ARCTIC
VOL. 70, NO. 3 (SEPTEMBER 2017) P. 259–272
https://doi.org/10.14430/arctic4665

Evaluating Evidence for Historical Anadromous Salmon Runs in Eklutna Lake, Alaska

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(*Received 19 September 2016; accepted in revised form 28 February 2017*)

ABSTRACT. We assessed historical presence of sockeye salmon in Eklutna Lake, Alaska, prior to construction of a diversion dam on the downstream Eklutna River in 1929, using nitrogen stable isotopes measured in a lacustrine core 93 cm long. Sediments in the core were dated using varve counts, verified by ^{210}Pb and ^{137}Cs measurements. The basal date of the core was AD 1859, and varves became slightly thinner and less distinct after 1929. Sediments were primarily clastic with carbon content below 1%. Nitrogen isotope values were generally low and stable throughout the core, ranging from 1.5‰ to 2.5‰. There is no statistical evidence for a change in isotopic composition after emplacement of the dam. In light of published evidence from oral history, cultural records, and habitat relationships that suggest sockeye salmon could have been present in the lake before 1929, we conducted a simple sensitivity test to assess the possibility that a small salmon run may have gone undetected by our technique. We found that a salmon run of up to 1000/year, and potentially as many as 15 000/year, would be possible without noticeably altering the measured isotopic composition of the sediments in Eklutna Lake. Our results provide no evidence that such runs occurred, but do not preclude the possible existence of a relatively small sockeye fishery in Eklutna Lake before 1929.

Key words: salmon; sockeye salmon; anadromous fish; marine fish remains; south-central Alaska; Eklutna Lake; lacustrine sediments; nitrogen isotopes

RÉSUMÉ. Nous avons évalué la présence historique du saumon rouge dans le lac Eklutna, en Alaska, avant la construction d'un barrage de dérivation sur la rivière Eklutna en aval en 1929, à l'aide d'isotopes stables de l'azote mesurés dans un noyau lacustre de 93 cm de longueur. Les sédiments du noyau ont été datés au moyen du dénombrement des varves et vérifiés avec les mesures du plomb 210 et du césium 137. La date de base du noyau était de 1859 A.D., et les varves devenaient un peu plus minces et moins distinctes après 1929. Les sédiments étaient principalement clastiques, leur teneur en carbone étant inférieure à 1 %. Les valeurs des isotopes d'azote étaient généralement faibles et stables dans l'ensemble du noyau, variant ainsi entre 1,5 ‰ et 2,5 ‰. Il n'existe pas de preuve statistique de changement de composition isotopique après l'aménagement du barrage. À la lumière de la preuve publiée à partir de l'histoire orale, des dossiers culturels et des relations avec l'habitat qui suggèrent que le saumon rouge aurait pu être présent dans le lac avant 1929, nous avons réalisé un simple test de sensibilité afin d'évaluer la possibilité qu'une petite montaison de saumon n'ait pas été détectée au moyen de notre technique. Nous avons constaté qu'une montaison pouvant atteindre 1 000 saumons par année, voire 15 000 par année, serait possible sans pour autant altérer considérablement la composition isotopique mesurée des sédiments du lac Eklutna. Nos résultats ne fournissent aucune preuve de telles montaisons, sans toutefois exclure l'existence possible d'une pêche relativement petite de saumon rouge dans le lac Eklutna avant 1929.

Mots clés : saumon; saumon rouge; poisson anadrome; restes de poisson de mer; centre-sud de l'Alaska; lac Eklutna; sédiments lacustres; isotopes d'azote

Traduit pour la revue *Arctic* par Nicole Giguère.

INTRODUCTION

In Alaska, historically strong populations of Pacific salmon (*Oncorhynchus* spp.) have contributed substantially to the ecological, cultural, and economic well-being of the biotic and human communities where they thrive. Fisheries researchers and managers therefore share an interest in documenting salmonid population variability and have directly monitored population sizes for more than a century (Byerly et al., 1999). Because these populations are sensitive not only to the short-term impacts of commercial and recreational fishing, but also to longer-term impacts of climatic fluctuations and other (non-fishing) human activities, some researchers have turned to macrofossil and

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biochemical markers in lake sediment cores as a means of estimating population sizes prior to development of a historic record (Gregory-Eaves et al., 2009).

The use of marine-derived nutrients (MDN) to estimate former salmonid populations was developed almost two decades ago by Finney (1998), and since then has been widely used, along with other proxies, to estimate past changes in escapement of sockeye salmon (*Oncorhynchus nerka*), the only Pacific salmon species to spawn in nursery lakes rather than rivers and streams (e.g., Finney et al., 2000; Adkison and Finney, 2003; Gregory-Eaves et al., 2009). Fundamentally, the technique relies on the measurement of the stable isotope ratio $\delta^{15}N$ in well-dated lacustrine sediments. Finney (1998) demonstrated that historical populations of spawning salmon are well correlated, over time, with the ratio of ^{15}N to the lighter, more common ^{14}N in lacustrine cores. This correlation is driven by the tendency of anadromous salmon to feed high on the marine food web, where more ^{15}N is available than in terrestrial and lacustrine environments. The salmon contribute this nitrogen to the lake when their carcasses decay, as regenerated nitrogen is used by phytoplankton and associated food webs and deposited into sediments, providing an opportunity to quantify prehistoric salmon abundance.

Finney et al. (2000) cautioned, however, that isotopic values of lacustrine sediments in some nursery lakes may be relatively insensitive to salmon escapement in cases where MDN constitute a small fraction of the lake's total nutrient input, and some subsequent investigators have found Alaskan and Canadian lake systems in which $\delta^{15}N$ was not clearly related to former salmon abundance (Holtham et al., 2004; Hobbs and Wolfe, 2007, 2008). Considering the question of what makes a "good" lake for the use of nitrogen isotopes to reconstruct former salmon numbers, Gregory-Eaves et al. (2009) developed a conceptual model to highlight factors that suggest a good opportunity for such reconstruction: "good" lakes have relatively large numbers of spawning salmon, long water residence times, low precipitation rates, minimal deposition of terrestrial organic matter, and low rates of ammonia volatilization and denitrification. Researchers interested in broad, regional studies of salmon abundance may well have the freedom to seek out lakes that exhibit these characteristics, but some studies are—by their nature—focused on the history of particular lakes that may or may not exhibit these ideal characteristics. In such cases, the isotopic signal may be small, and the interpretation of those results, ambiguous.

Here, we confront this challenge in the context of Eklutna Lake, a proglacial lake in south-central Alaska. Construction of a downstream diversion dam in 1929 isolated the lake from potential use by salmon as a nursery lake. Framed simply, our question is whether there was an anadromous salmon run into Eklutna Lake prior to 1929. This question is motivated by a general desire to better understand the natural history of salmon in the upper Cook Inlet region (Smith and Speed, 2013). This question is particularly important for salmon habitat conservation because contractual language in a 1991 agreement (in which the federal government sold the Eklutna hydroelectric project to a consortium of private utilities and local government entities) dictates that within 30 years of the purchase date, the purchasers must develop a program that protects, mitigates, and enhances fish habitat affected by hydroelectric development (APA, 1992). In other words, credible evidence of a sockeye salmon run into Eklutna Lake before initial hydroelectric development construction in 1929 would help to inform the nature and extent of actions needed to restore salmon access and habitat within the Eklutna River watershed. We undertook an isotopic study of Eklutna Lake sediments to search for such evidence, mindful of the caveats described above.

Here we describe the historic and landscape context for hydroelectric development at Eklutna Lake, Alaska, an isotopic study of sediments recovered from the lake, and a sensitivity analysis designed to quantify the conditions under which we could expect historical salmon abundance to yield a detectable signal. We evaluate the results in the context of oral history accounts, cultural records, and habitat relationships that bear on the question of whether sockeye salmon may have been present before dam construction.

STUDY SITE

Eklutna Lake (Fig. 1) is 14.1 km^2 and occupies a glacially eroded trough 10.5 km long in south-central Alaska, approximately 50 km northeast of the state's largest city, Anchorage. The lake was naturally dammed at its northwestern end by a Pleistocene-era terminal moraine of Eklutna Glacier, but the retreating glacier terminus is now 8 km upstream of the lake's primary inlet. The lake is fed by precipitation, snowmelt, and ice melt from a 307 km^2 basin that is 13% glaciated, and it derives approximately half of its annual inflow from the 64 km^2 sub-basin that includes Eklutna Glacier (Larquier, 2010). The few limnological studies of the lake are from the 1980s and focused on physical limnology and suspended sediment properties. The lake is dimictic, with weak thermal summer stratification. Summer surface temperatures may reach ~15˚C, though temperature distributions are strongly influenced by winds and inflow (R&M Consultants, 1986; Gosink, 1987). Turbidity varies with season and depth, with Secchi disk readings in the range of 0.4 – 0.9 m.

The climate of the region is subarctic and transitional between maritime and continental. Monthly average temperatures at the nearby Natural Resources Conservation Service "Moraine" Snotel site (640 m asl) range from −11˚ to +1˚C in winter and from 7˚ to 14˚C in summer (https://www.wcc.nrcs.usda.gov). Annual total precipitation, about 50% of which falls between July and October, ranges from about 40 to 60 cm. The elevation of the watershed ranges from 265 m (lake spillway elevation) to 2100 m. The predominant bedrock type of variably metamorphosed

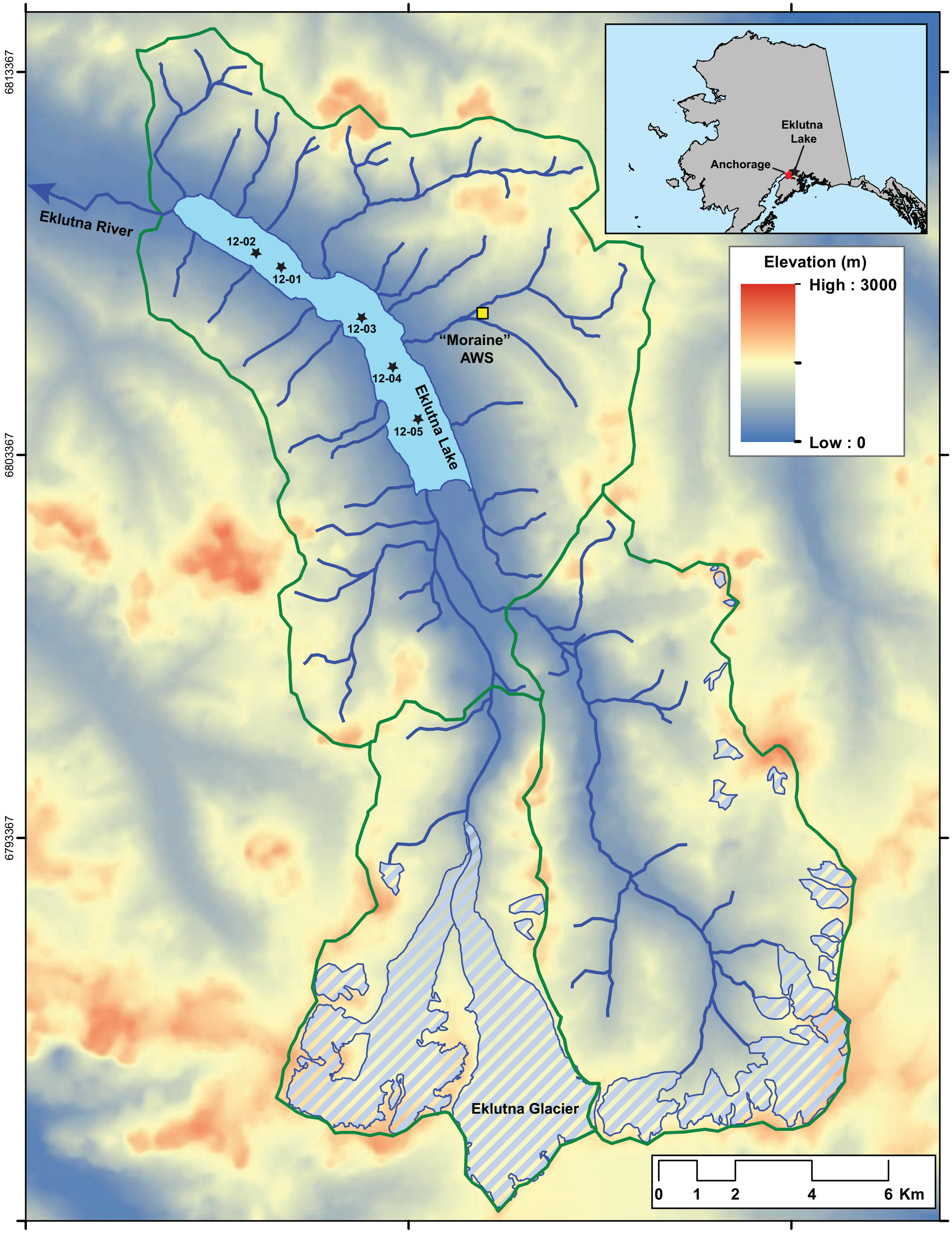

FIG. 1. Map of Eklutna Lake, showing coring locations (black stars), glaciers (blue diagonal crosshatching), and surrounding watershed (polygons outlined in green, subdivided into east, west, and lake sub-basins). Rivers are in blue; the arrowhead at upper left indicates the outlet river, downstream of the diversion dam. Boundary tick labels are UTM zone 7N m. Inset at upper right shows location of Anchorage (red star) and Eklutna Lake (black star) within Alaska.

non-clastic sedimentary and igneous rocks is mantled in many areas by colluvium, glacial moraines, and fluvial deposits (Brabets, 1993). Vegetation grades from mixed deciduous and coniferous boreal forest at lake level through brush and tundra up to bare rock and ice at the highest elevations.

The maximum elevation of Eklutna Lake has been raised by a series of storage dams constructed since 1928. The current dam, which has been in place since 1965, consists of an uncontrolled concrete spillway 265 m asl with no outlet. Lake level now fluctuates seasonally in response to the annual balance of inflow and withdrawals made by the power and water utilities for hydropower and municipal water supplies. The lake typically reaches a maximum elevation at the end of summer and a minimum just before spring breakup. When full, the lake has a maximum depth of more than 55 m and a total volume of ca. 500 million m^3 (Larquier, 2010). A shallow (~35 m) constriction just NW of the lake's midpoint divides it into a proximal flat-bottomed sub-basin (ca. 55 m deep) and a smaller distal sub-basin (ca. 45 m deep). Because the power and water utilities use the entire inflow to the lake in most years, and no water leaves the lake via the spillway, usage reported by the utilities provides a good estimate of annual inflow. From 2000 to 2010, average annual inflow was 300 million m^3 (Municipal Light and Power, 2014). This value suggests a water residence time in the lake of 1.7 years.

The hydrology of Eklutna Lake and the downstream Eklutna River has been altered since 1928 by developments that have culminated in the modern usage of virtually the entire water budget of the basin. The history of such development has been well described elsewhere (e.g., Simonds, 1995; Hollinger, 2002; USACE, 2011), but here we summarize from these sources the key events pertinent to the lake hydrology and salmonid persistence. The first dam on Eklutna Lake was an earthen dam 4.3 m tall built in the early winter of 1928 to increase the lake's water holding capacity. This dam was rebuilt on interlocking wood pilings the following summer (1929) after a flood damaged its original clay and muck foundation. Concurrently, a concrete diversion dam 19 m high was built on the Eklutna River about 12 km downstream of the lake outlet; the location of this dam and other features discussed in this section are shown in Figure 2. The diversion dam, which funneled river flow into a tunnel that led to a lower-elevation Pelton wheel, was the first barrier to any potential salmon migration towards the lake. The diversion dam remained operational through 1955, when an entirely new hydropower infrastructure was installed at the lake. In that year, a new earthen dam was completed on Eklutna Lake with a concrete spillway that raised the maximum lake level to 265 m asl. Concurrently, a new tunnel was built that siphoned water from an intake at 253 m asl, in the lake bottom, to a new power plant on the Knik River, in an entirely different watershed. Downstream, the original diversion dam remained the primary obstacle to salmon migration, but after 1955, the lake was managed with an objective of utilizing all flows for hydropower. Except in times of unusual runoff, therefore, the section of the Eklutna River below the storage dam ran dry until joined by several small tributaries and finally, by its major downstream tributary, Thunderbird Creek. In March 1964, the dam on the lake, the lake-bottom intake and tunnel, and associated infrastructure were all damaged by a large earthquake and required extensive repairs, but otherwise, the lake was essentially managed in the same way from 1955 through 1988. In that year, the Eklutna Water Treatment Facility was built near the location of the original diversion dam, and tapped a new pipe into the hydropower tunnel to divert water for the municipal water supply. This plant now provides more than 90% of Anchorage's total municipal water supply, but in most years that usage constitutes only 10%–12% of the total water supplied by the lake: the rest is still used for hydropower.

METHODS

Core Acquisition and Dating

To assess the geochemical evidence for a pre-1929 salmon run into Eklutna Lake, we relied upon five short lacustrine cores collected previously for use in a separate project that investigated the paleoseismicity of Eklutna Lake. Below, we describe that coring process, the age model for the cores, and the sampling and geochemical analyses and assess the sensitivity of our results to the magnitude of a hypothetical historic salmon run.

The five cores were collected from the lake bottom by colleagues from the Renard Centre of Marine Geology (RCMG), at Ghent University in Belgium, between 26 and 28 June 2012. All five cores were collected from approximately the centerline of the NW-SE trending lake (Fig. 1, Table 1) using a gravity corer with a sliding hammer weight. All cores were less than 1 m long and collected from a water depth of more than 45 m. Core locations were chosen on the basis of bathymetry and seismic mapping conducted concurrently by the RCMG group. They include two sites in the distal sub-basin of the lake (EK12-01 and 12-02) and three sites in the more proximal sub-basin (EK 12-03, 12-04, and 12-05). For a more detailed description of core collection methods, see Boes (2014).

We inspected and described the five short cores at the RCMG laboratory facilities, where they are archived, in January 2014. Except where noted, our work, along with subsequent development of the age model, was done independently of the RCMG's own work on the cores. All five cores were inspected, photographed in natural light at high resolution, and imaged with a Siemens SOMATOM Force X-ray computed tomography (CT) scanner. Lamination identification, delineation, and counting were later performed on all five cores using the software package ImageJ with imported, aligned copies of the photographs and CT scans. Individual laminations typically consisted of

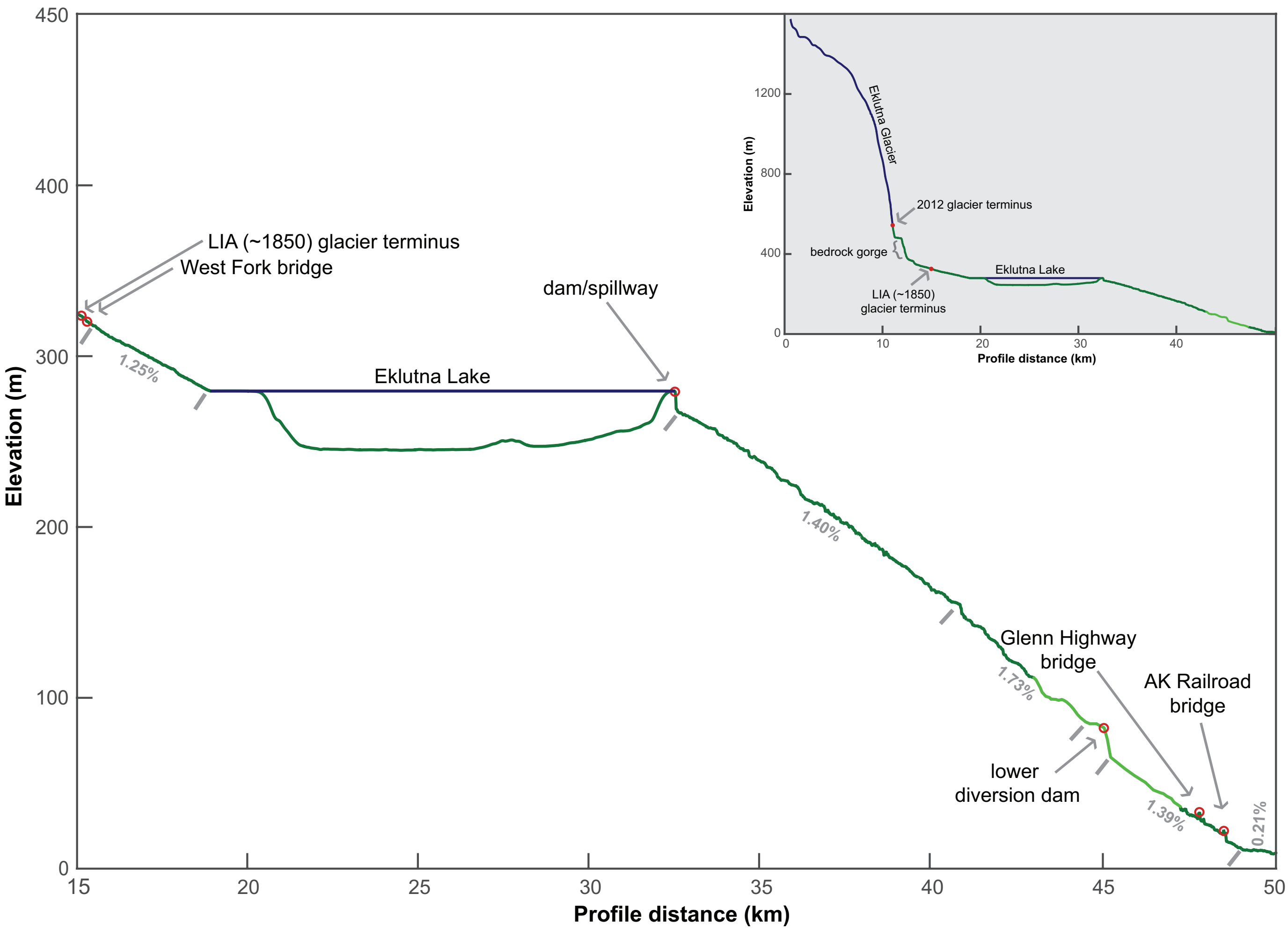

FIG. 2. Profile of Eklutna River and Lake showing select points of interest (red circles). Light gray bars below the profile bracket the reaches of the river over which average stream gradients were calculated. The portion of the profile in light green, near the lower diversion dam, denotes a section in which the profile was smoothed to remove noise generated by errors in the digital elevation model. Inset panel shows the same profile with the Eklutna Glacier (up to its head at Whiteout Pass) for context.

a fining-upward and lightening-upward (in color) sediment package with a distinct upper boundary. These upper boundaries were used to demarcate the boundary between individual units. Four anomalously thick strata that differed in appearance from the others were judged to be the products of discrete high-sedimentation-rate events and were eliminated from the Lead-210 age model, as described below.

Early in the description phase, we determined that core EK 12-01, the longest and most clearly laminated of all the cores, would be used as a master core for construction of the age model and isotope sampling. To supplement and confirm a primary age model developed using varve counts, we used measurements of ^{210}Pb and ^{226}Ra (for Lead-210 dating) and ^{137}Cs (for Cesium-137 dating). These measurements were based on 20 samples, distributed across the depth of EK 12-01, which were previously collected and freeze-dried by the RCMG group. Radioactive activities in these samples were counted at the University of Bordeaux using a Canberra low background, high-efficiency γ-detector (Schmidt et al., 2009). These activities are expressed in mBq/g with errors based on one standard-deviation counting statistics.

^{210}Pb ages were calculated based on the constant rate of supply (CRS) method, assuming a constant supply of excess ^{210}Pb to the sediment (Appleby, 2013):

$$t = \frac{1}{\lambda} \ln\left(\frac{I_o}{I_z}\right) \quad (1)$$

where t is the age of a sample at depth z in years, λ is the decay constant for ^{210}Pb (0.03114/yr), and I_o and I_z are the inventories of $^{210}Pb_{ex}$ at the surface and at depth z, respectively. In core EK 12-01, we applied the CRS model by calculating ages of each sample using equation (1) and then calculating a mean sedimentation rate as the slope of a line fit to the calculated ages (t) as functions of depth. Before applying this sedimentation rate to the whole core, we then created a "corrected" depth scale by removing the thicknesses of the four anomalous layers described above,

TABLE 1. Locations and lengths of short cores collected at Eklutna Lake in June 2012.

Core #	Latitude	Longitude	Water depth (m)	Core length (cm)
EK 12-01	61.3928˚ N	149.0876˚ W	47.9	93.0
EK 12-02	61.3990˚ N	149.1076˚ W	40.2	67.5
EK 12-03	61.3825˚ N	149.0467˚ W	54.4	43.0
EK 12-04	61.3695˚ N	149.0319˚ W	55.1	78.5
EK 12-05	61.3544˚ N	149.0174˚ W	53.7	75.8

for which the mean sedimentation rate was not appropriate. The ^{210}Pb age of each lamination (varve) was then calculated by dividing its corrected depth by the sedimentation rate.

^{137}Cs dating relies on the presence in lake sediments of a fission product of nuclear weapons testing and nuclear reactor incidents that is otherwise absent from the natural environment (Pennington et al., 1973). The majority of ^{137}Cs was deposited in the late 1950s and early 1960s, peaking late in 1963 when the Limited Test Ban Treaty banned nuclear weapon tests. Measured ^{137}Cs concentration was used to confirm the varve and ^{210}Pb age models.

Isotopic Composition

To test the geochemical composition of the lacustrine sediment in core EK 12-01, we continuously sampled a split section of the core in 1 cm intervals. Each of 93 samples included approximately 1 cm^3 of material and was immediately placed in a freezer. After about 24 hours, all samples were simultaneously freeze-dried for 48 hours.

Isotope measurements were made at the Idaho State University Stable Isotope Laboratory. Homogenized samples were combusted in an elemental analyzer to determine total organic carbon (TOC) and total nitrogen (TN) concentrations, and analyzed on an isotope ratio mass spectrometer for δ^{13}C and δ^{15}N measurements. Carbonates were not found in the sediments, and thus they were run untreated. All isotope values are reported in per mil units (‰) according to the relationship $X = [(R_{sample} / R_{standard}) - 1] \cdot 1000‰$, where X is the element of interest and R is the measured isotopic ratio. All carbon isotope measurements are relative to the Vienna Peedee Belemnite (VPDB) standard, and all nitrogen measurements are relative to atmospheric nitrogen. Analytical precision, calculated from analysis of standards distributed throughout each run, deviated less than ± 0.2‰ for both carbon and nitrogen stable isotopes, and less than ± 0.5% of the sample value for %N and %C.

Many of the 93 samples span more than one varve; in these cases we plot the measured composition of each sample against the average year represented by the sample (the mean age of all layers completely or partly contained within a given sample). To look for changes in isotopic ratios and geochemical concentrations coincident with the installation of the first salmon-blocking dam in the winter of 1928 – 29, we performed a Wilcoxon rank sum test on each of the measured parameters, comparing medians of the pre- and post-1929 samples. This procedure tests the null hypothesis that both sample groups come from the same continuous (but not necessarily normally distributed) population. If the test rejects the null hypothesis with a p-value of less than 0.05, we interpret that as evidence that the parameter of interest changed after 1929.

RESULTS

Core Stratigraphy

The five cores recovered from Eklutna Lake (Table 1) contained clear laminations with consistent stratigraphy traceable from one core to another. Macroscopic and microscopic characteristics of the five cores, and the correlations among them, are described thoroughly in Boes (2014) and Praet et al. (2016), and we focus here on our master core, EK 12-01. The master core contains clear laminations throughout its 93 cm length, with notable interruptions by distinctive thicker layers at 5 – 7, 22 – 24, 41 – 45, and 51 – 54 cm depths (Fig. 3). Upon close examination, the laminations consist of a repeating pattern of dark silt grading upwards into lighter-colored clay caps, separated from the next upward lamination by a clear boundary. We interpret these laminations as varves, or annual layers, with the clay cap representing slow deposition of the finest suspended sediment fraction in the lake water column during winter, and the abrupt transition to the next, darker and coarser layer representing the onset of breakup. Our radiogenic age models, presented next, confirm this interpretation, and we hereafter refer to these laminations as varves. The character of the varves changes around 41 cm, at the top of the thickest anomalous layer. Varves below that layer are clearer and more distinct, while those above that layer have less contrast between the dark and light layers. Varve thickness also changes at this time: varves below the 41 – 45 cm event, omitting the anomalous layers, average 0.65 cm thickness. Above 41 cm they average 0.48 cm. More details, including microscopic characteristics and quantitative grain-size measurements, are available in Boes (2014).

Age Model

We interpret the laminations in core EK 12-01 as varves, and therefore counted them to establish our primary age model. The four anomalously thick layers described previously were included in our varve counts, based on our interpretation of these layers as annual couplets that each include a high-sedimentation event. We identified 153 varves in the 93 cm core, yielding a basal date (assuming that the uppermost varve represents the full summer deposit of 2011) of AD 1859 (Fig. 3). This age model assigns the following years to the four anomalous layers (measuring from the top down): 1995 (2.37 cm thick), 1964 (1.47 cm), 1929 (4.42 cm), and 1919 (2.95 cm).

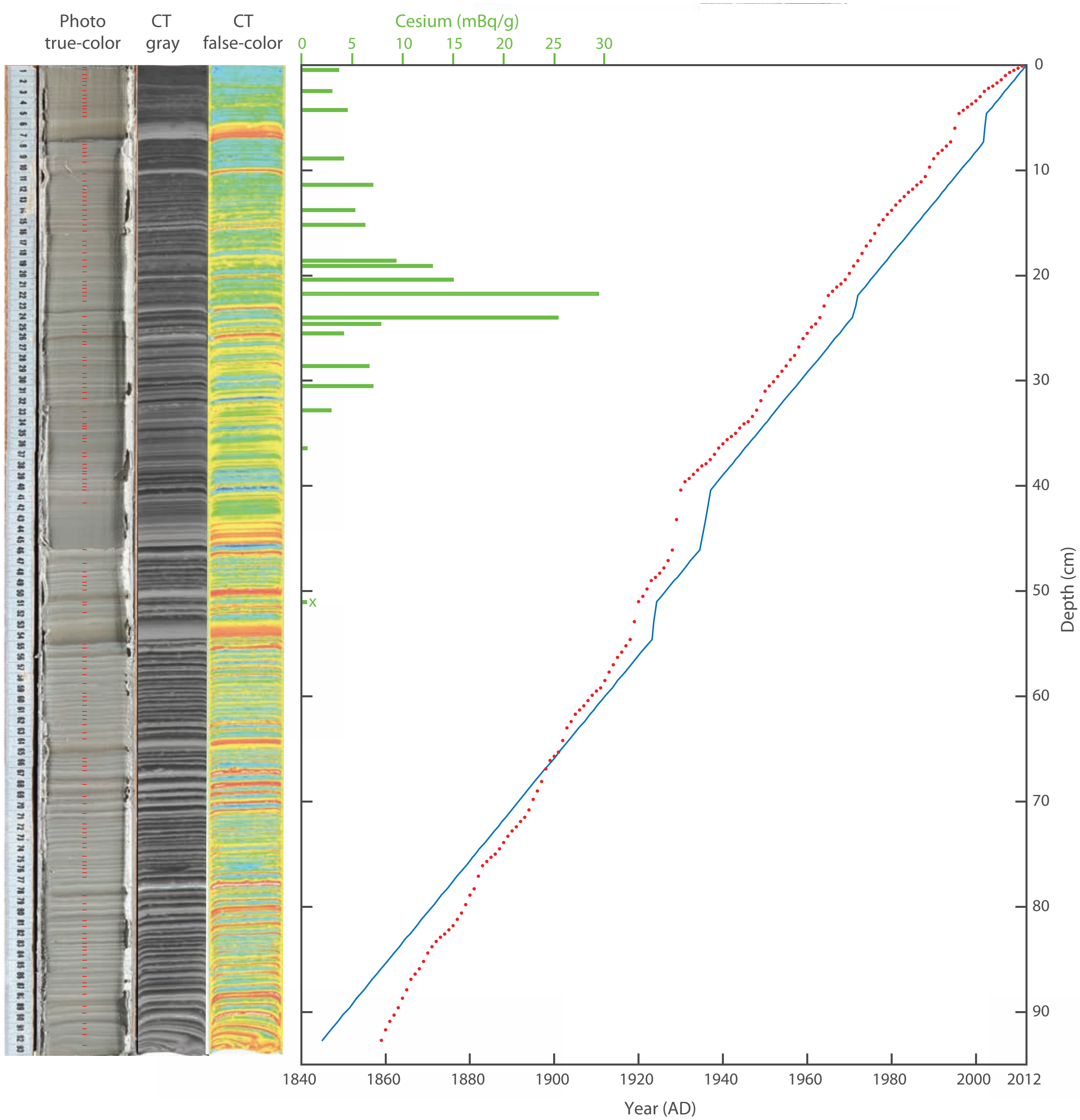

FIG. 3. Age model results for core EK 12-01. At left (L to R), vertical bars show a true-color photo and gray-scale and false-color CT scans of the split core. Boundaries between laminations are marked with faint red lines on the photo. At right, plot shows ^{137}Cs activity (green) and age models based upon varves (red dots) and ^{210}Pb (blue line). ^{137}Cs activity (green bars measured on x-axis at top of plot) includes a short bar at 52 cm depth, marked with an "x," which denotes a measurement with undetectable ^{137}Cs activity. The varve-based age model shows the inferred year of deposition (x-axis at bottom of plot) plotted on the average depth of each lamination. The ^{210}Pb-based age model reflects the estimated average sedimentation rate, with hiatuses (steps in the line) at four discrete high-sedimentation rate events.

We used ^{210}Pb and ^{137}Cs dating to corroborate both our assumption that the laminations are annual varves and our counts of those laminations. The ^{210}Pb CRS model predicted an average sedimentation rate of 0.49 cm/yr (Fig. 4), which when applied to all but the four anomalous layers yields a basal date of AD 1845. The resulting age model (Fig. 3) closely mimics our varve results, deviating only by slightly underpredicting layer ages (compared to the varve model) after about AD 1900, and overpredicting them before that. The ^{137}Cs results also corroborate our assumption that the laminations are annual varves. The highest ^{137}Cs activity was found at 21.5 cm, corresponding on our varve-based age model to AD 1966, and the activity tapered both up and downcore from there (Fig. 3). The two lowest (oldest)

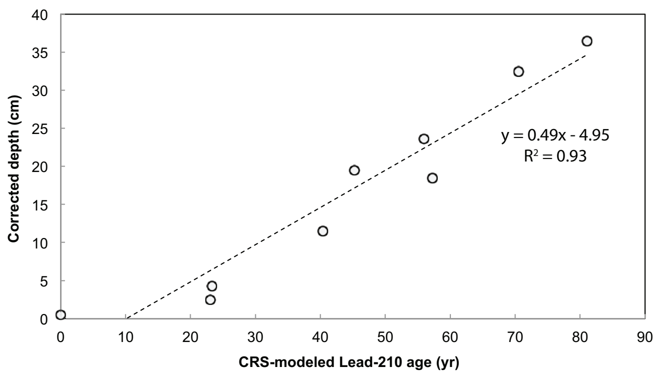

FIG. 4. Results of the ^{210}Pb-based constant rate of supply (CRS) model for individual samples from core EK 12-01, showing the equation and R^2 statistic for a linear trend line fitted to the data (dashed line).

layers sampled, at 36.4 cm (varve year 1939) and 51.0 cm (1920), had ^{137}Cs activities barely distinguishable from zero (+ 0.50 and − 0.37 mBq/g, respectively) in comparison with an average measurement error of 0.63 mBq/g.

Carbon and Nitrogen Content and Isotopic Composition

Throughout the period of record (~ AD 1859 – 2011), the sediments deposited in Eklutna Lake were predominantly clastic, with relatively small quantities of carbon and nitrogen (Fig. 5). Carbon content (by weight) ranges during that period from 0.6% to 1.0%, with an apparent trend towards slightly higher values in the mid-20th century, while nitrogen content ranges from 0.08% to 0.1% (Fig. 5). As with carbon, there is a slight shift over time toward higher values. The apparent increase in carbon and nitrogen was confirmed by a Wilcoxon rank sum test, which rejects the null hypothesis of equal medians before and after the 1929 dam ($p << 0.05$, Fig. 6). Because both C and N increased at approximately the same time, the C/N weight ratio (~8) did not change significantly (Wilcoxon rank sum $p = 0.89$) after installation of the dam.

Neither carbon nor nitrogen isotopic composition shows a clear response to installation of the 1929 dam (Fig. 5). The δ^{13}C values range from −26‰ to −27‰ over the period of record and show a general decline of about 1‰ starting around AD 1960. The change does not appear related to completion of the 1929 dam, and the distributions before and after the dam are not significantly different (Wilcoxon rank sum $p = 0.78$, Fig. 6). δ^{15}N values are generally low (1.5‰ to 2.5‰) and invariant. Over the whole core, the mean δ^{15}N value is 1.9‰, with a standard deviation of 0.2‰. Like δ^{13}C, δ^{15}N values show no obvious trend or change after 1929 (Wilcoxon rank sum $p = 0.13$, Fig. 6).

Nitrogen Isotope Mixing Model and Sensitivity Test

The nitrogen isotope approach to reconstructing salmon abundance is based on the concept of mass balance and assumes that input of nitrogen from salmon can be quantified in terms of lake N budgets and resulting isotopic composition. Thus, insignificant results do not demonstrate the absence of salmon, but raise a question: how large an escapement would be required to become evident in the isotopic results? To answer this question, we developed a simple mixing model based upon properties of Eklutna Lake in order to conduct a sensitivity test. Below, we summarize our approach—one that is simple and flexible enough to facilitate its use by investigators considering isotopic studies of MDN in other settings.

We begin with the assumption that the nitrogen isotope composition found in any lake sediments can be considered a mixture, for our purposes, of nitrogen contributed from two components: the carcasses of anadromous salmon ($\delta^{15}N_{anad}$) and all other (predominantly terrestrial) sources ($\delta^{15}N_{terr}$). If we know the proportions and isotopic signatures of those two components, we can predict the total nitrogen composition of the lake sediments ($\delta^{15}N_{lake}$):

$$\delta^{15}N_{lake} = x(\delta^{15}N_{terr}) + (1-x)(\delta^{15}N_{anad}) \qquad (2)$$

where x and $(1-x)$ are the relative proportions, by mass, of terrestrial and anadromous nitrogen in the Eklutna Lake system.

At Eklutna Lake, $\delta^{15}N_{terr}$ is easily quantified, since we know there have been no anadromous salmon in Eklutna Lake since 1929 (whether or not they were there previously). So we take the mean value of all post-1929 samples (1.94‰) as the lacustrine isotopic signature of all non-anadromous nitrogen sources in the watershed. Isotopic composition of salmon tissue has been quantified elsewhere, with values ranging from 10.72 to 11.38 (Satterfield and Finney, 2002; Barto, 2004; Johnson and Schindler, 2009). We use an intermediate value of 11.15‰ for Eklutna $\delta^{15}N_{anad}$.

Characterizing x requires knowledge of the nitrogen budget of the modern lake. We multiplied the annual lake inflow of 300 million m^3/yr (Municipal Light and Power, 2014) times the nitrogen concentration in the lake water, 0.14 mg nitrate-N per liter of mixed reservoir outflow (Anchorage Water and Wastewater Utility, 2014) to calculate the annual inflow of terrestrial nitrogen: approximately 42 000 kg. For the fish, we assume an average weight of 2.5 kg, the mean weight of sockeye in Alaska, and a mean nitrogen content of 2.47% (Barto, 2004). Annual salmon-N loads can then be calculated for a range of possible escapements, and lake annual total N input (salmon plus inflow) is adjusted accordingly. Note that we have no information about the proportion of dissolved or salmon-derived nitrogen that is deposited in lake sediments (rather than lost in outflow or by other processes), but we rely on the simplifying assumption that the fraction of dissolved terrestrial nitrogen deposited on the lake bottom is the same as the fraction of dissolved salmon-derived nitrogen, and hence we can rely on the total nitrogen loadings to assess proportional contributions to the lake sediments.

The results of our sensitivity test (Fig. 7) show the relationship between predicted lake δ^{15}N and the number of salmon entering the lake as increasing numbers of

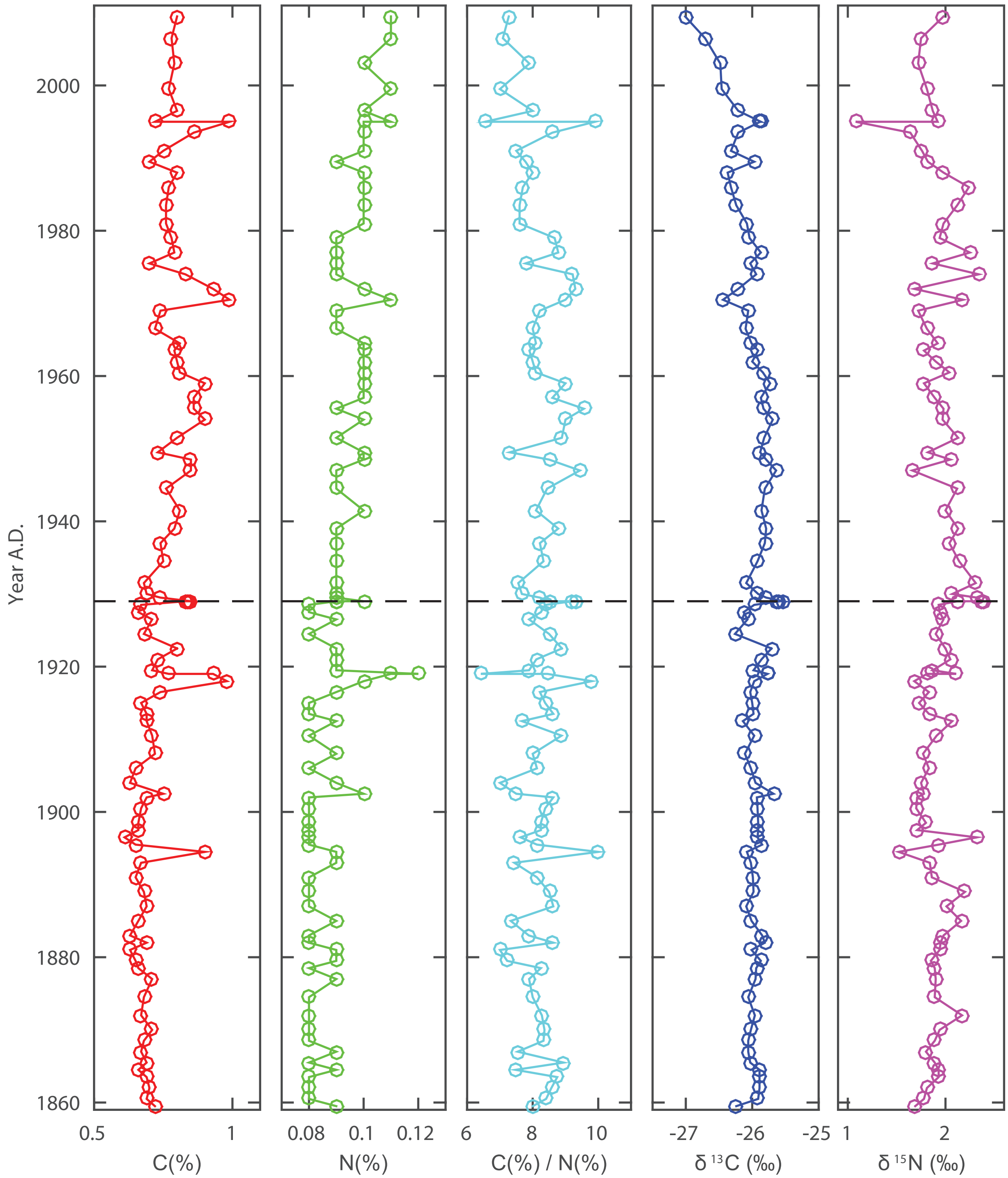

FIG. 5. Geochemical results from core EK 12-01 at Eklutna Lake. Values are plotted against the average year of deposition of each 1 cm^3 sample. The dashed horizontal line emphasizes the date (1929) when the first dam was installed on the Eklutna River.

salmon are added to the baseline condition (no salmon). Our analysis suggests that a modestly sized salmon run into Eklutna Lake could easily fail to noticeably alter the isotopic composition of such a large lake. For escapements below about 15 000 salmon per year, marginal increase of the nitrogen isotopic value of the lake due to MDN would not exceed the ± 0.2‰ analytical precision of the mass spectrometer, which is similar to the natural variability we observed in the post-1929 core (as defined by the variance of the data).

DISCUSSION

The nature of the sediments in Eklutna Lake is well suited to stable isotopic assessment of MDN influence.

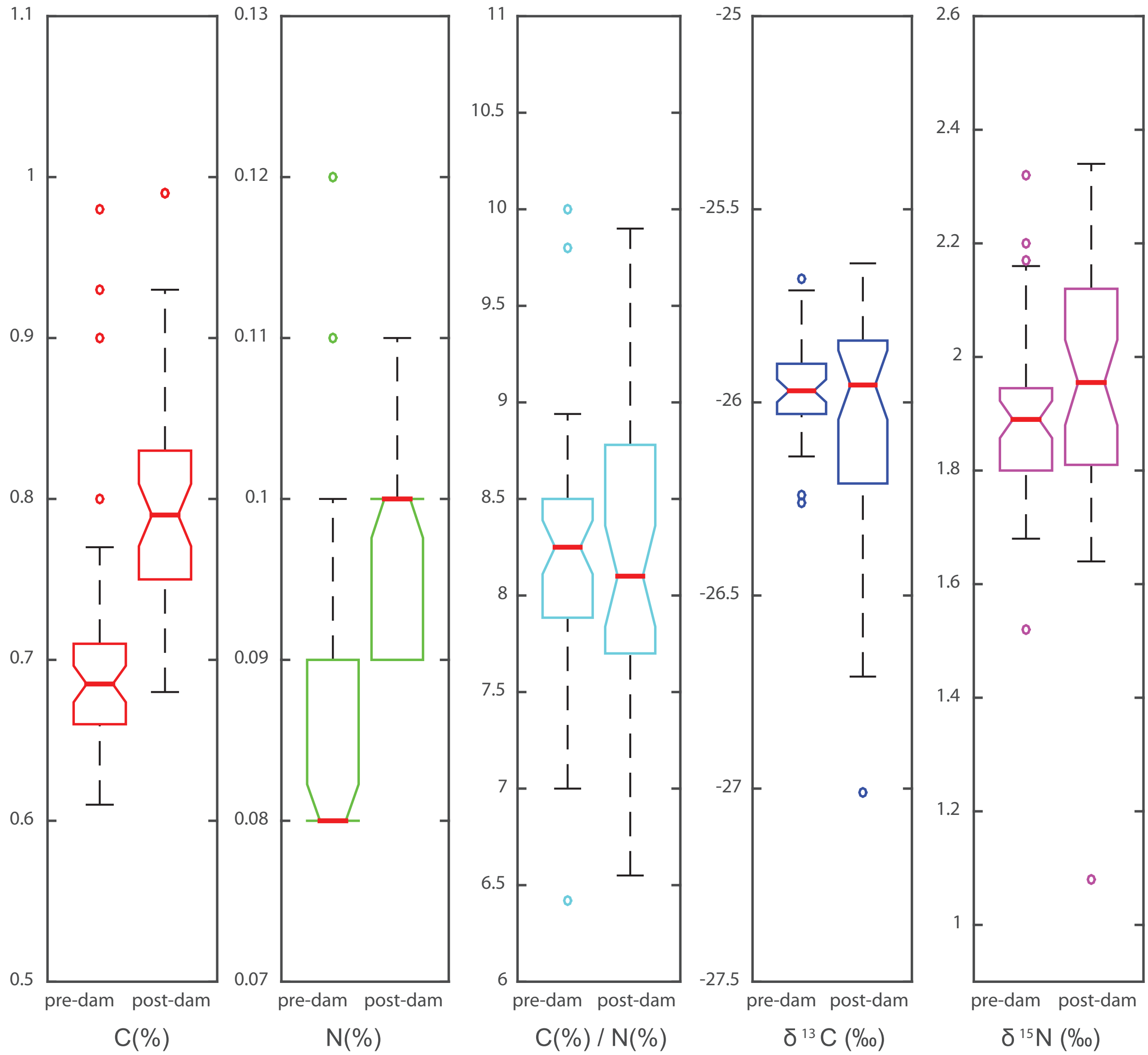

FIG. 6. Comparison of medians and distributions of the geochemical parameters of sediments in core EK 12-01 before and after installation of the first dam on the Eklutna River. Horizontal red lines are medians, and the top and bottom of each box enclose the interquartile range (IQR). The dashed black "whiskers" extend to include all data within 1.5•IQR of the box, and outliers are shown as hollow circles. A Wilcoxon rank sum test suggests that only the first two parameters (%C and %N) changed after 1929.

Though dominated by lithogenic material, the C/N ratio of the sediment is low and indicative of predominantly aquatic sources (Meyers and Ishiwatari, 1993). Conceptually, sediments in which terrestrial organic matter sources are important are not well suited for N-based salmon reconstructions (Holtham et al., 2004; Selbie et al., 2009). The general nature of the sediments, consisting of typical glacial varves, aquatic organic matter, and infrequent gravity-type deposition indicates sedimentation processes that involved vertical particle settling, ideal for reconstructing lake nutrient histories. Though the sediments were low in organic matter, the nitrogen content was such that large sample weights yielded optimal nitrogen signals in the mass spectrometer, and the accuracy and precision of the results are well within normal ranges. Our reliance on one core (among several) for the isotopic sampling was motivated by the clarity of the sedimentary deposits, and hence the chronology, in that single core, and is supported by the low spatial variability of stable nitrogen isotopes within other lake basins (e.g., Brock et al., 2006). Nitrogen from all sources, including salmon carcasses, is well mixed within lake waters during the processes of dissolution and uptake by phytoplankton and is thus likely to be well represented by the single core where we made our measurements.

Our results demonstrate no isotopic evidence for high concentrations of MDN in Eklutna Lake prior to 1929. Changes in $\delta^{15}N$ due to factors other than MDN input can be assessed by reference to profiles in nearby non-salmon lakes (Finney et al., 2000; Holtgrieve et al., 2011) and indicate that such factors have not influenced this conclusion. Downcore changes in %C, C/N, and $\delta^{13}C$ are minor and do not suggest

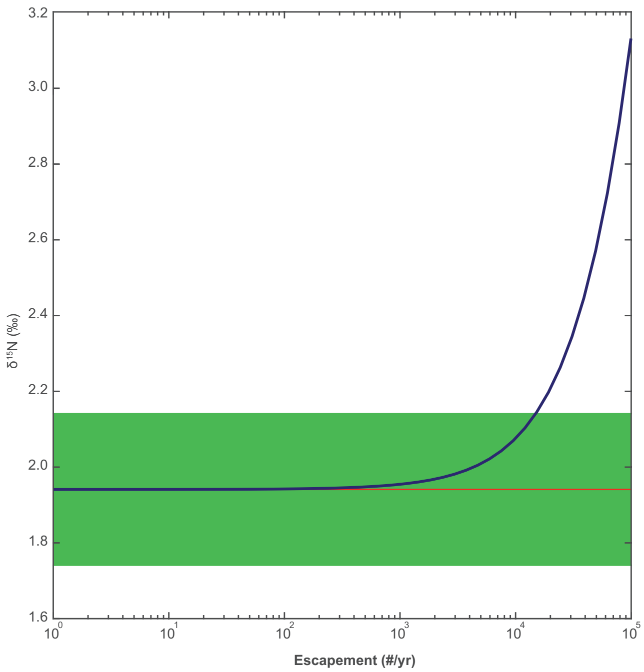

FIG. 7. Results of a sensitivity test predicting the impact of salmon escapement on the nitrogen isotopic composition of the lakebed at Eklutna Lake. The dark blue line shows the isotopic composition expected on the basis of salmon numbers; note that the x-axis is logarithmic. A non-linear relationship between escapement and $\delta^{15}N$ is expected from the mixing relationship (Finney, 1998; Schindler et al., 2005). The red horizontal line represents the average nitrogen isotopic composition of a completely non-anadromous system, where the width of the green bounding box reflects both the instrumental uncertainty and the observed natural variability around that mean.

productivity changes that might result from reduced salmon abundance (Finney et al., 2000).

Limitations of the Sensitivity Analysis

Our simple sensitivity test was based upon several assumptions. We based the per-salmon isotopic contribution on estimates of fish weight, nitrogen content, and isotopic composition that were measured in other lakes and that may not be representative of salmon (if any) that resided in Eklutna Lake before 1929. This fact contributes a small amount of uncertainty to our results. More significantly, we calculated the non-anadromous nitrogen isotopic contribution for the lake from a poorly constrained estimate of modern nitrogen abundance. Water utility measurements of nitrogen content in the lake water have been sporadic, and our use of 0.14 mg/l could be better constrained with additional testing. The sensitivity test is strongly affected by this value, and a lower estimate of modern nitrogen content would increase the calculated sensitivity of our results to historical salmon numbers. The use of the adult salmon $\delta^{15}N$ value as the 100% MDN end member assumes no net fractionation during uptake and sedimentation, an assumption made in previous mixing models (Schindler et al., 2005). Finally, we acknowledge that this model ignores some of the complexity of nitrogen cycling in terrestrial and aquatic systems. However, we contend that even a conservative interpretation of the model results demonstrates the possibility that sockeye salmon could have used Eklutna Lake before 1929 without leaving a detectable isotopic signal.

Qualitative Evidence for a Historic Salmon Run

Though our primary goal was to test for early anadromous salmonid presence in Eklutna Lake using isotopic analysis, evidence from oral tradition of salmon-related human activity at Eklutna, plus ecological evidence that the lake (and river) could support a sockeye run, strengthen interpretation of our results.

Dena'ina people—Athabascan people who have inhabited the Knik Arm drainages of Cook Inlet since prehistoric times—have lived in the Eklutna area for centuries. The modern village of Eklutna, near the mouth of the Eklutna River, was established in 1897, but according to Dena'ina oral traditions, Eklutna is an old village location (Fall et al., 2003). Yarborough (1996) believed there may have been a settlement there earlier, and the Alaska Department of Commerce, Community, and Economic Affairs Community Database Online, a secondary source of unknown provenance, states that the townsite has been inhabited for at least 800 years (CRA, 2015). The presence of a long-term settlement in Eklutna is important because salmon was generally the major food staple of all Dena'ina people living in the Cook Inlet region, including Eklutna (Fall, 1981).

Published accounts based on the oral histories of Eklutna village elders further confirm that Eklutna was a fishing village. According to several elders, Eklutna residents spent summers at fish camps distributed along the shore of Knik Arm from Fire Island to the Knik River, preserving ocean-caught salmon for winter use (Chandonnet, 1997; Kari and Fall, 2003). As the summer progressed, families moved back to the winter villages, which were traditionally "located along productive salmon streams, by the mouths of lakes, or on the high bluffs" above Knik Arm (Fall, 1981:4). Residents fished late runs of coho (*Oncorhynchus kisutch*) and sockeye salmon from nearby rivers (Stephan, 2001; Fall et al., 2003). Eklutna was one of these winter villages (Chandonnet, 1997:30). These accounts support the claims of Eklutna Native Village elders, reported in USACE (2011) and also in an unpublished manuscript assembled by Native Village of Eklutna (NVE) Land and Environment Director Marc Lamoreaux (2016), that all five species of Alaskan native salmon, including sockeye, were once abundant in the Eklutna River. All five salmon species are still found in the lower Eklutna River below the diversion dam, although in lower numbers, especially for sockeye salmon, which are now the least common and stray only occasionally into the river (USACE, 2011).

Additional evidence suggests that salmon were also once present in the upper river, and in the lake itself. Fall (1981) reports that hunting parties who walked into the upper Eklutna River drainage in autumn of each year also fished, then built skin boats to float dried meat and fish back to the village. NVE Chief Lee Stephan says that his father, Leo Stephan, learned from his teachers and elders that before the (lower) Eklutna River dam, salmon went to Eklutna Lake and spawned in the Eklutna River inflow. In the 1970s, Native elders (now deceased) reported to Maria Coleman, NVE Cultural Manager, that there used to be several sheep-hunting cabins around Eklutna Lake, and that these seasonal subsistence camps were provisioned by fish caught from the lake. The campers also hunted moose and picked berries (Lamoreaux, 2016). The Environmental Assessment accompanying the sale of the Eklutna hydroelectric project in the early 1990s concluded that the sale was complicated by "loss of a Sockeye salmon run that once spawned in Eklutna Lake" and that "complete loss of the anadromous salmon run (Sockeye) undoubtedly occurred with the construction of the 1929 dam" (APA, 1992:181, 183). And finally, it is perhaps relevant that kokanee—the "landlocked" variety of sockeye salmon—are found in Eklutna Lake (USACE, 2011) despite being uncommon in Alaska generally (Burgner, 1991). The kokanee could be descendants of the original sockeye run (Ricker, 1940) suggested by evidence above.

Before hydroelectric development, habitat conditions in Eklutna River and the lake presented no obvious obstacles to sockeye use of the upper river and lake. Turbidity in the lake, from its glacial headwaters, has been suggested as a potential limitation on the success of spawning anadromous salmon in the lake (USACE, 2011), but many glacial systems support stable sockeye runs (USACE, 2004). One well-documented example of the use of a glacial river system by sockeye is the Matanuska River, a glacial river much more turbid than the Eklutna (Anderson and Bromaghin, 2009; Tanner and Sethi, 2015). These investigators used telemetry to document extensive use of the Matanuska River by sockeye, though most observed sockeye spawned in clear side-channel habitat, rather than in upstream lakes—a possibility that should be considered in further studies of any pre-1929 sockeye run on the Eklutna River. Importantly, however, authors of the latter study acknowledged that their methods prevented them from documenting spawning in more turbid reaches of the river and provided seven citations of comparable studies that document such direct use of turbid habitats by sockeye (Tanner and Sethi, 2015). The gradient of the Eklutna River, below the lake, provided no evident barrier for the historical migration of sockeye. Between Eklutna Lake and the head of the canyon where the diversion dam is located, a distance of 7.8 km, the river's gradient is 1.40% (Fig. 2). For the 3.6 km through the canyon, the gradient is 1.73% (disregarding the obstacle presented by the diversion dam), and between the canyon and the flats of Knik Arm, the river's gradient is about 1.39%. Those gradients are steep, but there are no known waterfalls, cascades, or other natural barriers to salmon migration along the river. From this brief review, we cannot assess in detail the quality of the migration, spawning, and rearing habitat Eklutna Lake might once have offered sockeye salmon, but it appears that prior to 1929 there were no obvious barriers preventing sockeye salmon from using Eklutna Lake.

CONCLUSIONS

We assessed the age and nitrogen isotopic composition of a core 93 cm long from Eklutna Lake and found that nitrogen composition was not significantly different before and after the construction of a diversion dam in 1929. Our results therefore provide no isotopic evidence for a large sockeye salmon run into Eklutna Lake between 1859 (the oldest date in our core) and 1929. In contrast, both cultural and historical evidence strongly suggest that residents of the Eklutna townsite fished for salmon in the Eklutna River and provide more limited evidence for their presence in the lake. We are aware of no ecological reason why sockeye would not have used the lake prior to hydroelectric development, and we note that kokanee (landlocked sockeye) are present in the lake today. Our sensitivity test may reconcile these apparently contradictory lines of evidence by estimating the impact of hypothetical salmon escapement numbers on the lake's nitrogen budget. This test shows that a modestly sized salmon run into Eklutna Lake could easily fail to shift the isotopic composition of the lake sufficiently to be detected in our data. This result suggests that the isotopic approach to salmon reconstruction is subject to large uncertainties in Eklutna Lake, and that interpretations of isotopic data as evidence of the historical absence of salmon in other lakes (e.g., Child and Moore, 2017) could benefit from a similar sensitivity analysis.

Our laboratory results provide only one piece of evidence regarding the question of historic salmonid presence or absence. Considering analytical uncertainties and natural variability, even a conservative interpretation of our sensitivity test confirms that thousands of salmon per year could have run into Eklutna Lake without being detected, and it is possible that a run as large as 15 000 salmon per year could have escaped notice. Our results do not demonstrate that such runs existed, but neither can our results be construed as evidence that they did not.

ACKNOWLEDGEMENTS

This work would not have been possible without the generosity of our colleagues at the Renard Center of Marine Geology at Ghent University. They procured the cores, shared them and additional data with us, and graciously supported one of us (R. Johnson) in Belgium during the sampling and inspection of the cores. Marc De Batist, Jasper Moernaut, Koen De Rycker, Maarten Van Daele, and Nore Praet, thank you. Thanks also to Sabine Schmidt at the University of Bordeaux for radionuclide dating, to the Mat-Su Basin Salmon Habitat Partnership, and to Marc Lamoreaux from the Native Village of Eklutna for his assistance with procuring documentation of oral histories. This report was produced under U.S. Fish and Wildlife Service Award Number F14AC00048 and benefited from the guidance of Bill Rice, David Wigglesworth, and Meg Purdue. Matching funds were provided by Municipal Light and Power (Anchorage) and Alaska Pacific University. The views and conclusions contained in this document are those of the authors and should not be interpreted as representing the opinions or policies of the U.S. Government or of Municipal Light and Power.

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