A paleoscience approach to estimating the effects of climatic warming on salmonid fisheries of the Columbia River basin

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Abstract: Efforts to estimate the effect of climate change on fisheries are hampered by the lack of models that project realistic aquatic habitat conditions at the regional scale. Data from the paleosciences are a suitable alternative both for environmental scenario development and model validation. We are using a paleoscience approach to calculate the potential effect of global warming on anadromous salmonid stocks of the Columbia River basin, western North America. First, archaeologically dated fluvial sediments and bivalves were used with terrestrial paleoecological data to reconstruct the flow, flow patterns, temperatures, and bed conditions 6000–7000 yr ago, when paleoclimatic indicators and atmospheric models suggest regional temperatures were up to 2°C warmer. Next, these conditions were imposed on Columbia system subbasins and their effects on salmon stocks were modeled. Results thus far indicate a 30–60% decline in salmon stocks relative to current conditions. Finally, fish remains from archaeological sites were analyzed for evidence of actual salmon production under the reconstructed stream conditions to assess the validity of model projections. Preliminary findings are comparable to model predictions.

Résumé : Les efforts visant à estimer les effets du changement climatique sur les pêches sont entravés par le manque de modèles exprimant des conditions réalistes pour les habitats aquatiques à l'échelle régionale. Les données des paléosciences constituent une option valable autant pour l'élaboration de scénarios environnementaux que pour la validation des modèles. Nous utilisons la démarche paléoscientifique pour calculer l'effet éventuel du réchauffement global sur les stocks de salmonidés anadromes du bassin du fleuve Columbia, dans l'ouest de l'Amérique du Nord. En premier lieu, nous nous sommes servis de sédiments fluviaux archéologiquement datés et de bivalves en plus des données paléoécologiques terrestres, pour reconstituer le débit, les configurations d'écoulement, les températures et les conditions du lit du fleuve il y a 6 ou 7 000 ans, époque où les indicateurs paléoclimatiques et les modèles atmosphériques permettent de croire que les températures régionales étaient jusqu'à 2° C plus chaudes. Par la suite, nous avons appliqué ces conditions sur les sous-bassins du bassin du Columbia et avons modélisé leurs effets sur les stocks de saumons. Les résultats jusqu'à maintenant font état d'un déclin de 30 à 60 % des stocks de saumons par rapport aux conditions actuelles. Enfin, nous avons analysé les fossiles de poissons de sites archéologiques pour trouver des preuves de la production réelle de saumons selon les conditions reconstituées du fleuve en vue d'évaluer la validité des projections faites avec le modèle. Les constatations préliminaires sont comparables à celles qui résultent du modèle.

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Introduction

The standard approach to predicting the effect of climatic changes on fish populations is a three-part process. The researcher begins either by conducting a careful analysis of the behaviour, habitat needs, and reproductive biology of the target organism and the influence of temperature on these variables, or by making a series of observations on population response to small-scale climatic variations occurring within the present-day equilibrium climate. Observations are then analyzed to generate an empirical model of a species' response to environmental conditions. Finally, the potential effects of future climates are inferred by driving the empirical model with scenarios generated by general circulation models (GCMs) and extrapolating from the effects of observed climatic extremes (see, for example, DeAngeles and Cushman 1990).

This approach produces thought-provoking results, as many of the papers in this symposium demonstrate. Certainly, the careful collection of empirical data and the derivation of empirical models therefrom is indispensable to our understanding of climatic effects on an important resource base. However, the plausibility of predictions based on GCMs and extrapolation from recent climatic variation is uncertain. Currently available GCM-generated climatic scenarios address the globe at grid scales that often mask regional-scale variability; regional-scale models derived from GCMs are still in the development stage. Therefore, to predict the effects of large-scale climate changes on fisheries, it is necessary to assume that great rises in air and sea-surface temperatures, for example, will produce regional climate changes of the same type, but simply of greater magnitude than those observed historically. This assumption may be invalid; historical records contain evidence of climatic fluctuations within one equilibrium state, but air temperature increases of 2–5°C may generate new equilibria, with regional effects that are not mere extrapolations of what we currently observe. In their present forms, no two GCMs agree on the regional-scale characteristics of future climates (Cushman and Spring 1989; Kalkstein 1991).

At Pacific Northwest Laboratory, we have been exploring the use of data from the paleosciences as a solution to this dilemma. Paleosciences are the disciplines, including geology, paleoecology, paleontology, paleohydrology, paleooceanography, and archaeology, that use the physical traces and remnants of processes and organisms to reconstruct and under-

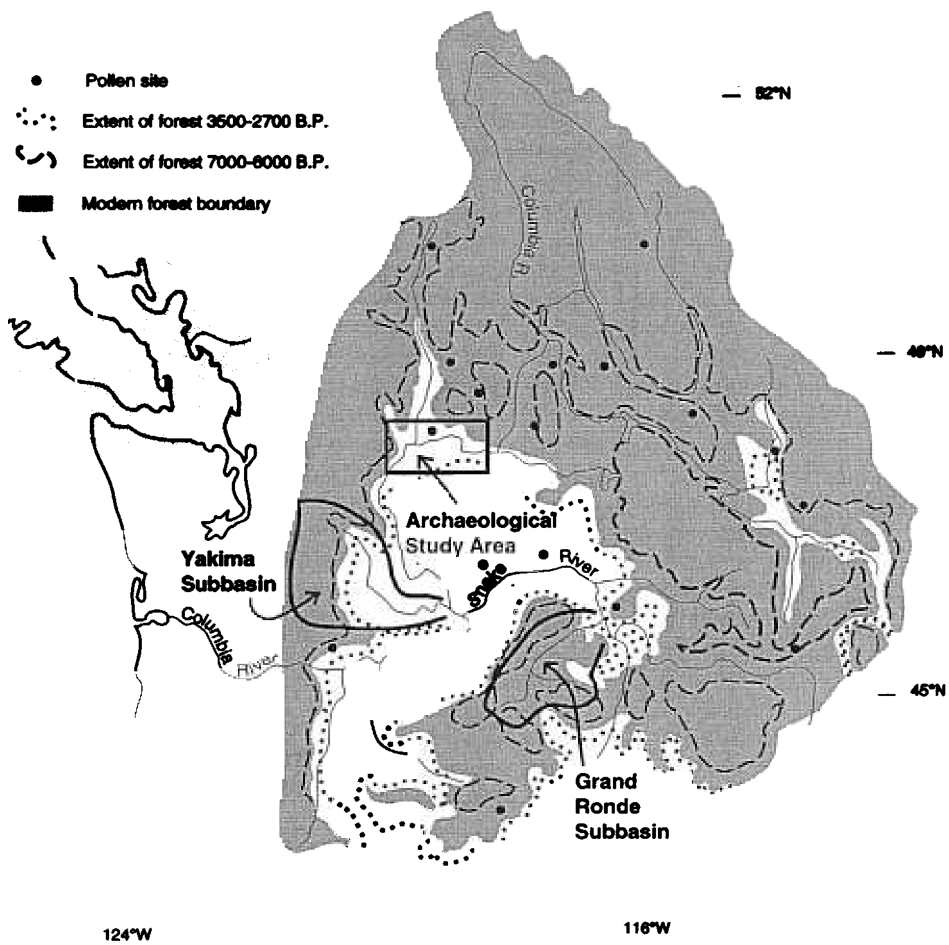

Fig. 1. The northern portion of the Columbia River Basin, showing the source of archaeological data used in this study, the Yakima and Grand Ronde subbasins, and generalized vegetation cover. Approximate forest distributions at 6000–7000 yr B.P. and 3500–2700 yr B.P. are reconstructed from pollen data.

stand ecosystems and cultures of the past. Such data can be used to generate plausibl, even probable, environmental analogs for possible future climate states and to validate dynamic environmental models (e.g., COHMAP members 1988).

We are applying the paleoscience approach to estimate the potential effect of climates 2°C warmer than today on the anadromous salmonids of the Columbia River basin, western North America (Chatters et al. 1991; Neitzel et al. 1991) and to validate the model used in that analysis. The results are intended to assist the Northwest Power Planning Council (NPPC), Bonneville Power Administration, and other resource-management agencies that are developing initiatives to enhance salmonid productivity in this basin. The study is also designed to help the U. S. Department of Energy and the U. S. Environmental Protection Agency identify the consequences global warming might have for water resources and national energy policy. This work is still in progress, so the results reported here are preliminary.

The paleoscience approach

To understand how climatic warming might affect salmonid populations, we are following a four-step procedure, incorporating paleoenvironmental data at the beginning and ending points. First, we used geomorphic, paleobotanical, and paleomalacological data to reconstruct stream conditions during the last 8000 yr. Second, we estimated the effect on salmon (*Oncorhynchus*) of conditions extant approximately 6000–7000 radiocarbon years before present (B.P.), when temperatures were as much as 2°C warmer than at present (Kutzbach 1983). This became an analog of future warmer climate and its effects on spawning, incubation, and rearing parameters of the NPPC's Tributary Parameter Model (TPM) for estimating salmonid production. Third, we ran the TPM in conjunction with the NPPC System Planning Model (SPM) to calculate the effect of these analog conditions on the population of returning adult fish in selected stream systems. Ultimately, we will run the models for all salmon-accessible subbasins of the Columbia River system. Finally, we are identifying fish remains obtained from archaeological sites along the Columbia River to compare variations in the taxonomic composition of ancient fish assemblages with model predictions.

Reconstructing ancient stream environments

Estimates of stream flows, annual flow patterns, bed characteristics, and temperatures have been obtained by analyzing past vegetation patterns, geologic stratigraphy of archaeological sites, and archaeological collections of freshwater mussels (Chatters 1989; Chatters and Hoover 1992). Data for this reconstruction come primarily from the Wells Reservoir Archaeological Project in Okanogan and Douglas Counties, Washington (Chatters 1986). Associated climate scenarios are derived from a synthesis of paleoclimatic indicators, including pollen sequences, cave and lake sediments, subfossil wood, and geomorphic evidence of glacial activity (see Chatters and Hoover 1992).

The distribution of vegetation, as indicated by studies of fossil pollen sequences throughout the river basin (Fig. 1; see Mehringer 1985), was used to estimate mean annual flows; the amount of water available for runoff is assumed to be proportional to that available for plant growth. Estimated flows ranged from 30 to 40% below modern levels under warm, arid climates prior to 6000 yr B.P. to as much as 30% above modern levels in the coolest, wettest times (Chatters and Hoover 1992).

Composition of the bed and suspended sediment loads of ancient streams were inferred partially from the texture, bedding structure, and rate of build-up of fluvial sediments, but primarily from the taxonomic composition of mussel assemblages (Chatters et al. 1991). There are two species of large mussels occurring in the flowing water of the U. S. Pacific northwest. *Margaritifera falcata* prefers swift-flowing, clear, gravel-bedded, stable streams, while *Gonidea angulata* favours slower water, higher suspended sediment loads, sand to silt bottoms, and unstable beds (Lyman 1980; Vannote and Minshall 1982). The percent *Gonidea* in assemblages from a time interval was taken as a crude indicator of the percent sand and silt in the river's bed. *Gonidea* ranged from zero between 300 and 700 yr B.P. to nearly 40% around 6700 yr B.P. (Fig. 2; Chatters 1986).

The annual distribution of flow, or hydrograph, was partially reconstructed from the season at death of river mussels from archaeological middens. Assuming, as one Native American elder stated, that people consumed mussels at any time of year, as long as they were available, and knowing that high stream flows make mussels unavailable as a result of water velocity and turbidity, the period when people were not collecting mussels indicates the period of peak flow. The pre-dam Columbia River, which was snowmelt fed, rose in May, peaked in mid-June during the freshet, and fell to near base flow by mid-July. Season at death for mussels was determined by measuring annual growth increments along the resilial tuberosity, where the hinge ligament attaches to the shell (Chatters 1987). A growth index was calculated by dividing the final growth increment by the expected growth for the death year. The growth indices were compared to the annual growth curve for modern *M. falcata* to estimate the time of death for each sample of mussel shells, or collection event. Finally, collection events were graphed by time period to determine the timing of the freshet. Results showed that freshets typically ended by late June between 7900 and 5500 yr B.P., and ended as late as early August between 3300 and 2200 yr B.P. (Fig. 2; Chatters 1986).

Stream temperatures are also derived from increments of mussel shell growth. Unpublished research by Chatters on modern *M. falcata* has shown that growth rate is closely correlated with water temperatures. Mean growth in the ninth and tenth years has a linear relationship with the number of days above 6, 8, and 10°C, with the strongest correlation ($R^2 = 0.89$) at 10°C. Growth rates in mussels from the Wells Reservoir area of the Columbia River indicate remarkable changes in water temperature over the past 8000 yr. Prior to 3900 yr B.P., the water was above 10°C for approximately 200 d, but since that time this has dropped to an average of less than 130 d (Fig. 2).

As an analog of possible future climate, we chose the period between 6000 and 7000 yr B.P., a time during which both paleoscientific indicators (Chatters 1989) and climate models (Kutzbach 1983) indicate temperatures in western North America were approximately 2°C warmer than at present.

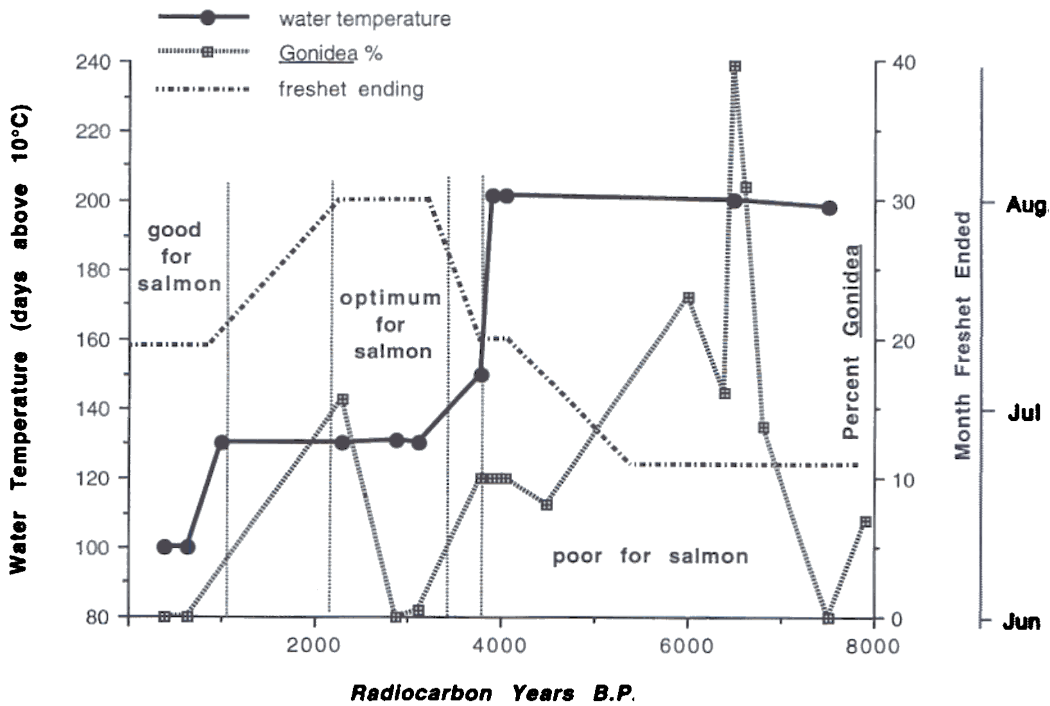

Fig. 2. A summary of evidence for stream conditions in the Wells Reach of the Columbia River since 8000 yr B.P.and their inferred effects on salmon production if they were manifested basinwide.

Based on the four lines of evidence described above, the Columbia River during this period had 30% lower flow, freshets ending nearly a month earlier, temperature above 10°C for nearly twice as long, and a bed with nearly 20% more sand and silt than found under predam conditions.

Altering parameters of the TPM

The NPPC system for simulating salmon production uses both the TPM, which calculates the effects of environmental changes on life stages critical to salmon survival in subbasins, and the SPM, which calculates cumulative salmon survival over multiple generations from TPM outputs, plus data on ocean and main-stem river survival (NPPC 1989, 1992). Although neither is biologically elegant, both models are readily understandable and, more importantly, guide the NPPC's salmon enhancement program.

The TPM contains four key parameters: adult prespawning survival, egg-to-smolt survival, smolt-to-smolt survival, and smolt capacity, which are computed for each reach of a tributary basin. We used reconstructions of 6000–7000 B.P. conditions in the Wells Reach of the Columbia River to modify each of these parameters (Chatters et al. 1991). Water temperature was used to estimate changes in adult prespawning survival because elevated temperatures increase the incidence and severity of disease at this life stage (Becker and Fujihara 1987). Texture of the stream bed was used to alter egg-to-smolt survival because increased sedimentation can suffocate eggs and displace fry (McNeil and Anhel 1964; Hall and Lantz 1969). Freshet timing affects smolt-to-smolt survival by accelerating or retarding outmigration to salt water. If the freshet is too early, smolt may reach salt water before they are physiologically prepared, or if left behind by the freshet, they may experience increased predation during a prolonged migration. Differences between present and past flow rates were used to directly modify smolt capacity, which was assumed to be proportional to stream volume (VanHyning 1973; Smith 1985). For the details of parameter value changes made in one simulation, see Chatters et al. (1991).

Simulating the effects of 6000–7000 yr B.P. stream conditions

Thus far, we have conducted simulations for two tributaries of the Columbia River system: the Yakima subbasin, on the east flank of the Cascade Mountains of Washington, and the Grand Ronde subbasin in mountainous northeastern Oregon (Fig. 1). Simulations estimated the productivity of the spring chinook salmon (*O. tshawytscha*) under a continuation of current environmental conditions and with the 2°C climate warming scenario represented by the 6000–7000 yr B.P. analog. Changes to the four TPM parameters differed slightly between basins largely because of differences in stream gradient and expected residence time of smolts. Relative to current conditions, productivity estimates under climate change were 60% lower for the Yakima subbasin (Chatters et al. 1991) and 30% lower for the Grand Ronde subbasin (Fig. 3). Although we cannot assert that these two subbasins sample the full range of variability in the Columbia River system, they indicate an average decline in productivity of 45%.

Evaluating the model with fish remains from archaeological sites

Human inhabitants of the Columbia River system have been exploiting the fishery for at least 10 000 yr (Cressman 1960; Butler 1993). Presumably, within the limits of available

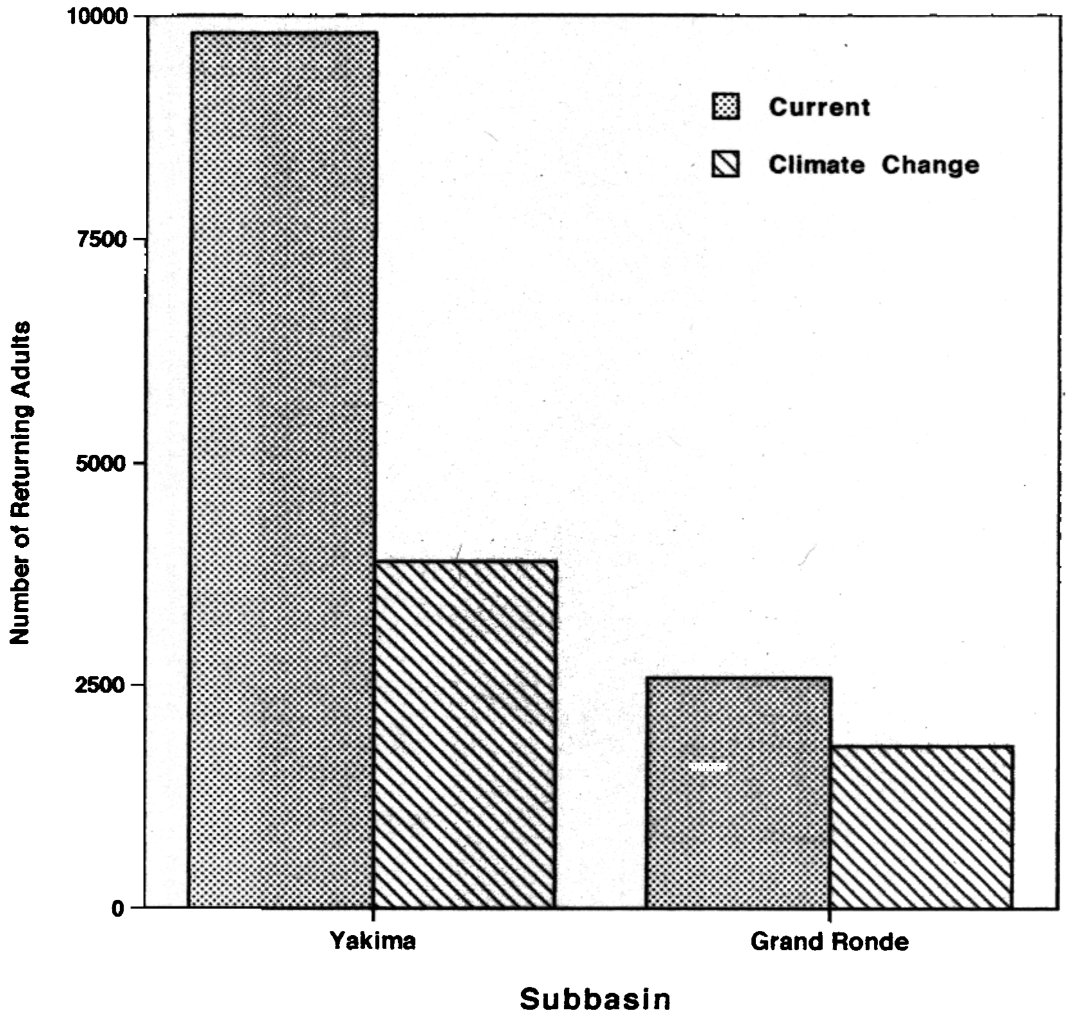

Fig. 3. Results of model runs under current and climate change analog stream conditions for two Columbia River system subbasins.

technology, fish exploitation patterns were consistent with the expectations of optimal foraging theory (MacArthur and Pianka 1966; Winterhalder and Smith 1981). Fish would have been taken in numbers proportional to their size and relative ease of capture. Salmon, among the largest and at times most numerous fishes in the ecosystem, would have been among the first exploited, followed by smaller and/or less numerous or accessible species. Assuming discard of fish remains in habitation sites or kitchen middens and equivalence in the durability of the remains of various species, taxonomic abundances among fish remains in archaeological bone assemblages (archaeofaunas) should reflect availability of various species, particularly the more desirable salmonids. Therefore, archaeofaunas offer data with which to evaluate models of the climate's effect on salmon productivity.

Archaeological research has been conducted in the Columbia River Basin for four decades, stimulated largely by hydroelectric projects along the Columbia and Snake rivers. Archaeofaunas have been collected systematically since the 1960s, providing an extensive data base for model evaluation. We are assembling and systematically identifying these fish archaeofaunas, in an attempt to generate a history of the fishery that is chronologically comparable with the reconstructions of stream conditions.

This part of our research program is the least developed. Thus far, we have analyzed samples from the Chief Joseph Dam Archaeological Project (CJDAP) (Campbell 1985) and Wells Reservoir Archaeological Project (WRAP) (Chatters 1986), two of the largest and most detailed archaeological data recovery efforts yet conducted in the region. Chatters (1986) has identified the fish remains from the WRAP; Butler has re-analyzed selected archaeofaunas from the CJDAP and, to make the data as comparable as possible, is reanalyzing WRAP assemblages. Comparability is somewhat affected by the collection procedures used on the two projects. The CJDAP used 3.2-mm mesh screen for data recovery and sifted the matrix dry; the WRAP used 1.0-mm mesh for 2.5% of the matrix and 6.4-mm mesh for the remainder, all screened using water. Quantification of the CJDAP data is preliminary; each site contained material from multiple habitation events, often spanning several thousand years. We have not yet separated the archaeofaunas by time period, but in each case, over 75%

of th fish remains come from one time interval. A general picture of fish use through time can be obtained by assuming that all fish in a site come from the dominant time interval.

To date, we have results on 13 archaeofaunas from 10 sites, ranging in age from 300 to nearly 8000 yr B.P. Although the oldest archaeofaunas date within the time period of our analog stream environment, we are uncertain how to use them. Before 4500 yr B.P., occupants of the region moved frequently throughout the year, exploiting foods that were in season at each locality (Campbell 1985; Chatters 1986). For this reason, the three archaeofaunas we have from this period may not fully represent the exploitation of Columbia River fish. Analyzed sites that postdate 4500 yr B.P., however, consist almost entirely of pithouse-containing base camps, which were either occupied year round or were the winter setting for consumption of foods gathered during all times of year (Lohse 1984a, b; Chatters 1986). The remainder appear to have been fishing camps (Miss 1984a, b).

As a preliminary evaluation of the model, we can compare the fish archaeofaunas from a period of time with stream conditions similar to those of 6000–7000 yr B.P. with those times when stream conditions existed under an essentially modern climate. Stream conditions comparable to those existing under the warmer climate persisted until approximately 3900 yr B.P. (Fig. 2). Although the freshet ended at approximately the same time as it does now, water temperatures continued to be warm and the stream bed contained a significant amount of sediment. Conditions for salmonid production before 3900 yr B.P. can be characterized as poor, equivalent to the results of climate change simulations for the Yakima and Grand Ronde subbasins. The period after 1200 yr B.P., with modern freshet timing, much cooler waters, and variable amounts of bed sedimentation, is equivalent to the current climate scenario. We characterize these conditions as good. Between 3400 and 2300 yr B.P., conditions were optimum for salmon production, with cool waters, a belated freshet, and virtually no bed sedimentation. Data are largely lacking for the periods between 1200 and yr 2300 yr B.P. and between 3400 and 3900 yr B.P., and we make no suggestions about their suitability for salmon.

Representatives of six genera have been identified from the fish archaeofaunas: *Oncorhynchus* (steelhead, trout, and salmon), *Prosopium* (whitefish), *Catostomus* (suckers), *Ptychocheilus* (squawfish), *Mylocheilus* (peamouth), and *Acipenser* (sturgeon). For this analysis, we present only the percentage of *Oncorhynchus* in each assemblage (Table 1).

Fish archaeofaunas dating between 300 and 4500 yr B.P. closely follow the expected pattern (Fig. 4). Results from the CJDAP and WRAP are remarkably similar, despite the differences in analysts and data-recovery techniques. The percentage of *Oncorhynchus* is lowest before 3700 yr B.P. (mean = 23.2%), highest from 3300 to 2200 yr B.P. (mean = 95.5%) and moderate thereafter (mean = 69.8%). The difference in *Oncorhynchus* frequencies between our analog for current conditions and the warmer climate scenario is 66.8%, which is remarkably close to the 60% difference between the current and climate change simulations for the Yakima subbasin.

Although this analysis is preliminary, it does indicate that our parameter manipulations and the TPM may accurately simulate effects of climate change. If anything, our results are conservative estimates of climate's effects. However, several nonenvironmental factors could also affect patterns of *Oncorhynchus* representation. First, differences in bone density between *Oncorhynchus* and other genera may cause relatively accelerated deterioration of salmon bone. Two of us (V.L. Butler and J.C. Chatters) are investigating this issue and its relationship to taxonomic composition of archaeofaunas. Second, human beings interact selectively with their environment, and may not assemble a representative sample of the available biota (Grayson 1981). Optimal-foraging theory and the general edibility of salmon argue against the importance of selectivity in this instance, however. Third, technological advances can improve the accessibility of fish species. For

Table 1. Data on fish archaeofaunas from Columbia River sites after 4500 yr B.P.

Site	Assemblage	Age range in radiocarbon yr B.P.	Screen size (mm)	Analyst	Percent *Oncorhynchus*	Number of fish bones	Reference for radiocarbon ages
45-DO-285	Zone 1 [a,b]	290±90 – 340±80	3.2	V.L. Butler	83.6	116 [d]	Miss 1984a:112
45-DO-372	Occupation II	630±70	6.4, 1	J.C. Chatters	61.0	2510	Chatters 1986:89
45-DO-214	Zones 2, 3 [a,b]	1035±65 – 1205±160	3.2	V.L. Butler	64.7	173 [d]	Miss 1984b:172
45-DO-372	Occupation III	2220±60 – 2400±80	6.4, 1	J.C. Chatters	97.1	1413	Chatters 1986: 89
45-DO-372	Occupation IV	2760±70 – 3000±90	6.4, 1	J.C. Chatters	95.0	1227	Chatters 1986:89
45-DO-211	Zone 4	2712±80 – 3117±119	3.2	V.L. Butler	93.4	394 [d]	Lohse 1984a:26
45-DO-372	Occupation V	2960±170 – 3340±80	6.4, 1	J.C. Chatters	96.4	56	Chatters 1986:89
45-OK-383	Occupation II	3770±80 – 4010±90	6.4, 1	J.C. Chatters	37.0 [c]	79	Chatters 1986:89
45-OK-11	Kartar	3720±80 – 4490±110	3.2	V.L. Butler	6.5	1537 [d]	Lohse 1984b:315
45-OK-382	Occupation II	4040±110	6.4, 1	J.C. Chatters	26.0 [c]	41	Chatters 1986:89

[a] These sites are not pithouse occupations, so depositional conditions and preservation maydiffer from the rest of the samples.
[b] Counts are from the site as a whole, which contains material from other time periods, but more than 72% of fish elements are from this zone.
[c] Butler has also identified these collections, obtaining *Oncorhynchus* percentages of 28.0% for 45-OK-383 and 14.3% for 45-OK-382.
[d] This number excludes vertebrae fragments, spines, ribs, and gill rakers.

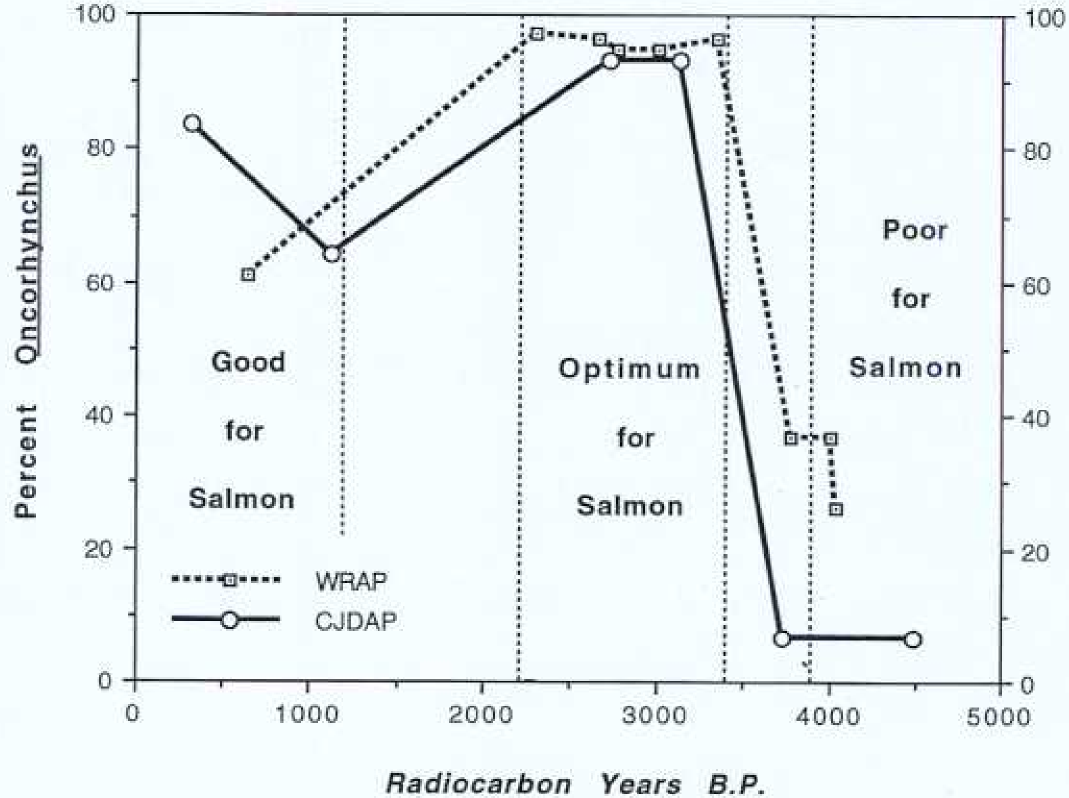

Fig. 4. The percentage of *Oncorhynchus* in archaeological collections after 4500 B.P. from the Wells Reservoir Archaeological Project (WRAP) and Chief Joseph Dam Archaeological Project (CJDAP) on the Columbia River, compared with expectations of salmon production based on inferred stream conditions. Where the radiocarbon age of a collection has a range of 200 yr or less, only the median of dates is shown; otherwise earliest and latest dates are both included.

example, salmon migrate in deep, swift water, whereas suckers can be found in shallower areas, making more complex tools necessary for salmon exploitation in some parts of the river system. Finally, human population density may be a factor. As the number of consumers increased relative to a constant prey population, people would have turned increasingly to less desirable prey species, lowering the relative contribution of salmon in archaeofaunal assemblages. We intend to address these last two issues by analyzing existing archaeological data from the Columbia River Basin, comparing the chronological pattern of fish use with evidence for technology and human population density. Intuitively, however, neither technology nor population pressure alone could generate the observed pattern; technological advances should produce a rising emphasis on salmon, while predation pressure from increasing population would produce a decline.

Summary

The paleosciences offer a viable alternative to GCMs as a source of information that can be used to model the effects of climate on northern fish populations. They also can provide direct evidence of fish communities that can be used for model validation or as a direct measure of climate's effects. Our research team is using information from the paleosciences to estimate anadromous salmonid production in the Columbia River Basin under warmer climatic conditions by (1) reconstructing stream conditions for a warm period of the past, (2) altering parameters of the NPPC's Tributary Parameter Model based on this analog environment, (3) running the TPM in conjunction with the SPM to simulate effects of current and warmer climate scenarios, and (4) comparing simulated salmon production with past salmon productivity indicated by the taxonomic composition of fish archaeofaunas. The results thus far are encouraging; simulated fish production under the analog climate compares closely with the archaeological evidence. If anything, the model underestimates the severity of climate's impact.

Analogs drawn from the paleosciences, like GCM-generated scenarios, have their limitations. Future warming, forced by greenhouse gas build-up rather than orbital variations, may have regional effects that differ from those of the past. Also, reconstructions are based on proxy indicators of environmental conditions, not direct measures, and may incorrectly represent past realities. Because they are based on empirical data, however, analogs from the past at the very least present us with plausible, readily understandable images of how important resources can be influenced by climate changes.

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References

Becker, C.D., and M.P. Fujihara. 1987. The bacterial pathogen *Flexibacter columnaris* and its epizoology among Columbia River fish. Am. Fish. Soc. Monogr. 2. American Fisheries Society, Bethesda, MD.

Butler, V.L. 1993. Natural versus cultural salmonid remains: origin of the Dalles Roadcut Bones, Columbia River, Oregon, U.S.A. J. Archaeol. Sci. (In press)

Campbell, S.K. 1985. Summary of results, Chief Joseph Dam Archaeological Project, Washington. Office of Public Archaeology, University of Washington, Seattle, WA.

Chatters, J.C. 1986. The Wells Reservoir Archaeological Project. Vol. 1. summary of findings. Cent. Wash. Archaeol. Surv. Archaeol. Rep. 86–6. Central Washington University, Ellensburg, WA.

Chatters J.C. 1987. Shell of *Margaritifera margaritifera falcata* as a source of paleoenvironmental and cultural data. Appendix F. *In* M.S. Kelly, E. Nilsson, and J. Cleland [ed.] Archaeological Investigations at Lake Britton, California. Pacific Gas and Electric Company, San Francisco, CA.

Chatters, J.C. 1989. Hypsithermal paleohydrology as an analog of greenhouse effects on the Columbia River Basin, Washington. Geol. Soc. Am. Abstr. Prog. 21(6).

Chatters, J.C., and K. A. Hoover. 1992. Response of the Columbia River fluvial system to Holocene climatic change. Quat. Res. 37: 42–49.

Chatters, J.C., D.A. Neitzel, M.J. Scott, and S.A. Schankle. 1991. The effect of climate change on stream environments: the salmonid resource of the Columbia River Basin. Northwest Environ. J. 7: 271–293.

COHMAP Members. 1988. Climatic changes of the last 18,000 years: observations and model simulations. Science (Wash., D.C.) 241: 1043–1052.

Cressman, L.S. 1960. Cultural sequences at The Dalles, Oregon. Trans. Am. Philos. Soc. 50(10).

Cushman, R.M., and P.N. Spring. 1989. Regional differences among GCM climate projections for resource analysis. Environ. Manage. 13: 739–795.

DeAngeles, D.L., and R.M. Cushman. Potential application of models in forecasting the effects of climate change on fisheries. Trans. Am. Fish. Soc. 119: 224–239.

Grayson, D.K. 1981. A critical review of the use of archaeological vertebrates in paleoenvironmental reconstruction. J. Ethnobiol. 1: 28–38.

Hall, J.C., and R.L. Lantz. 1969. Effects of logging on the habitat of coho salmon and cutthroat trout in coastal streams. H. R. MacMillan Lectures in Fisheries, University of British Columbia, Vancouver, B.C.

Kalkstein, L.S. [ed.]. 1991. Global comparisons of selected GCM control runs and observed climate data. Publ. 21P-2202 U. S. Environmental Protection Agency, Washington, DC.

Kutzbach, J.E. 1983. Modeling of Holocene climates, p. 271–277. *In* H.E. Wright, Jr. [ed.] Late Quaternary environments of the U.S. Vol. 2. The Holocene. University of Minnesota Press, Minneapolis, MN.

Lohse, E.S. 1984a. Archaeological investigations at site 45-DO-211, Chief Joseph Dam Project, Washington. Office of Public Archaeology, University of Washington, Seattle, WA.

Lohse, E.S. 1984b. Archaeological investigations at site 45-OK-11, Chief Joseph Dam Project, Washington. Office of Public Archaeology, University of Washington, Seattle, WA.

Lyman, R.L. 1980. Freshwater bivalve mollusks in southern Plateau prehistory. Northwest Sci. 54: 121–135.

MacArthur, R.H., and E.H. Pianka. 1966. On optimal use of a patchy environment. Am. Nat. 100: 603–609.

McNeil, W.H., and W.H. Anhel. 1964. Success of pink salmon spawning relative to size of spawning bed materials. Spec. Sci. Rep. Fish. 469. U.S. Fish and Wildlife Service, Corvallis, OR.

Mehringer, P.J. 1985. Late Quaternary Pollen Records from the Interior Pacific Northwest and Northern Great Basin of the United States, p. 167–189. *In* V. Bryant and R. Holloway [ed.] Pollen records of late Quaternary North American sediments. American Association of Stratigraphic Palynologists, Dallas, TX.

Miss, C.J. 1984a. Archaeological investigations at site 45-DO-285, Chief Joseph Dam Project, Washington. Office of Public Archaeology, University of Washington, Seattle, WA.

Miss, C.J. 1984b. Archaeological investigations at site 45-DO-214, Chief Joseph Dam Project, Washington. Office of Public Archaeology, University of Washington, Seattle, WA.

Neitzel, D.A., M.J. Scott, S.A. Schankle, and J.C. Chatters. 1991. The effect of climate change on stream environments: the salmonid resource of the Columbia River Basin. Northwest Environ. J. 7: 271–293.

Northwest Power Planning Council (NPPC). 1989. Salmon and steelhead system planning documentation, user information for the System Planning Model. Monitoring and Evaluation Group, Portland, OR.

Northwest Power Planning Council (NPPC). 1992. Salmon and steelhead system planning documentation, 1992 update of user information for the System Planning Model. Monitoring and Evaluation Group, Portland, OR.

Smith, R.J.F. 1985. The control of fish migration. Springer-Verlag, New York, NY.

VanHyning, J.M. 1973. Factors affecting the abundance of fall chinook salmon in the Columbia River. Fish Commission of Oregon, Portland, OR.

Vannote, R.L., and G.W. Minshall. 1982. Fluvial processes and local lithology controlling abundance, structure, and composition of mussel beds. Proc. Natl. Acad. Sci. U.S.A. 79: 4103–4107.

Winterhalder, B., and E.A. Smith. 1981. Hunter–gatherer foraging strategies. University of Chicago Press, Chicago, IL.