An Estimation of Historic and Current Levels of Salmon Production in the Northeast Pacific Ecosystem:

Evidence of a Nutrient Deficit in the Freshwater Systems of the Pacific Northwest

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Abstract

We used historical cannery records and current escapement and harvest records to estimate historical and current salmon escapement to western North American river systems, in order to determine the biomass and marine-derived nitrogen and phosphorous levels delivered by adult salmon, and the deficits corresponding to the diminished returns of adult salmon over the past century. We have estimated the historic biomass of salmon returning to the Pacific Northwest (Washington, Oregon, Idaho, and California) to be 160–226 million kg. The number of fish now returning to these rivers has a biomass of 11.8–13.7 million kg. These numbers indicate that just 6–7% of the marine-derived nitrogen and phosphorous once delivered to the rivers of the Pacific Northwest is currently reaching those streams. This nutrient deficit may be one indication of ecosystem failure that has contributed to the downward spiral of salmonid abundance and diversity in general, further diminishing the possibility of salmon population recovery to self-sustaining levels.

During the past 140 years, beaver trapping, logging, irrigation, grazing, pollution, commercial and sport fisheries, dams, and urban and industrial development have constrained the production of Pacific salmon (*Oncorhynchus spp.*) at every stage of their life cycle. The commercial harvest of salmon peaked between 1882 and 1915 in the major production areas south of the Fraser River (Table 1) (Cobb 1930) and since then, salmon abundance has declined continuously in the southern reaches of their range. Today, Pacific salmon have disappeared from approximately 40% of their historical range in Washington, Oregon, Idaho and California (NRC 1996; Nehlsen et al. 1991).

Throughout the past century of decline, salmon managers evaluated the results of their efforts primarily through quantitative indices of production. These performance measures include catch (sport and commercial), anglers days, economic value of the catch, licenses sold, pounds of fish released from hatcheries, and escapement (Lichatowich 1996). While these statistics are useful measures of performance, they are incomplete because they ignore the ecological processes that determine ecosystem health and ultimately the production of salmon. They focus primarily on economic ends while ignoring ecological means.

Several recent studies suggest that salmon escapement is significant beyond its obvious importance for the reproduction of the species (Wipfli et al. 1998; Bilby et al. 1998; Bilby et al. 1996; Larkin and Slaney

Table 1 shows the peak salmon cannery packs in major production areas south of the Fraser River.

Area	Peak Year	Cases	Kg of Salmon (Millions)
Sacramento River	1882	200,000	4.30
Columbia River	1895	634,696	13.70
Fraser River	1901	998-913	21.50
Willapa Harbor	1902	39,492	.81
Grays Harbor	1911	75,941	1.62
Coastal Oregon Rivers	1911	138,146	2.30
Klamath River	1912	18,000	.39
Puget Sound	1913	2,583,463	558.00
Coastal Washington Rivers	1915	31,735	0.67

(Source: Cobb 1930)

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1997). For example, decomposing salmon carcasses are now recognized as a source of marine-derived nutrients (MDN), which play an important role in the ecology of the Pacific Northwest. Reduced MDN transport to the watershed is another consequence of the past century of decline in salmon abundance. The MDN are delivered by adult salmon returning to fresh water to spawn in what historically was a mass transfer of biomass and nutrients from the ocean to fresh water. In individual river systems from Alaska to Washington, MDN link the abundance of salmon escaping to spawn to the ecological productivity of the stream system (Kline et al. 1990; Bilby et al. 1996; Larkin and Slaney 1997). For example, the growth and survival of young salmon depends, in part, on the marine-derived nitrogen, carbon and phosphorous delivered to nutrient-poor systems by adult salmon (Wipfli et al. 1998; Bilby et al. 1998; Bilby et al. 1996; Larkin and Slaney 1997). Until recently, the decline of Pacific salmon was primarily treated as an economic or aesthetic loss. Biologists now suspect that salmon depletion is also an enormous ecological loss. The purpose of this study was to estimate the historical and current salmon spawning escapements to streams ranging from Alaska to California. We then examined recent data for Washington, Oregon, Idaho and California to determine the regional nutrient deficit caused by the diminished returns of salmon during the past century.

Materials and Methods

Historical Run Sizes

We used two data sources for estimates of salmon abundance prior to the arrival of Euro-Americans (precontact): (1) historical cannery records for the Oregon coast, Washington coast, Puget Sound, British Columbia, and Alaska; and (2) previously published estimates of historical abundance for the California coast and Central Valley, Columbia River Basin, and Fraser River. We assumed that estimates of abundance derived from the early years of commercial fishing would approximate the size of the salmon runs prior to the arrival of Euro-Americans.

Cobb (1930) summarized cannery production for the main fishing areas from California to Alaska. The cannery pack is the longest continuous index of salmon abundance, dating back to 1866. Although the cannery pack is reported for several individual streams, salmon were routinely transferred among canneries and among river systems. Consequently, the cannery pack is not a reliable estimate of the catch for an individual river system, but it is a reasonable index of the historical abundance of salmon for larger regions.

To estimate the precontact abundance of salmon, we averaged the five largest cannery packs between 1866 and 1920 for each river system and for each species (Lichatowich 1989). We used the five largest packs from this period so we could estimate the maximum nutrient loss that has occurred. We used this range of data because, before 1920, salmon were harvested primarily from in-river fisheries. Offshore trolling and interception fisheries were not yet significant. This means the cannery pack largely measured the regional production of salmon and did not include fish from distant regions harvested in interception fisheries. Parts of the individual salmon carcasses such as the head, fins and organs were not canned. To account for this discarded weight, each case of 48 one-pound cans of salmon was converted to 68 pounds (149.6 kg) of total salmon biomass (Craig and Hacker 1940; Mullen 1981).

Often during the peak of a salmon run, more fish were caught than could be accepted by canneries. The usual practice was to dump the dead salmon back into the river. Since these fish were not processed, they were not included in the cannery records. Ricker (1987) estimated that waste of this type amounted to as much as 50% of the harvest of Fraser River sockeye salmon. We assumed the waste of unused fish was 25% of the cannery pack. The total biomass of salmon caught (weight of salmon canned, discarded and wasted) was divided by the average weight of each species to estimate the number of fish harvested (Table 5). Total run sizes (catch plus escapement) were calculated by dividing catch by estimated harvest rate. Harvest rates for all areas were assumed to be 35%–75% of the total run. The low end of this range was derived from studies of the harvest rates of coastal Oregon gillnet fisheries in the 1950s (Table 2). We used the upper end of the harvest rates in Table 3, because by the 1950s harvest restrictions were beginning to reduce the catch in some rivers. For the high end of the abundance range we assumed a harvest rate of 75% which is generally consistent with Chapman's (1986) use of probable optimum exploitation rates to estimate peak runs of Pacific salmon in the Columbia River basin. Those were 68% for spring and summer chinook salmon (*O. tshawytscha*),

Table 2 gives the estimated exploitation rates for coho and for chinook salmon by commercial fisheries in Oregon coastal rivers.

Species, River	Year	Estimated exploitation rate (%)	Source
Coho Salmon			
Alsea	1951	15	Morgan and Cleaver (1954)
Tillamook Bay	1951	32	Willis (1954)
Nehalem	1952	29	Henry (1955)
Tillamook Bay	1953	29	Henry (1964)
Siletz	1954	12	Morgan (1964)
Chinook Salmon			
Tillamook Bay	1953	36	Henry (1964)
Siletz	1954	36	Morgan (1964)

(Source: Lichatowich 1989)

88% for fall chinook salmon, 77% for coho salmon (*O. kisutch*), 73% for sockeye salmon (*O. nerka*), and 48% for chum salmon (*O. keta*). Our use of the range of harvest rates from 35% to 75% probably encompasses the actual harvest rates during the early years of the commercial fishery.

Previous Estimates of Historical Abundance

We used published estimates of predevelopment abundance of Pacific salmon for the Columbia River, California's Central Valley, the Klamath/Trinity River system and California's coastal streams. The Northwest Power Planning Council (NPPC 1986) estimated 10 million–16 million fish for the Columbia River based on watershed size, available habitat and fishery records. Radtke and Davis (1996) estimated the historical salmon abundance in the Central Valley to be between 2 million–4 million fish. Using the same methods employed by the NPPC (1986), Radtke estimated an abundance of 4 million fish that he used as the upper bounds of historical run size. Then he used Fisher's (1994) estimate of 2 million fish as the lower bounds. Radtke (pers. comm.) also estimated the historical range of salmon abundance for the Klamath/Trinity system to be 650,000–1 million fish. For coho salmon in California coastal streams, what little evidence is available indicates an abundance of approximately 1 million spawners (Mills et al. 1997).

Data from the Pacific Salmon Fisheries Commission (Roos 1991) were used to estimate the abundance of sockeye and pink salmon (*O. gorbuscha*) in the Fraser River. The abundance of Fraser River sockeye fluctuates on a four-year cycle. Because of the pronounced cyclic dominance of Fraser River sockeye salmon, we calculated the average of all years between 1901 and 1913. This allowed for an average based on four, four-year cycles. This estimate is conservative because it underestimates the impact of the massive nutrient input from the largest dominant years (see Table 3). Puget Sound and Fraser River sockeye and pink runs were adjusted to account for the large interception fisheries. Historically U. S. fishers harvested 65% of the Fraser River sockeye run (Roos 1991). To account for this interception fishery, we subtracted the biomass harvested by U.S. fishers from the total for Puget Sound. Since our estimates of the Fraser run are based on the total catch as a percentage of the entire run, we did not adjust the Fraser estimates based on Puget Sound catch.

Table 3 presents the annual Fraser River sockeye runs from 1901–1916. The runs from dominant years are in bold.

Year	Total Run
1901	**30,970,177**
1902	7,629,255
1903	4,722,619
1904	2,599,071
1905	**30,831,236**
1906	4,532,154
1907	1,921,569
1908	2,939,880
1909	**25,656,474**
1910	5,220,817
1911	2,343,633
1912	3,708,294
1913	**37,793,039**
1914	6,363,067
1915	2,195,463
1916	1,416,316

(Source: Roos 1991)

Precontact Native Fisheries

The methods described above gave us an estimate of the approximate level of salmon production before the arrival of Euro-Americans in the Pacific Northwest. Native Americans had relied on the return of salmon for centuries. While the harvest of fish for native consumption and trade may have been as high as 57 million kilograms (Hewes 1947), that biomass of fish was not removed from the system, as was the case with the canning industry. The traditions and customs of Native American populations ensured the retention of salmon nutrients mostly within the system. (The transportation of dried salmon is a notable exception.) In terms of their removal of nutrients from the system, the impact of Native American harvest and use could be considered the same as the bears, eagles, and other inhabitants of the region that depended on salmon returns for their existence.

Current Run Sizes

We obtained current run sizes from various management agencies. Every attempt was made to use escapement records that exclude hatchery returns. Coho salmon escapement in all coastal areas and Puget Sound, Chinook escapement for the Washington Coast, and all salmon escapements for the Columbia River were taken from the Review of 1996 Ocean Salmon Fisheries (PFMC 1997). The PFMC review of ocean salmon fisheries provides escapement data beginning in 1970 for coastal areas of Washington, Oregon, and California; Puget Sound; and the Columbia River. Chinook escapement estimates for the Oregon coast were taken from the 1995 *Report on the Status of Wild Fish in Oregon* (ODFW 1995). Washington Department of Fish and Wildlife provided escapement numbers for pink, chum, and sockeye salmon in Puget Sound (Jim Ames, WDFW, pers. comm.). The Department of Fisheries and Oceans provided ten-year mean averages for salmon escapements in British Columbia (Kim Hyatt, Canadian Department of Fisheries and Oceans, pers. comm.).

Escapements to Alaskan streams were based on catch and estimated harvest rates during the past seven years. We used harvest rates ranging from 35%–75%, based on information provided by Alaska Department of Fish and Game (Herman Savviko, ADFG, pers. comm.). In Alaska, the percentage of hatchery fish in the commercial harvest has grown steadily over the past 20 years. We eliminated fish produced by hatcheries from the data since they generally did not contribute to natural production.

Nutrient Contribution

Once we calculated the historical and current levels of salmon escapement to the rivers of the northeast Pacific coast, we estimated the potential contribution of marine-derived nutrients. Biomass of the current escapement of fish was determined using the average weights of each species for each region. In recent years, average weights of salmon have decreased (Ricker 1981; Bigler et al. 1996). We used these smaller average weights for the current escapement (Table 4).

Table 4 gives the average weights (kg) of Pacific salmon used to determine current biomass estimates.

Current Weight	Chinook	Coho	Sockeye	Chum	Pink
California	5.25	2.74			
Oregon	3.76	2.07			
Columbia	8.19	1.77		4.84	
Washington	3.31	2.83			
British Columbia	6.04	2.52	2.55	4.63	1.43
AK Average	8.25	3.20	2.59	3.29	1.42
Historic Weight	9.00	4.05	1.58	5.40	1.80

(Source: Bigler et al., 1996)

We used the findings of Larkin and Slaney (1997) for the nutrient content of salmon carcasses: 3.03 % nitrogen and .35 % phosphorous by wet weight. We multiplied those percentages by the total biomass of the historical and the current escapement to estimate the amount of marine-derived nitrogen and marine-derived phosphorus delivered annually to the Pacific Northwest by spawning adult salmon.

Results

A comparison of historical and current run sizes showed two significant changes in regional salmon production. (Tables 5, 6 and 7) First, salmon distribution has dramatically shifted, with much higher numbers of fish returning to Alaska, while a mere remnant of historical abundance remains in the Pacific Northwest. Second, the reduction in biomass is proportionally greater than the change in salmon numbers. The historical level of salmon production was 228 million–351 million fish annually, with the following distribution: 56%–65% of fish returned to Alaska; 19%–26% returned to British Columbia; and 15%–16% returned to California, Oregon, Washington, and Idaho. Today, 142 million–287 million fish are produced by the Northeast Pacific Ocean ecosystem, and 81%–90% return to Alaskan rivers; 8%–17% return to British Columbia rivers; and 1%–1.5 % to rivers in California, Oregon, Washington, and Idaho. These data show a dramatic shift in relative abundance of salmon throughout their range and a 20%–40% reduction in the overall number of fish returning to spawn in the region as a whole.

The historical estimate of 228 million to 351 million salmon yields a biomass of 640 million kg–991 million kg of salmon returning annually to the rivers from Alaska to California (Table 5). The current estimate of abundance of 142 million–287 million salmon yields a biomass of 305 million kg to 606 million kg (Table 7), a 47%–61% decrease in annual salmon biomass compared to historical levels.

We have estimated the annual biomass of salmon entering the river systems of the Pacific Northwest (Washington, Oregon, Idaho, and California) prior to European settlement to be 160 million kg–226 million kg (Table 7). The number of fish now returning to these rivers has an annual biomass of 11.8 million kg to 13.7 million kg (Table 7). This means that just 5%–7 % of the marine-derived nitrogen and marine-derived phosphorous once delivered annually to the rivers of the Pacific Northwest is currently reaching those streams. As a result we calculated that the region now suffers from an annual nutrient deficit of 5–7 million kilograms of marine-derived nitrogen and marine-derived phosphorous (Table 7).

Discussion

The salmon's return to the rivers of the Northwest makes a significant contribution to the flora and fauna of terrestrial and riverine ecosystems. Salmon carcasses strewn along riverbeds and in river channels provide abundant food and nutrients to the animals and plants in those ecosystems. The wide range of animals that rely on the regular availability of spawning salmon reinforces the importance of anadromous fish as a component of wildlife ecology and important element in the biodiversity in the Pacific Northwest (Willson and Hallupka 1995).

On the Olympic Peninsula in Washington, 22 different animal species were observed feeding on salmon carcasses (Cederholm et al.

Table 5 presents the historic run sizes and biomass (kg) for the Pacific salmon in the North Pacific ecosystem. Numbers in 000s.

Historic		Total Fish	Biomass of Run–kg
Alaska	Low	150,134	356,423
	High	200,179	475,231
BC	Low	43,627	122,940
	High	93,486	263,442
Puget Sound	Low	12,750	36,861
	High	27,322	78,989
Wash. Coast	Low	2,027	8,912
	High	5,842	25,192
Columbia	Low	11,170	77,117
	High	14,974	103,387
Oregon Coast	Low	1,983	9,846
	High	4,165	20,715
California	Low	5,484	24,882
	High	6,360	28,623
Totals	Low	227,175	636,981
	High	352,328	995,579

1989). Analysis of bone samples from the skeletons of grizzly bears (*Ursus arctos*) killed in the Columbia Basin between 1856 and 1931 show 35%–91% of carbon and nitrogen were derived from marine nutrients (Hilderbrand et al. 1996). It is possible that some animals alter their territorial and mating behavior to enhance access to adult salmon. The mating in mink (*Mustela vison*) populations varies according to latitude, with northern populations mating later in the year. The mink population on Chichagof Island in southeast Alaska delayed its mating to allow the raising of their young to correspond with the availability of salmon carcasses as an easy food source (Ben-David 1997).

It is now realized what a critical role salmon play in the survival of their own species. MDN have been shown to be vital for the growth of juvenile salmonids (Bilby et al. 1998; Bilby et al. 1996). The presence of abundant salmon carcasses in a stream can significantly increase the mean fork lengths of juveniles, and up to 40% of the carbon in a coho smolt can come from nutrients derived from decaying carcasses of the previous generation of salmon (Bilby et al. 1996). Juvenile salmon consume salmon eggs as well as feeding directly on the spawned-out carcasses. Juvenile fish also benefit from an increased abundance of aquatic invertebrates (Wipfli et al. 1998; Kline 1990) and increased algal growth enhanced by the release of nutrients (Wipfli et al. 1998; Minshall et al. 1991; Ritchy et al. 1975).

The benefits of enhanced nutrient input into a salmon-rearing stream was tested in two small streams in southwestern Washington. Salmon carcasses were added to a section of stream to evaluate their impact on the juvenile population. Compared to a control site where hatchery carcasses were not added, both the size and density of juvenile fish that had access to planted carcasses were greatly enhanced. (Bilby et al. 1998) Overwinter survival rates of juvenile coho salmon have been shown to improve with increased body size (Hartman and Scrivner 1990; Quinn and Peterson 1996). In addition, an increase of body size has been shown to increase the survival rates from smolt to adult (Bilton et al. 1982; Ward and Slaney 1988; Holtby et al. 1990).

Our research suggests a substantial nutrient deficit in areas that have experienced dramatic declines in salmon abundance. Evidence of the role of MDN and energy in ecosystems infers this deficit may indicate an ecosystem failure that has contributed to the downward spiral of salmonid abundance (Bilby et al. 1996; Larkin and Slaney 1997; Northcote 1988). In addition, current management, which maximizes wild salmon harvest, relying heavily on artificial propagation,

Table 6 presents the current run sizes and biomass (kg) for the Pacific salmon in the North Pacific ecosystem. Numbers in 000s.

Current		Total Fish	Biomass (kg)
Alaska	Low	115,363	239,081
	High	259,568	538,027
BC		24,800	59,312
Puget Sound		1,600	4,123
Wash. Coast		72	197
Columbia	Low	109	583
	High	333	1,820
Oregon Coast	Low	104	329
	High	322	996
California		278	1,258
Totals	Low	142,326	304,883
	High	286,973	605,733

Table 7 presents the historic and current run biomass (kg) and nutrient contribution for the Pacific salmon in the Pacific Northwest. Numbers in 000's

Historic Runs		Biomass (kg)		Nitrogen (kg)		Phosphorous (kg)		Change in Biomass	Change in nitrogen (kg)	Change in Phosphorous (kg)
		Historic	Current	Historic	Current	Historic	Current			
Puget Sound	Low	36,861	9,141	1,119	278	132	33	1,252	841	99
	High	78,989		2,399		284		2,682	2,399	284
Wash. Coast	Low	8,575	387	260	12	31	1	291	248	30
	High	24,132		733		87		820	733	87
Columbia	Low	75,808	583	2,302	18	272	2	2,574	2,284	270
	High	101,632	1,820	3,087	55	365	7	3,451	3,032	358
Ore. Coast	Low	9,943	329	302	10	36	1	338	292	35
	High	20,922	996	635	30	75	4	711	605	71
California	Low	24,882	1,404	756	43	89	5	845	713	84
	High	28,623		869		103		972	869	103
Totals	Low	156,069	11,843	4,853	360	574	43	5,427	4,493	531
	High	254,298	13,747	6,854	418	810	49	7,664	6,436	761

may be exacerbating the removal of valuable nutrients and carbon from the natural stream ecosystems, perpetuating the low survival of wild salmon (Lichatowich 1996).

The nutrients in salmon biomass are delivered in an organic form and reach far up into watersheds. Currently large amounts of nutrients are deposited into the river systems from human activity. In some cases these deposits are at levels high enough to cause eutrophication (Daniel et al. 1998). While there is a significant quantity of these anthropogentic nutrients, they are not in an organic form that can be directly utilized by juvenile salmon or other inhabitants of the watershed. In contrast, the carcasses and eggs contributed by the spawning fish are eaten directly by juvenile salmon, other fish, insects and wildlife. In addition, the nutrients are delivered throughout the watershed, reaching far into the headwaters of small streams that might otherwise be nutrient deficient. The timing of this delivery also is crucial because it is available for young salmon upon their emergence from the gravel (Bilby et al. 1998).

Fisheries management has historically ignored such ecological implications of the salmon-spawning escapement. Harvests were regulated to provide the minimum number of spawners needed to seed the habitat. The contribution of "surplus" salmon carcasses to the growth and survival of juvenile salmon was not considered when harvest and escapement targets were set. The degree to which this oversight may have contributed to the overall decline in salmon productivity cannot be determined but can be inferred from experimental evidence as discussed earlier. The difference between ecologically sound escapement and conventional escapement is substantial. In streams where only coho are known to return, 93–155 salmon carcasses per kilometer of stream are thought to be needed in order to provide the maximum ecological benefit from MDN (R. E. Bilby NMFS, pers. comm.). In contrast, the escapement goal for Oregon's coastal coho stocks is 26 fish per kilometer, and between 1990 and 1995 the actual escapement to those streams was 2–7 fish per kilometer (PFMC 1997).

Revisions to the Oregon Coastal Natural Coho Salmon Fisheries Management Plan (Amendment 13) suggest that current fisheries management fails to appreciate the ecological importance of carcasses to increase salmon populations. Harvest levels are limited to 35% under the best of conditions, but fishing pressure of 15%–20% is planned for medium to low adult returns. The decision to go to a higher level of harvest is based on an escapement level of adult coho that uses 50% of available habitat. This is described as proof that "significant progress is being made in rebuilding" of stocks. We would argue that an ecological approach must be addressed when considering escapement. Fisheries management must begin to reflect the results of research that shows the significance of marine derived nutrients to the freshwater system. If management goals are indeed intended to rebuild the depleted stocks of salmon in the Northwest and British Columbia, the determination of a minimum ecological escapement must be developed and offered as an alternative to the harvest-minded approached currently embraced by state and federal fisheries management.

We recommend that the salmon management institutions take the current nutrient deficit into account in setting salmon harvest and escapement levels. In addition, the current suite of performance measures should be expanded to include indicators of important ecological processes in watersheds. Both recommendations will require a major shift in the way we value salmon-from purely commodities to an appreciation of their ecological role in maintaining healthy watersheds.

Acknowledgments

This paper is one of four studies emerging from the Pacific Salmonscape research program, a comprehensive study of the economic, ecological, and biological status of Pacific salmon in the Northeast Pacific, organized by Ecotrust in Portland, Oregon. The authors wish to acknowledge financial support from the Compton, Ford, and Giles W. and Elise G. Mead foundations and the M.J. Murdock Charitable Trust that made this work possible.

An earlier manuscript was reviewed by Robert Bilby, Daniel Bottom, Hans Radtke and Michael Black and their comments were greatly appreciated. The authors would also like to especially thank Ted Wolf for his invaluable support and input in the evolution of this paper.

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