). Declines in body size can affect fertility (Healey and Heard 1984), mate choice and breeding behavior (Quinn and Foote 1994; Esteve 2005), and redd construction and defense and subsequent fry survivorship (van den Berghe and Gross 1989; Steen and Quinn 1999).

Some authors have also argued that fishing can affect migration timing (Quinn et al. 2007). For example, Quinn et al. (2002) demonstrated that run timing of both Chinook and coho salmon from three hatcheries in Washington has shifted in recent decades as a result of selection of brood stock which has responded to fishing patterns. For Atlantic salmon in Ireland, Quinn et al. (2006) documented a long-term delay in run timing, as well as a decline in weight, changes which they argued probably resulted from patterns of angling pressure on returning adults.

These studies point to the importance of considering selective fishing as a factor in altering salmon life history. Unfortunately, most inferences about fishing selection are based on an evaluation of selectivity or fishing mortality rate and therefore focus on only one aspect of adaptive evolution: the opportunity for directional change through an apparent measure of selection intensity. Because evolution involves change in gene frequencies, an evolutionary response requires genetic variability, and inferring evolution in response to fishing pressure in the absence of this information is far from straightforward.

What we need to know about fisheries-induced evolution

The changes in life history observed in many exploited fish populations are fueling controversy among biologists and conservationists over whether these fisheries and the populations that support them can persist (e.g. Birkeland and Dayton 2005; Kuparinen and Merilä 2007). Our review of this body of work in salmon, summarized in Table 2, suggests one reason: none of these studies provides direct evidence for evolutionary responses to fishing, or whether such responses reduce viability. Nevertheless, the collective evidence across a variety of species and environmental conditions highlights trends in size, age, and other traits – traits that have large influences on productivity and fitness – that are consistent with evolutionary responses to size-selective fishing (International Council for the Exploration of the Sea (ICES) 2007; Jørgensen et al. 2007). As Law (2007) noted, such responses may often be modest over the short term and difficult to detect without evaluating longer trends.

A concerted empirical attempt to dissect effects of fishing from those of other factors is clearly warranted. This would include careful experiments to discriminate these factors in a real-world – spatially or temporally structured but carefully monitored – evaluation of fishing effects on abundance, size, and life history of free-ranging salmon, such as the experiments suggested by McAllister and Peterman (1992) and McAllister et al. (1992). These authors emphasized the difficulty in evaluating fishing effects empirically but provided valuable guidance for how to structure the necessary experiments with adequate statistical power. Among their recommendations are to focus on species with simple life histories, such as pink salmon, and to employ adequate spatial replication; both of these recommendations can improve power considerably for relatively short-term (~5 generation) experiments.

Large-scale manipulative experiments and evaluation of management strategies in the context of conceivable responses in the fishery (see Walters 1994) are logistically and politically challenging to implement, and would be met with resistance from fishers without adequate compensation or a clear sense of a perceived longer-term benefit. Nevertheless, such approaches, when coupled with data on trends and knowledge of selectivity and genetics, would be more convincing to scientists and more compelling to managers. As suggested by Wright (2007), additional lines of inquiry that would likely prove profitable include comparisons of patterns of reproductive investment and allocation among populations varying in exploitation history, and contrasts of state-dependent thresholds for maturation among populations that differ in exploitation history.

Implications for fisheries management

Conceptually, the simplest way of reducing fisheries-induced selection pressures and consequences of excessive exploitation in general is to reduce overall fishing pressure. However, such overall reductions are hardly ever practical, and more specific measures are probably required. Considerable discussion in the literature has focused on the merits of minimum size limits, slot limits, and other fishing strategies as means to maintain current and preserve future yields. Some researchers have argued that minimum size limits tend to lead to 'recruitment overfishing,' whereas practices that increase catch of smaller, younger fish tend to lead to 'growth overfishing,' which is often thought to have less deleterious impacts on productivity and yield (Ricker 1976; Larkin 1978).

Other management options such as fisheries moratoria, time and area closures or catch limitations, and marine reserves also merit consideration to reduce long-term effects of fishing. Baskett et al. (2005) showed in a quantitative genetic model mimicking a cod life history that marine protected areas (MPAs) could help to reduce fisheries-induced selection for size at maturation in some long-lived species. MPAs may, however, have limited utility in mitigating for evolutionary change in highly migratory fish unless reserves are very large or are carefully networked. Protecting adults on spawning grounds could favor earlier maturation for some life histories, for example (Law 2007). In practice, the boundaries of MPAs that will be effective for anadromous salmon might not be difficult to identify but they will be difficult to implement and manage.

The socioeconomic factors that maintain exploitation are unlikely to ease until a clear biological threat is identified. Because resistance to reducing fishing rates will remain high in such circumstances, reducing fishing selectivity should become a tool for management, as reducing selectivity will preserve genetic and life history variability. Even so, as Policansky (1993b) pointed out, it must be recognized that a nonselective fishery will affect a population's evolutionary trajectory to the extent that it alters the mortality schedule. The key issue is where and how intense these pressure points are exerted by fishing on the mortality schedule relative to growth and maturation profiles.

Discussions that solely focus on productivity and yield often overlook the importance of standing genetic variation for size and associated life history traits to the resilience of an exploited population (Nelson and Soulé 1987). If exploited populations are to cope with the ecological and evolutionary pressures posed by fishing they must retain the adaptive capacity to respond. This capacity may be threatened by several of the characteristics of size-selective exploitation, especially selective removal of individuals with higher reproductive potential and elevation of the rate of stochastic genetic processes through reduction of genetic diversity (Smith et al. 1991; Harris et al. 2002).

The potential consequences of fisheries-induced evolution to viability of salmon remain poorly understood. Adaptation to fishing might reduce vulnerability of salmon to fisheries and thereby improve population viability compared to a hypothetical situation where evolution is not permitted. However, fishers may quickly adjust their capture strategies to changing fish characteristics, thereby engaging in a co-evolutionary 'arms race' and eradicating potential viability benefits (Heino 1998). Furthermore, when fish adapt to fishing they are likely to evolve away from configurations that natural and sexual selection alone would favor.

For example, a modest genetic influence on size at age ($h^2 \sim 0.3$) appears to permit adaptation of Chinook salmon to selection on size imposed by fishing (Hard et al., unpublished data); this adaptation is generally expressed as increased growth rate and earlier age at maturation, which tends to reduce fishery vulnerability under a fixed minimum capture size threshold. Such adaptation can take considerable time, however – several to many generations. During this period, evolution is likely to entail a period of reduced fitness, which Walsh et al. (2006) referred to as repayment of a Darwinian 'debt.' Thus, under some circumstances, an evolutionary response to fishing selection can negatively affect population viability. Fisheries-induced evolution might compound the demographic risk posed by overfishing, and this evolutionary trend may be difficult to reverse. Yield might decline, and vulnerability to other threats to viability during this period is likely to remain high (Hard et al., unpublished data).

The consequences of environmental variation for fish growth, size, and age at maturation might – at least in some years – overwhelm the impacts of fishing. Indeed, what cannot be determined yet is whether the selection imposed by fishing, the evolutionary response to it, and any attendant effects on viability will be sufficiently large to precipitate a fishery collapse. It is unfortunate that our knowledge of the long-term consequences of fishing in salmon has not changed appreciably since the commentaries of Larkin (1978) and the reviews by Nelson and Soulé (1987) and Policansky (1993a,b). Whether fishing selection on salmon is in most cases intense enough to pose a problem for long-term management and conservation remains unclear, but it behooves managers, in the spirit of the precautionary principle, to work with scientists to incorporate the possibility in management planning.

Given sufficient genetic variability and a stable fishing regime, salmon populations will evolve in ways that reduce fishing mortality (and yield), primarily by increasing growth rate (and, in species with complex age structure, potentially accelerating the maturation schedule). Short-term adaptation will probably not be enough to compensate for the loss of aggregate yield due to size-selective fishing. Two assumptions that are critical to recovery of exploited populations suffering from changes caused by fisheries-induced evolution are that genetic variability in size and age is not eroded by fishing selection, and that productivity is not depleted by fishing-induced changes in size and age of spawners. Quantitative genetic models indicate that aggressive reduction of fishing mortality to a fraction of initial values within several generations might be sufficient to permit an exploited salmon population to show recovery of abundance, but achieving pre-fishing maturation schedules and size distributions after adaptation to fishing mortality can take a very long time (Hard et al., unpublished data).

Salmon are unique among exploited fishes in the scale on which cultured individuals are released from hatcheries to the wild where they can be caught in fisheries or potentially spawn with naturally reproducing fish. Thus, for many stocks the hatchery and fishery regimes must be considered components of an integrated management system. To what degree selection in hatchery fish (i.e., domestication) and natural and sexual selection on spawning grounds might alter responses to fishing selection remains unclear. Understanding how hatchery and wild fish might differ in response to fishing and how domestication in hatcheries may degrade fitness of wild fish that interbreed with hatchery fish is critical to the development of sustainable hatchery production-fishing systems for salmon. For example, it is possible that fish spawned in hatcheries might have different short-term responses than fish spawning in the wild to fishing selection owing to the relaxation of natural and sexual selection on adult size in hatchery fish at time of spawning, but this issue remains unexplored (Hard 2004).

Conclusions

Do we know enough about the genetic effects of fishing on salmonids to justify reassessing current approaches to managing them? We believe so. Our survey of the literature indicates that the opportunity for fishing selection is amply demonstrated, even if it does not yet provide unambiguous evidence for rapid evolution. There are three critical uncertainties: whether trends in life history of exploited salmon are genetically based (Kuparinen and Merilä 2007), how quickly fisheries-induced evolution might occur, and whether such evolution is 'reversible' through management responses. Addressing these uncertainties is necessary to develop management regimes that are most effective in limiting evolutionary change caused by fishing. Meantime, a precautionary approach to fishery management that limits opportunity for adverse fishing selection is clearly warranted, and we recommend that this approach incorporate sufficient monitoring of key demographic parameters and life history traits such as run size and timing, escapement, size at age, and reproductive condition (Kuparinen and Merilä 2007). Fisheries management that promotes reduced gear selectivity with respect to size to allow sufficient larger, older individuals to breed, and focuses fishing activity on mature individuals in areas close to spawning grounds to reduce directional selection on maturation will provide some benefits to exploited populations. This is likely to be particularly important for species with restricted age structure, such as coho salmon, where variation in size of individuals vulnerable to size-selective fishing directly reflects variation in marine growth rate and high harvest rates could impose substantial negative selection differentials on growth and size at maturation.

Several researchers (e.g. Law 1991b, 2007; Heino 1998; Jørgensen et al. 2007; Kuparinen and Merilä 2007; Hutchings and Fraser 2008) are urging managers and scientists to coordinate in developing management schemes that directly account for fisheries-induced evolutionary change. The weight of evidence from the large number of studies summarized in Table 2 and the estimates of heritability in Table 3 indicate that we can be confident that evolution is being caused by fishing even if none of the individual studies is entirely conclusive. It is time to incorporate evolutionary principles into the management of salmon fisheries.

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