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FOR SOCKEYE SALMON *(Oncorhynchus nerka)*
REHABILITATION AND ENHANCEMENT

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BACKGROUND

In 1979 the Alaska Department of Fish and Game launched the statewide limnology program. The program was initiated under the Division of Fisheries Rehabilitation, Enhancement and Development (FRED), and is aimed at rehabilitation and enhancement of sockeye salmon, *Oncorhynchus nerka*, by manipulating nursery lakes through nutrient enrichment and fry stocking.

Early on it was decided that a systematic approach to field investigations and decision making regarding the benefits of these techniques to sockeye salmon populations would be required. For example, guidelines set forth the standards for the type and amount of data to be obtained from lakes prior to enhancement and, more importantly, include the types of information required to judge whether or not the sockeye salmon population has benefited. The latter encompasses what is known as project evaluation. Evaluation, directed either to lake enrichment or to fry outplants, is keyed to several benchmarks or trophic responses of the lake ecosystem. These include responses of the phytoplankton (primary production) and zooplankton (secondary production) communities, and responses of rearing juvenile sockeye salmon (tertiary production) to changes in the preceding trophic levels.

In conjunction with cooperators such as the U.S. Forest Service, regional aquaculture associations, and others, lakes that would serve as candidates for study were selected from around the state. Sockeye salmon lakes in Alaska were first categorized based on appearance of the water: clear, stained or tea-colored, and silty or milky because of intrusion of glacial meltwater (Koenings et al. 1986, 1987). Lakes finally chosen as study lakes included representatives from each of these categories.

FINDINGS

Lake Classification and Sockeye Salmon Production

Synthesis of research results obtained from Alaskan lakes formed the basis for the development of predictive models of the carrying capacity and production of sockeye salmon systems. By using performance data from a variety of lake types, we were able to classify lakes into categories which reflect the limitation to sockeye salmon production. Lakes limited by low numbers of juvenile recruits entering the rearing area were "recruitment-limited." Lakes limited by the quality and quantity of forage production in the rearing area were "rearing-limited." Each type of limitation was found to be linked to specific characteristics of the smolt populations (age, size, number) and to the rearing area (forage, temperature, light). In particular, the rearing-limited lakes were further classified into "forage-limited" and "environment-limited" systems (Koenings and Burkett 1987a).

Furthermore, we grouped lakes according to numbers of sockeye salmon fry per lake unit (population density) and lake fertility (capacity to produce suitable forage). Production in these two groups of lakes is described and subdivided as follows:

A. Recruitment-limited (low initial input and density of fry)

1. Escapement-limited (density independent)
2. Spawning-area-limited (density independent)

B. Rearing-limited (poor lacustrine conditions or fry-forage interaction)

1. Forage-limited

   a. poor quantity and quality of forage base (density dependent)
   b. poor spatial/temporal concurrence of fry and forage (density independent)

2. Environment-limited

   a. unfavorable temperature regime (density independent)
   b. short growing season (density independent)

The classification indicates that rearing limitation can be either forage- or environment-based, or both; that forage limitation can be density-dependent or -independent; and that density-independent growth can be either recruitment- or rearing-limited.

Sockeye Salmon Production and Enhancement Strategies

Use of a lake-classification scheme provides an approach for matching the appropriate enhancement strategy (e.g., lake plants of fry or lake enrichment) to the limiting feature of the lake. Our investigations have linked one physical feature of lakes (euphotic volume [EV]) to the base of the food chain and, in turn, to sockeye salmon production. Koenings and Burkett (1987a) developed a series of life-stage relationships which can be used to forecast baseline sockeye salmon production from lakes, and to determine numbers of spring-rearing juveniles necessary to meet smolt and adult production goals.

When developing the sockeye salmon production/capacity model, we measured the number and biomass of threshold-sized sockeye salmon smolts from several lakes throughout Alaska (and one Canadian system). The measured number and biomass of smolts was then related back to a habitat characteristic representing the magnitude of the carrying or rearing capacity of each nursery lake. The important concept was that only those lakes were included that produced smolt populations consisting of 60 mm-65 mm age-1 smolts, or a majority of age-2 smolts; i.e., the sockeye salmon juveniles grew only to minimal smolting size (or less) in one growing season (Koenings and Burkett 1987a). Threshold-sized smolts indicate, under density-dependent rearing regimes, that sufficient juveniles are being produced by the number of spawners to cause the amount of rearing capacity to limit numbers and biomass of smolts. It remained only to relate the number and biomass of smolts to some measure of the capacity of the lake's rearing habitat to be able to predict potential fish production from lakes where only the rearing habitat has been estimated. The estimator turned out to be EV, which is the volume (m^3) of water within a lake that photosynthesis (the basis of the aquatic food chain leading to fish) can occur. One million m^3 of lake water represents one EV unit and, basically, the mean number of threshold-sized smolts produced per unit of EV was 23,000. This number represents the long-term production on a sustained basis of an average lake; i.e., some lakes will be higher and others lower depending on characteristics unique to each lake.

Second, we investigated the relationship between the size of smolts and their survival at sea in order to estimate the number of threshold-size smolts required to produce one adult sockeye salmon returning to the lake. We found that on average it takes 8-9 smolts 60 mm-65 mm (1.8 g-2.2 g) in size to produce one adult sockeye salmon; i.e., a survival at sea of about 12%. Thus, if a lake produced 23,000 threshold-sized smolts per EV unit on a long-term-average basis, about 2,800 adults per EV unit (23,000 x .12) would result. Empirical studies that directly related the total number of adults produced by a series of lakes to the number of EV units suggested the production of between 2,400 and 2,500 adults per EV unit (Koenings and Burkett 1987a).

Third, we followed the survival of juvenile sockeye salmon outplanted to nursery lakes and found that on average 4-5 juvenile sockeye salmon outplanted in the spring produced one threshold-sized smolt. Thus, if a lake was to produce 23,000 threshold-sized smolts per EV unit, between 92,000 and 115,000 spring juveniles per unit of EV would be required, resulting in a freshwater survival of about 22%. Finally, by outplanting a lake with annually increasing numbers of juvenile sockeye salmon, we found that 110,000 juveniles per EV unit produce a threshold-sized smolt.

Since empirical evidence agreed with experimental results, we developed a stocking model (110,000 spring juveniles, 23,000 smolts, 2,500 adults) that uses the number of EV units unique to each lake to estimate numbers of fish. Thus, through validating empirical observations with experimental results, a series of standards or benchmarks emerge that are useful in estimating sockeye salmon smolt and adult production levels from stocking densities based on EV and the knowledge of density-dependent versus density-independent rearing. By modeling existing sockeye salmon production based on the above approach, we can now define (1) the enhancement approach most likely to result in a positive benefit, and (2) a realistic appraisal of expected adult production and the number of fry required, both of which are especially useful in planning and benefit/cost projections.

EVALUATION

Approaches to Lake Manipulation: Fry Outplants and Nutrient Enrichment

Since 1979 sockeye salmon rehabilitation and enhancement in Alaska has proceeded successfully along two fronts. The first is outplanting of sockeye salmon fingerlings (0.2 g-0.3 g) into type A or recruitment-limited lakes to take advantage of a preexisting excess in natural forage production. The second is enriching type B 1. or rearing-limited lakes with nutrients to increase forage production for a high preexisting level of juvenile recruits.

Briefly, results of fingerling outplants from three hatcheries located in southeast and southcentral Alaska are summarized in Table 1. All lakes have a continuous record of annual juvenile outplants and have been successful at consistently producing both smolts and harvestable adults through the hatchery program. Results of the nutrient

Table 1. Synopsis of sockeye salmon fry out-plants from three State of Alaska hatcheries and the mean annual production of smolts and adults for the number of years indicated in parentheses.

Hatchery	Out-plant lake[a]	Release years	Mean number of sockeye fingerlings released[b]	Hatchery: Mean number of smolts produced	Hatchery: Mean number of adults produced
Crooked Creek	Tustumena	80-87	12,800,000 (9)	2,490,000 (7)	409,000 (5)
	Leisure	80-84	1,420,000 (5)	277,000 (5)	95,400 (3)
	Chenik	78-81	450,000 (3)	--	46,000 (4)
Trail Lakes	Hidden	83-88	2,786,000 (5)	348,333 (4)	120,000 (3)
Beaver Falls	Bakewell/ Badger	85-86	373,150 (2)	96,890 (2)	--

[a] 839,000 fry released in 1986 not included.
[b] Mean release size was between 0.2-0.3 g.

enrichment of two lakes located in southcentral Alaska are shown in Table 2. The goal of nutrient enrichment is to produce larger and younger smolts so that the freshwater and marine survival advantages of larger size can result in greater adult returns. For equivalent numbers of spring fry planted in Leisure Lake, we have been successful at producing younger, larger, and more numerous smolts after enrichment. No adult returns are available to compare, as the first postfertilization smolts left the lake in 1986. In Packers Lake, the response to the nutrients is similar in terms of larger and younger smolts. However, Packers Lake serves as an example of the potential for error when having to use escapement numbers as an index to successful fry recruitment. Thus, perhaps the less numerous smolts observed in this one postfertilization year.

In review, we have found that the outplants of juvenile sockeye salmon, and the enrichment of sockeye salmon nursery lakes have been beneficial and have provided substantial numbers of adults to commercial fisheries. The most powerful tool may be the combination of both technologies on an intensive basis. However, the key to the success of either technology lies in its application to the proper environment and such recognition can only come from a proper preenhancement study.

<u>Frazer Lake: An Analog for Sockeye Salmon Production at Turner Lake</u>

In 1985 limnological studies were initiated on Turner Lake (southeast Alaska) to define the existing rearing capacity for sockeye salmon juveniles. In particular, they were designed to refine the productive capacity equations presented earlier. Turner Lake, presently a barriered system, is predicted to produce 5.2 million smolts and ~568,000 adults when numbers of rearing juveniles match the ability of the lake to produce forage (Table 3). This prediction was based on an extensive evaluation of the productive potential of sockeye salmon nursery lakes, located throughout Alaska, having euphotic zone depths ranging from 1 m to ~23 m. Again, using the euphotic zone depth as a guide to fertility, lakes were found to support stocking densities of $\leq$110,000 spring juveniles/EV (natural and hatchery production), 23,000 smolts/EV of minimal (1.8 g-2.2 g) size, and 2,400-2,500 adults/EV (Koenings and Burkett 1987a). Thus, instead of using a passive feature (surface area) to normalize sockeye salmon carrying

Table 2. Synopsis of changes in sockeye salmon smolt characteristics for Leisure and Packers Lakes resulting from nutrient enrichment.

Lake	Smolt year	Spring density (millions)	Smolts: Age 1 Length (mm)	Smolts: Age 1 Weight (g)	Smolts: Age 1 Age composition (%)	Smolts: Age 2 Length (mm)	Smolts: Age 2 Weight (g)	Smolts: Age 2 Age composition (%)	Total smolt production
Leisure:	Pre-fert. 1985	2.1	62	1.8	26	75	3.4	74	178,000
	Post-fert. 1986	2.1	84	4.8	60	110	11.5	40	376,000
		Parent year adults							
Packers:	Pre-fert. 1983	13,000	96	7.0	5	104	9.4	92	246,000
	Post-fert. 1986	18,400	120	16.0	63	140	26.0	33	167,000

Table 3. Physical characteristics, and measured sockeye smolt and adult production for Tustumena, McDonald, and Frazer Lakes compared to production levels predicted for Turner Lake [after the sockeye production model of Koenings and Burkett (1987a)].

Lake	Surface area (km^2)	EZD (m)	Euphotic volume ($m^3 \times 10^{+6}$)	Smolts production (millions)	Smolts per EV	Total return (number)	Adults per EV
Tustumena	295.0	1.2	354	8.10 (1981-86)	23,000	653,000 (1983-85)	1,850
McDonald	4.2	8	34	1.14 (1983-87)	33,529	112,500[a] (1980-85)	3,300
Frazer	16.6	15	249	--	--	617,370 (1985)	2,500
Turner	12.6	18	227	5.2 (predicted)	23,000 (model)	568,000 (predicted)	2,500 (model)

[a]Harvest rate estimated at ~20% from coded-wire tagging data.

capacity between lakes, a correction is made of inter-lake differences in productive capacity or fertility (Koenings et al. 1986; Lloyd et al. 1987). For example, Tustumena (Cook Inlet), McDonald (Southeast), and Frazer (Kodiak) Lakes are found to produce between ~1,900 and 3,300 adults per/EV. These lakes range in surface area between 4.2 km^2 and 295 km^2 with euphotic zones ranging between 1.2 m and 15 m. In contrast, surface area projections of adult production range between 2,200/km^2 Tustumena), 27,000/km^2 (McDonald), and 37,000/km^2 (Frazer). Thus instead of a <2-fold range (per EV) based on lake fertility, an ~17-fold range (per km^2) exists based on surface area. Similar comparisons can also be made for smolt production.

Of the lakes listed in Table 3, Frazer Lake comes closest to matching Turner Lake in terms of size, general morphometry, typology, and previous history. However, Turner Lake is considerably deeper than Frazer Lake, as the mean depth is nearly four times that of Frazer Lake (Table 4). Also, prior to 1951, Frazer Lake (Kodiak Island) was sockeye salmon-free due to an outlet barrier (40-foot falls). A series of two steeppass fish ladders provided access for adults produced from egg and fry plants that initiated the Frazer Lake sockeye salmon run (Blackett 1987).

Informative changes have occurred in the lake concurrent with the building of the run (Table 5). As potential spawners increased, the smolt sizes dropped, the number of macro-zooplankters decreased, and the zooplankton community (size and species composition) changed. The decrease in smolt size and zooplankton density was expected as a consequence of density-dependent juvenile rearing; however, the change in zooplankter species composition indicated a change in lake fertility. That is, prior to the introduction of adults, Frazer Lake was very oligotrophic with a zooplankton population dominated by copepods (cladoceran to copepod ratio of 0.06). During this period (1964-1969), nutrients contributed through carcass decomposition was low (117 kg), contributing only 7.1 mg P/m^2/yr to the lake, and adding only 0.21 mg P/m^3 to phosphorus levels of the lake. However, in recent years (1977-1986), escapements have supplied 2,062 kg P which added 124.2 mg P/m^2/yr to the lake and contributed 3.6 mg P/m^3 to the P concentration. Currently (1987-1988), from a loading of 220 mg P/m^2/yr to the lake from all sources, the lake contains 3,000 kg P and a spring P level of 5.5 mg P/m^3.

Table 4. Comparisons between physical features of Frazer and Turner Lakes.

Feature	Lake	
	Frazer	Turner
Mean depth (m)	33.2	122.9
Surface area (km^2)	16.6	12.6
Euphotic Volume (units)	249	227
Water residence time (yrs)	2.0	3.2
Water clarity	Clear	Clear
Outlet	Barriered	Barriered

Table 5. Changes in nutrient loading (phosphorus), zooplankton density and taxa ratio, and sockeye smolt sizes concommitant with increases in adult escapements at Frazer Lake, Alaska.

Historical period	Mean sockeye escapement	Zooplankton (No./m^3)[a]		Cladoceran to copepod ratio	Smolt sizes		Carcass-P		
		Macro	Total		(g)	(mm)	(kg)	(mg/m/yr)	(mg/m^3)
Early (1964-69)	14,684	10,620	14,110	0.06	29.5	148	117	7.1	0.21
Middle (1970-76)	66,887	3,590	6,996	0.17	18.8	127	539	32.5	0.96
Late (1977-86)	257,737	1,450	6,907	8.86	5.9	89	2,062	124.2	3.62

[a]Total zooplankton refers to cladocerans, copepods, and rotifers whereas macrozooplankton refers to only cladocerans and copepods.

Krokhin (1967, 1975) indicated the need for salmon carcasses to contribute 1.3 mg P/m^3 to lake P concentrations in order to stimulate fertility. Quite clearly this level was exceeded in Frazer Lake after the middle period (Table 5). Thus, during the more recent period, the lake was annually undergoing bioenrichment which increased lake fertility. As a result, the zooplankton community changed from essentially no cladocerans (ratio of 0.06:1) to complete dominance (ratio of 9:1), even though sockeye salmon juveniles prefer to feed on cladocerans and tend to avoid the more agile copepods. Thus, adult fish provide two elements to nursery lake systems: (1) potential recruits through successful spawning; and (2) carcass-derived nutrients which increase lake fertility and stimulate forage production for rearing juvenile sockeye salmon.

Forage production is a key element to successful sockeye salmon rearing in lakes. In addition, prey size must be greater than 0.30 mm, and forage should be available in the spring when fry enter the limnetic area (Koenings and Burkett 1987b). In Turner Lake, the zooplankton community is comprised of two types: the earlier-peaking copepod *Cyclops* and the latter-peaking cladocerans *Bosmina, Holopedium,* and *Daphnia.* All are of a body size capable of being consumed by juvenile sockeye salmon. While densities are not as great as that found for the fish carcass-enriched Frazer Lake, the higher range of densities found for Turner Lake do exceed the lower densities observed for Frazer Lake and exceed the seven-year range in densities found for Tustumena Lake (Table 6). In addition, the cladoceran-to-copepod ratio for Turner Lake (0.34:1) is greater than that found for the middle period at Frazer Lake (0.17:1) and is greater than that at Tustumena Lake (0:1), but lags behind that of Frazer Lake in 1985-1986 (51:1) (Table 6).

Overall forage production (quality and quantity) in Turner Lake exceeds that of Tustumena Lake and is below that of Frazer Lake in terms of cladoceran production. However, in terms of total macro-zooplankters, Frazer and Turner Lakes are fairly comparable. Moreover, given the comparability of Turner and Frazer Lakes, the ability of carcass nutrients to increase the fertility of the nursery area of Turner Lake, as occurred for Frazer Lake, is certainly feasible. Without such nutrient input, the lake's

Table 6. Summary of zooplankton population characteristics in Tustumena, Frazer, and Turner Lakes. Shown are the taxa composition (%), their ratio, and the range in spring and seasonal densities for the years listed.

Lake	Station	Cladocera (A)	Copepods (B)	Cladocera to copepod ratio		Range of density (No./m^2) Spring	Seasonal
Tustumean (1980-86)	B	0%	100%	0.0:1	A	0	0
					B	26,000-88,000	30,000- 62,000
Frazer (1985-86)	3	97%	3%	51.0:1	A	11,170-34,502	136,235-178,619
					B	529- 4,843	2,388- 5,308
Turner (1985-86)	2	26%	74%	0.34:1	A	10,422-11,335	27,654- 33,995
					B	62,830-97,513	77,882-106,470

natural fertility will have to drive forage production. As such, stocking densities will have to be closely evaluated to ascertain at what point forage production is unable to withstand annual increases in sockeye salmon predation. This point may occur at juvenile sockeye salmon densities below 110,000/EV unit. Indeed, Koenings and Burkett (1987a) suggest that for nursery lakes lacking adult access, a stocking density of 54,000-55,000/EV unit may be more appropriate. Nonetheless, from an initial escapement of 6 adults in 1956 (Kyle et al. 1988), the sockeye salmon run at Frazer Lake developed to average nearly 500,000 adults during 1980-1982 and exceeded 600,000 adults in 1985. Such levels of production are consistent with the EV of Frazer Lake (*See* Table 3), and the modeled production of 2,400-2,500 adults/EV unit. Similar levels of adult production/EV unit are expected from Turner Lake (*See* Table 5).

Finally, through estimates of EV units, juvenile sockeye salmon densities, expected smolt production, and estimated adult returns for 23 lakes in southeast Alaska can be modeled (Table 7). Hence, we have developed an extremely powerful tool for the resource manager: one that can be refined with proper evaluation to further sustain and enhance sockeye salmon stocks throughout Alaska.

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Table 7. Projected sockeye production levels in 23 Southeast Alaska lakes based upon euphotic volume (EV) units and assumed rearing-limitation (after Koenings and Burkett 1987a).

	Lake	Surface area (km^2)	Euphotic zone depth (m)	EV (units)	Total spring fry[a] (millions)	Total smolts[b] (millions)	Total adult return[c]
1	Speel	1.7	--	--	--	--	--
2	Indian	2.2	8	18	2.0	0.4	45,000
3	Crescent	3.3	9	30	3.3	0.7	75,000
4	Chilkoot	7.0	7	46	5.1	1.1	115,000
5	Lower Sweetheart	5.1	10	51	5.6	1.2	128,000
6	Redoubt	12.8	10	130	14.3	3.0	325,000
7	Chilkat	9.8	18	172	18.9	4.0	430,000
8	Turner	12.6	18	227	24.9	5.2	568,000
9	Heckman	1.6	6	10	1.1	0.2	25,000
10	Old Franks	2.5	5*	13	1.4	0.3	33,000
11	Neck	4.1	4	17	1.9	0.4	43,000
12	Patching	2.1	9	19	2.1	0.4	48,000
13	Hetta	2.1	12	25	2.8	0.6	62,500
14	Klawock	11.8	5	59	6.5	1.4	147,500
15	Woodpecker	0.7	10	7	0.8	0.3	18,000
16	Bakewell	2.9	5	15	1.7	0.3	37,500
17	Hugh Smith	3.2	6	20	2.2	0.5	50,000
18	Badger	2.1	10	21	2.3	0.5	52,500
19	McDonald	4.2	8	34	3.7	0.8	85,000
20	Reflection	3.0	15	45	5.0	1.0	113,000
21	Lake Grace	6.1	15 (est)	92	10.1	2.1	230,000
22	Ella	6.2	15 (est)	93	10.2	2.1	230,000
23	Manzanita	6.3	15 (est)	95	10.5	2.2	238,000

*Mean depth
[a] 110,000 fry/EV unit
[b] 23,000 smolt/EV unit
[c] 2,500 adult/EV unit

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