

Estimates of a Biologically-Based Spawning Goal and Management Benchmarks for the Canadian-Origin Stikine River Sockeye Salmon Stocks

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The Pacific Salmon Commission is charged with the implementation of the Pacific Salmon Treaty, which was signed by Canada and the United States in 1985. The focus of the agreement are salmon stocks that originate in one country and are subject to interception by the other country. The objectives of the Treaty are to 1) conserve the five species of Pacific salmon to achieve optimum production, and 2) to divide the harvests so each country reaps the benefits of its investment in salmon management.

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TABLE OF CONTENTS

	Page
LIST OF TABLES.....	II
LIST OF FIGURES.....	III
REVIEW PROCESS	1
Working Group.....	1
ABSTRACT	2
BACKGROUND.....	2
Local Knowledge of Tahltan People	2
Local knowledge, harvest patterns, and community uses of salmon in Wrangell, Alaska	4
Clan Use of Stikine River	5
Clan Trade in Area Wildlife Resources	6
Early EuroAmerican Contact.....	6
Early Economy	7
Early Population and Demography	7
Early Prosecution and Management of Salmon Fisheries in the Wrangell Area	8
Present day.....	8
INTRODUCTION.....	9
STUDY SITE	10
OBJECTIVES.....	10
METHODS.....	10
U.S. TERMINAL AREA FISHERIES& STOCK ASSESSMENT DATA.....	10
CANADIAN FISHERIES & STOCK ASSESSMENT DATA.....	11
Age and Otolith Analysis.....	11
Lower River Commercial Fishery	11
Lower River Assessment (Test) Fishery.....	12
Upper River Commercial Fishery	12
First Nation Fishery	12
Excess Salmon to Spawning Requirements (ESSR) and Assessment – Tahltan Lake and Tuya River.....	13
ESCAPEMENT AND ABOVE BORDER RUN	13
Tahltan Lake Spawning Escapement:.....	13
Stikine River Above Border Run and Escapement	13
Mainstem Above Border Run and Escapement	14
DATA ANALYSIS	14
Brood Tables.....	14
Spawner-Recruit Models	14
Basic Ricker Model and Extensions.....	14
Model Fitting	15
Model parameters and priors	15
Diagnostic Tools for Assessing Mixing and Convergence.....	15
Biological Benchmark Estimation for Management	16
Model parameters based on expected mean and expected median recruits	17
MSY Profile (Optimal Yield Profile).....	18
Expected Sustained Yield.....	19
RESULTS.....	19
Fitted Model	19

Diagnostic Tools for Assessing Mixing and Convergence	19
Stock productivity, Capacity, and Yield	20
Tahltan natural stock.....	20
Mainstem stock.....	20
Biological Benchmarks.....	21
Tahltan natural stock.....	21
Mainstem stock.....	21
DISCUSSION.....	22
Considerations for Choosing a Spawning Escapement Goal.....	22
Time-variant alpha model.....	22
Sources of Uncertainty	22
Uncertainties in data	22
CONCLUSIONS	23
Biological Benchmarks.....	23
Tahltan natural stock.....	23
Mainstem stock.....	23
Future Data Requirements and Recommendations.....	23
U.S. Data.....	23
Canadian Data.....	24
ACKNOWLEDGEMENTS.....	24
REFERENCES	24
TABLES	30
FIGURES	38

LIST OF TABLES

Table	Page
Table 1. Estimated escapement and brood year returns of the Tahltan natural stock of Stikine River sockeye salmon by age.....	30
Table 2. Estimated escapement and brood year returns of the mainstem stock of Stikine River sockeye salmon by age.....	32
Table 3. Prior distributions for the model parameters. The different models are the basic Ricker, the first-order autoregressive Ricker model (AR1 Ricker), and the time-variant alpha model (TVA).	33
Table 4. Parameter estimates (posterior medians, posterior means, the 95% credible intervals, the coefficients of variation (CVs)) from the first-order autoregressive Ricker model for the Tahltan natural stock of Stikine River sockeye salmon in brood years 1983–2014.....	34
Table 5. Parameter estimates (posterior medians, posterior means, the 95% credible intervals, the coefficients of variation (CVs)) from the first-order autoregressive Ricker model for the mainstem stock of Stikine River sockeye salmon in brood years 1983–2014.	35
Table 6. Estimates of alpha by year (posterior means, standard deviation, the 95% credible intervals, and the alpha by regime) from the time-variant Ricker model for the Tahltan natural stock and for the mainstem stock of Stikine River sockeye salmon in brood years 1983–2014.....	36
Table 7. The optimal yield probabilities (probability of achieving at least X% of MSY in column two) are the probabilities (column three) that a given level of spawning escapement will produce average yields exceeding 70%, 80%, or 90% of MSY for each stock.	37

LIST OF FIGURES

Figure	Page
Figure 1. U.S. District 106 and 108 fishing area.	38
Figure 2. Stikine River drainage and Canadian fishery areas.	39
Figure 3. Estimates of $\ln(\alpha)$ with 95% credible intervals (shaded regions) based on the time-variant alpha models for the (A) Tahltan natural stock and the (B) mainstem stock of Stikine River sockeye salmon.....	40
Figure 4. (A) Model residuals and (B) natural logarithms of recruits by brood year (1983–2014) from a first-order autoregressive Ricker model for the Tahltan natural stock of Stikine River sockeye salmon.	41
Figure 5. Spawner-recruit relationship (dashed line) with 90% and 95% credible intervals (shaded regions) for (A) the Tahltan natural stock of Stikine River sockeye salmon and (B) the mainstem stock of Stikine Ricker sockeye salmon stock as derived from a first-order autoregressive Ricker model for brood years 1983–2014.	42
Figure 6. Optimal yield profiles (OYPs) for the (A) Tahltan natural stock of Stikine River sockeye salmon stock and the (B) mainstem stock of Stikine Ricker sockeye salmon stock as derived from a first-order autoregressive Ricker model for brood years 1983–2014.	43
Figure 7. Expected sustained yield curve (based on median recruitment) with 90% and 95% Bayesian credible intervals (shaded regions) for the (A) Tahltan natural stock of Stikine River sockeye salmon and the (B) mainstem stock of Stikine Ricker sockeye salmon stock as derived from a first-order autoregressive Ricker model for brood years 1983–2014.	44
Figure 8. (A) Model residuals and (B) natural logarithms of recruits by brood year (1983–2014) from a first-order autoregressive Ricker model for the mainstem stock of Stikine River sockeye salmon.	45

REVIEW PROCESS

WORKING GROUP

In 2020, the Transboundary Technical Committee (TTC) established a bilateral U.S. – Canada Stikine Sockeye Working Group to direct and complete the review of current spawning objectives. Members included Fisheries and Oceans Canada (DFO) staff, Alaska Department of Fish and Game (ADF&G) staff, Tahltan Central Government (TCG) staff, as well as an external consultant. The working group met for the first time in April 2020 and monthly meetings were conducted (at a minimum) throughout the entirety of the project. The purpose of the working group was to gather and share relevant data and supporting documents, develop and conduct bilaterally agreed to analyses, and develop science-based recommendations on spawning objectives for Tahltan Lake and mainstem sockeye salmon stocks. These recommendations will subsequently be presented through the TTC to the Transboundary Panel for consideration and review.

The Stikine River Sockeye Salmon Working Group members were an integral part of the assimilation of historical data and the stock assessment review throughout the escapement goal process. The working group consisted of:

Jody Mackenzie-Grieve – DFO (Co-chair) - Senior Aquatic Science Biologist & TTC member

Julie Bednarski – ADF&G (Co-chair)– Fishery Biologist & TTC member

Dr. Rich Brenner – Former ADF&G – Salmon Stock Assessment Biologist

Andrew Piston – ADF&G – Fishery Biologist

Teresa Wallace – DFO – Aquatic Science Biologist

Dr. Sara Miller – ADF&G – Biometrician

Gottfried Pestal – DFO – Consulting Biometrician

Kerry Carlick – Tahltan Central Government – Fisheries Manager, TTC member, TBR Panel member

Cheri Frocklage – Tahltan Central Government – Fisheries Director & TTC member

Bill Waugh – DFO – Manager, Transboundary Rivers Operations & TTC co-chair

Ed Jones – ADF&G – Fish & Game Coordinator & TTC co-chair

Johnny Sembsmoen – DFO – Senior Resource Management Technician & TTC member

Kristin Courtney – ADF&G – Fishery Biologist & TTC member

ABSTRACT

In 2020, under the directive of the Transboundary Panel of the Pacific Salmon Commission, the Transboundary Technical Committee established a bilateral U.S.–Canada Stikine Sockeye Salmon Working Group (working group) to update the spawning objectives for Stikine River sockeye salmon. Members included Fisheries and Oceans Canada staff, Alaska Department of Fish and Game staff, Tahltan Central Government staff, as well as an external consultant. Through this process, the working group developed and conducted bilaterally-agreed to analyses, and developed science-based recommendations for the range of spawning escapements that would likely result in maximum sustained yields, and identified the appropriate biological benchmarks (management reference points) for management of the Canadian-origin Stikine River sockeye salmon *Oncorhynchus nerka* stocks (Tahltan natural and mainstem). A linearized Ricker spawner-recruit function with an autoregressive lognormal process error with a lag of one year was fit to data from brood years 1983 to 2014. The spawner level that produces maximum sustained yield (S_{MSY}) was estimated at 18,100 spawners for the Tahltan natural stock and at 21,000 spawners for the mainstem stock.

Key words: Tūdeḡe, Stikine River, Dēk’āne, sockeye salmon, *Oncorhynchus nerka*, spawner-recruit, escapement goal, Tahltan stock, mainstem stock, Ricker model

BACKGROUND

LOCAL KNOWLEDGE OF TAHLTAN PEOPLE

The Tūdeḡe (Stikine River) watershed is the center of the traditional territory, Dahlenhe (our land), of the Tahltan people. Historically in the summer, the Tahltan people would gather at permanent villages on Tūdeḡe (Stikine River) and tributaries to harvest Łuwe¹ (salmon), feast, and trade with other tribes. In the fall, they would disperse into small family groups for hunting (Albright 1984; Callison 2002). The area around the Tūdeḡe (Stikine River) and Tahltan River confluence was considered the tribal headquarters; it is where many of the fishing and trading camps were located (Albright 1984). Large quantities of Geḡ (Chinook salmon; *Oncorhynchus tshawytscha*), Dēk’āne (sockeye salmon; *Oncorhynchus nerka*), and Tlūga (coho salmon; *Oncorhynchus kisutch*) were harvested and eaten fresh or dried and stored for later use. Annually, each extended family unit would process roughly 1,600–2,000 Łuwe (salmon) (Albright 1984). The Tahltan population was estimated at 11,000 in the era of precontact. Presently, the Tahltan people gather at various family fishing camp sites in the vicinity of the community of Tlēgōhīn, Telegraph Creek (located on Tūdeḡe (Stikine River)) in the summer to harvest Łuwe (salmon). From 1972–2020, the reported Tahltan First Nation harvest of Dēk’āne (sockeye salmon) on the Tūdeḡe (Stikine River) has ranged from an average of 5,700 to as high as 10,000 Łuwe (salmon). “Modern Tahltan rely heavily on our aboriginal food Łuwe (fish) harvest for food security during the long harsh winter

¹ Łuwe translates to fish. There is no direct translation to salmon. This is the word Tahltan people would use for salmon.

months, just as our ancestors did for centuries before us, and as our children's, children will continue to do.”²

Much of the early 20th Century ethnographic research in Tahltan traditional territories focused on the Tūdeṣe (Stikine River) where the Tahltan peoples were populous and their villages easily reached by steam driven riverboats from Wrangell, Alaska that could sail inland as far as Telegraph Creek (Dawson 1867; Emmons 1911; Teit 1906). More recent studies have shed a broader light on the more extensive land use that includes Tahltan Lake, and varied hunting, trapping, and fishing strategies employed by the Tahltan Nation (Albright 1980, 1982, 1984)

The Dēk'āne (sockeye salmon) run was the most important to the Tahltan, with its major Dēk'āne (sockeye salmon) spawning rounds located at Tahltan Lake. According to past research on fishing villages and stations on the Tūdeṣe (Stikine River) system (Albright 1982), there were three fishing villages on the Tahltan River including Thūludlīn on the north side of the Tahltan River, 20 km above the Tūdeṣe (Stikine River); another location at Tahltan Forks identified by local Tahltans to anthropologist James Teit (1906) in the early 1900s as an unnamed village, and Saloon, situated on the Little Tahltan River below its confluence with Saloon Creek. In the past, there were four or more major Dēk'āne (sockeye salmon) runs from mid-June through August that moved up the Tahltan River to spawn at Tahltan Lake, arriving from seven to ten days apart (Albright 1982:75). Ethnographic research (Thorman n.d.; Albright 1984) indicates that the Tichaanoteen, a clan from the Raven kinship group who once harvested their resources in the Tahltan Valley, were driven from their lands due to a fishing dispute at the mouth of the Tahltan River by the neighbouring Talagoteen, a clan from the Wolf kinship group. The Tichaanoteen moved their central village to a new location at Ghūne (bubbling up water) on the northwest shores of Tahltan Lake, the spawning grounds of the Dēk'āne (sockeye salmon).

Being close to the mountains, Ghūne was also well supplied with mountain goats, marmots, and beavers. After several years of hardship due to the failed Łuwe (salmon) runs not reaching the lake, people moved westward and established another village on the Chutine River which provided easier access to the resources of the Tūdeṣe (Stikine River) (Albright 1984; French 1980; Millennia Research 1998; Thorman n.d.). Subsurface cache pits, or duwe'ged (a safe place hidden), used to store Łuwe (salmon) and other perishable game are numerous in Tahltan territory and are evidence of occupation and land use extending back for centuries. Cache pits are common features on the banks of the Tūdeṣe (Stikine River) and the Tahltan River all the way to Tahltan Lake. During a recent postfire archaeological survey from Glenora to the Tuya River (Gray et al 2019), a duwe'ged site (IaTr-3) along the east bank of the Tahltan River yielded radiocarbon dates as old as 7,440-10,500 BP. One hundred and forty-seven cache pits were recorded during this brief field study. According to Tahltan social customs, the duwe'ged were tended by caretakers that included the older women of the village, accompanied by their juvenile daughters and great granddaughters. Dried and compressed bundles of 15–20 Łuwe (salmon) were wrapped with willow bark and small tied root strands, “resembling bundles of shingles.” Once stored and sealed, a duwe'ged was not opened until the winter months, when Łuwe (salmon) bundles were distributed under a village clan system. According to the ethnographic notes of Reverend Thorman, an early 20th Century missionary who pastored at St. Mary's Mission at Tahltan village in the early 1900s, there were

² As written by the Tahltan Central Government

more than 1,500 of these storage pits from Chich'an Ahda, a major fishing station and duwe'ged location on the Tūdeṣe (Stikine River), eight miles downriver from Tahltan village, and upriver as far as the Tuya River. There were an equal number of duwe'ged from the Tūdeṣe (Stikine River) and Tahltan River confluence up to Tahltan Lake. As Thorman observed, "The salmon run in the Tahltan River was abundant beyond belief" (Thorman n.d.). The extensive use of the Tahltan River and Tahltan Lake in the past is underscored by an archaeological record that expands with each new field season.

The presence of obsidian at Tahltan Lake archaeological sites reflects the common resource use and omnipresence at these locations throughout Tahltan traditional territories. The sources of this obsidian are quarry sites at one or more of ten different obsidian flows from within the Mount Edziza and Spectrum Range Volcanic Complex. This Complex is home to some of the largest known obsidian outcrops in Canada and is less than 65 km southwest of Tahltan Lake. During the 2019 fireguard survey from Glenora to the Tuya River, and approximately 30 km south of Tahltan Lake, 96% of the assemblages from 41 recorded archaeological sites included obsidian. This raw material was considered a valuable trade commodity that was transported along major river systems over long distances. The Mount Edziza and Spectrum Range Volcanic Complex is the source some of the earliest known archaeological sites in the Pacific Northwest, including On-Your-Knees Cave on Prince of Wales Island, Ground Hog Bay along the southern Alaskan coast, and the Namu village site on the Northwest Coast of British Columbia. Mount Edziza obsidian has also been found as far east as western Alberta (Ackerman et al. 1979; Carlson 1994; Fladmark 1984; Gray et al. 2019; Reimer 2015).

LOCAL KNOWLEDGE, HARVEST PATTERNS, AND COMMUNITY USES OF SALMON IN WRANGELL, ALASKA³

Wrangell was located in the heart of the territory claimed by the *Shtax'héen* Kwáan Tlingits, a powerful and warlike tribe with a reputation for ferocity. Swanton, an early scholar, considered the *Shtax'héen Kwáan* the most populous and most important group in southern Alaska (Swanton 1908:411). "The first chief *Ceks* (commonly spelled 'Shakes') is credited with uniting the people to protect them from aggression by neighboring groups" (Campbell 1982:23). "Probably more than any other tribe [the Stikine Tlingit] were a riverine people and their settlements and summer camps extended upriver as far as Telegraph Creek or a little beyond" (Olson 1967:3).

Five clans of the Eagle/Wolf moiety, *Naanyaa.aayí*, *Sik'nax.ádi*, *Xook'eidí*, *Kayaashkiditaan*, and *Xilkweidí*, and 5 of the Raven moiety, *Kiks.ádi*, *Teeyhittaaan*, *Kaach.ádi*, *Kaasx'agweidí*, and *Taalkweidí*; were represented among the Stikine Tlingit (Goldschmidt and Haas 1998:14). The origins of these several clans are complex. The *Naanyaa.aayí*, Wolf/Eagle moiety, were thought to be of Athabascan origin. According to oral history related by key respondents, the *Naanyaa.aayí* came down the Stikine River to the coast in ancient times, when resources in the interior became scarce, by floating down the river through a hole under a glacier. An elderly couple volunteered to

³ ©Alaska Department of Fish and Game. Used with permission. Any errors or deficiencies in reproduction, subsequent analysis, or interpretation; and any statements, findings, conclusions, and recommendations herein do not necessarily reflect the views of ADF&G. The text included in the section titled *Local Knowledge, Harvest Patterns, and Community Uses of Salmon in Wrangell, Alaska*, is quoted directly from the following citation:

Paige, A.W., S. Churchill, N. Ratner, M. Turek, and P. Coiley-Kenner. 2009. Local knowledge, harvest patterns, and community use of salmon in Wrangell, Alaska. Alaska Department of Fish and Game, Division of Subsistence Technical Paper No. 323, Juneau. <https://www.adfg.alaska.gov/techpap/TP%20323.pdf>.

take the dangerous and uncertain trip through what appeared to be a passageway under a glacier in an attempt to explore the possibility of finding a territory richer in resources. After weeks had passed, it was assumed they had perished, but when those left behind climbed to a high overlook, the couple was seen in the distance, safe, on the other side of the glacier. The rest of the people followed to the place now referred to as “Old Village” or “Old Town”, south of Wrangell.

Other histories described the *Naanyaa.aayí* as one of the *Sik'nax.ádi* Tlingit clans that traveled down the Taku River from the interior to the coast. The *Sik'nax.ádi* settled at the mouth of the Taku River, while the *Naanyaa.aayí* went south to Wrangell. According to the testimony collected in 1946 by Goldschmidt and Haas (1998:74), the *Naanyaa.aayí* clan claimed aboriginal use and ownership of the upper reaches of Stikine River from above Shakes Place to beyond Telegraph Creek.

The *Kiks.ádi*, Raven moiety, moved to the area from the south, near the border with the Tsimshian people. According to some accounts, the *Kiks.ádi* were the first to arrive at the Stikine coast. They explored the Stikine River and settled at several locations on the mainland shores of the Eastern Passage. Other clans migrated to the area, including the Wolf/Eagle *Xook'eidi* clan, and the Raven *Kaach.ádi*, *Teeyhittaán*, *Taalkweidí*, and *Kaasx'agweidí* clans (Goldschmidt and Haas 1998).

Clan Use of Stikine River

The mouth of the Stikine River, its tidal flats and islands, and the mainstem and subsidiary channels upstream of the Canadian border to Shakes Place were used by several Wrangell clans. The lands and waters claimed by the *Shtax'héen Kwáan* were more extensive than that of any Tlingit tribe, and included many rich salmon streams and lakes. Their territory stretched from Cape Fanshaw on Frederick Sound in the north, the east side of Kupreanof Island, including Portage and Totem bays, Duncan Canal, and Mitkof Island, and across Sumner Strait to Red Bay on the north coast of Prince of Wales Island, south along the coast of Prince of Wales Island to Thorne Bay, across Clarence Strait to Union Bay on the Cleveland Peninsula, and east up Ernest Sound to Bradfield Canal. Their territory also included Etolin and Zarembo islands, and extended up the Stikine River into Tahltan Athabaskan territory, to present day Telegraph Creek in British Columbia (Goldschmidt and Haas 1998:73).

Within this territory, the several clans claimed exclusive ownership of some hunting and fishing areas, and shared ownership and uses in other areas. Like their fellow Tlingits at the mouths of the Taku and Chilkat Rivers, their position at the mouth of the Stikine River allowed the *Shtax'héen Kwáan* to monopolize the trade route to the interior, trading with the Tahltan Athabaskan, and Russian and Hudson Bay Company fur traders (Cohen 1989:13).

Tlingit and Tahltan territorial rights overlapped in the upper reaches of the river:

Here for a distance of some 15 miles, from just below Glenora to Telegraph Creek, the Tlingit claimed exclusive fishing rights on all the tributaries along the northern shore, as well as ownership of the adjacent berry patches, but not the hunting rights in the area, nor fishing rights on the Stikine itself. (Emmons 1991:7)

These interior areas offered the drier and sunnier climate needed for drying salmon, as well as abundant berries, which were not available on the coast.

According to testimony collected by Goldschmidt and Haas (1998), the *Kaach.ádi* clan claimed the uppermost reaches of the Stikine River below Telegraph Creek. The *Kiks.ádi* claimed

Wrangell Island itself as well as the south end of Etolin Island. Several clans claimed ownership of portions of Etolin Island, including the *Xook'eidí*, the *Kaach.ádi* and the *Teeyhittaán*. Also, within the Wrangell territory, the *Kaach.ádi*, *Taalkweidí*, the *Kaasx'agweidí* clans claimed portions of eastern Kupreanof Island, and the *Taalkweidí* claimed Mitkof Island and the mainland area as far north as Farragut Bay on the mainland (Goldschmidt and Haas 1998).

Clan Trade in Area Wildlife Resources

The most prominent Tlingit groups traditionally had rights to at least 1 sockeye salmon stream. Productive sockeye salmon streams were most often claimed by a clan house, with summer camps and smokehouses established near the mouths of such streams (Emmons 1991). For Tlingits, ownership and control of resources implied rights, privileges, and prestige, as well as responsibilities. In the Stikine territory, this involved control of Stikine River traffic and trade. Several Wrangell clans shared the mainstem of the river, but certain sites, especially confluence areas, were claimed by different clans who controlled use of the resources at those locales (Goldschmidt and Haas 1998). A U.S. government report on the area describes the trade relationship between the Wrangell Tlingit and the Tahltan Indians:

These fish they clean and dry in large quantities both for their own use and for trading with the Indians in the interior for furs, bear and deer meat. A regular trade is thus kept up by them with the interior tribes, and they are exceedingly jealous of any outside interference with it. Much of their antipathy to White people going up their rivers arises from this cause; the coast Indians fearing that the White will steal away their trade. (Scott 1953:81)

In the late 1940s, a researcher working in Wrangell noted a respondent's description of the early Wrangell Tlingit's control of Stikine River trade and traffic, control which excluded the Russians, the British, and the Americans:

No, only the natives. They would get things like clams, ulakan [candlefish] grease, dried seaweed, herring eggs — they used to like those — dried salmon, kelp, and all the things from the sea. They'd go up to Tahltan and get skins like bear, marten and lynx. [*Did the Tahltan people ever bring the furs down here or did the Wrangell group always go up there?*] The Wrangell people always went up there because they [Tahltan] didn't have any canoes. (Scott 1953:81)

By the 19th century, the Stikine people had established their principal settlement at Kotzlitzna, or "Old Town." Here, they continued to monopolize and control the trade with the interior Tahltan Athabaskan Indians, exchanging coastal marine products such as eulachon oil and sea mammal products for interior products such as moose and caribou hides (Oberg 1973:106).

Early EuroAmerican Contact

The Stikine Indians had "probably the longest and most continuous [contact with EuroAmericans] of any except the Sitka tribe" (Goldschmidt and Haas 1998:73). In 1833, during the Russian occupation of what is now Southeast Alaska, the Russian–American Company established a garrison at Wrangell, which they called Redoubt St. Dionysius, to protect the fur trade with the Stikine Tlingits. The garrison attracted people from Kotzlitzna and other settlements, and continued to serve as a gateway to the rich fishing grounds and trade routes of the Stikine River, as well as the waters of Frederick and Ernest sounds, and Sumner and Zimovia straits. The

Russian garrison was transferred to the Hudson Bay Company as part of the terms of an 1840 treaty between Russia and Britain. The 1840 treaty also transferred control of the Stikine trade and changed the name of the garrison to Fort Stikine. Before Alaska was purchased by the United States, the garrison became known as Fort Wrangell, and then Wrangell. The community attracted settlers from camps and settlements across the territory of the Stikine Tlingit, as well as EuroAmerican gold seekers, fur trappers, and traders.

The arrival of EuroAmericans in Wrangell and the economic opportunities offered in town played a large role in altering the Native population and its social and cultural life. The establishment of salmon processors at Wrangell quickly altered the traditional Tlingit stream ownership patterns and the networks that controlled harvest practices. Key respondents reported that ever since contact with EuroAmericans, Tlingits have continually lost ownership and control of salmon streams.

Early Economy

Beginning in late 1870s, Christian missionaries arrived and settled in the community. In 1877, Presbyterian and Catholic missionaries established churches and schools in Wrangell. The gold rushes of the Stikine, Cassiar, and Klondike in the late 1800s brought successive waves of prospectors and surveyors. The local economy benefited from the mining industry, especially in the form of transportation services, with steamboats carrying passengers up the Stikine River as far as Telegraph Creek. By the late 1800's, the salmon canning industry brought more people to the region, and Wrangell became the location of several fish processing companies. Salmon canneries and salteries required lumber for construction and shipping crates, resulting in construction of a sawmill in 1888 (Cohen 1989:14).

Commercial riverboat service on the Stikine River as far upriver as Glenora provided access to the interior. The riverboat service continued, at a reduced level, through the 1960s, and ended in 1969. The Tongass National Forest was established in 1907, leading to the growth of the logging and timber processing industries. Prospecting, mining and trapping also contributed to the economic life of the community in those decades. During World War II, the Stikine River was used by the military to transport men and equipment used to build part of the Northwest Staging Route.

Early Population and Demography

In 1839, Wrangell District population studies recorded indigenous settlements at Etolin Island and Stikine Village, as well as at other unnamed locations. The study recorded an estimated total population of 1,510, of which only 20 were reported as non-Native (Veniaminov 1984:382). By 1880, the indigenous population in the nearby settlements had dropped to 317 (De Laguna 1990:205), while the population of the town of Wrangell had risen to 106. In the next decade, the population of the Native settlements experienced a sharp drop: by 1890, only 73 people were enumerated there, while the population of the town of Wrangell rose to 316 (see Boyd 1990:144 for discussion of epidemics among Tlingit). In the 10 years between the 1890 and 1900 censuses, the non-Native population of Wrangell increased from 71 to 434 (Rogers 1960).

The Tlingit population also rose, but more modestly, from 243 to 364. The district's population rose to 868 in 1900, with only 21 enumerated in "other" places in the Wrangell District. The City of Wrangell was incorporated in 1903. The population outside the town of Wrangell was low

through the 1930s, while that of the town grew as Native people relocated there. In 1932, the Wrangell Institute, a U.S. Bureau of Indian Affairs school for Alaska Native children, opened 5 miles south of town, and was a major contributor to the increase to 207 of the population outside of town. The Wrangell Institute operated from 1932 to 1975. By 1939, 34% of Wrangell's population was Alaska Native. By 1950, the town population was 1,263, and the population outside Wrangell was 405. Wrangell continued to grow steadily throughout this period, reaching 1,275 by 1958 (Rogers 1960).

Early Prosecution and Management of Salmon Fisheries in the Wrangell Area

In 1889, Congress adopted the Alaska Salmon Fisheries Act, which prohibited the “erection of dams, barricades and other obstructions,” including Natives’ uses of traditional traps and weirs (Arnold 1997:115). The Act was amended in 1896 to prohibit commercial fishing above tidewater in streams fewer than 500 ft in width. The 1924 White Act prohibited stationary fish weirs and traps in tidal river mouths. Salmon fishing for personal consumption gradually became subordinate to participation in the commercial salmon fisheries after the establishment of the canneries at Wrangell and other nearby locations (Arnold 2008:74). Fish and shellfish for subsistence uses could be retained from commercial catches for home use. There was no distinction between “commercial” and “personal use” and “subsistence” fishing in the management of the salmon fisheries (Bosworth 1991:27).

Since no regulations specifically allowed for “subsistence” fishing, many Wrangell residents believed that there were no openings allowing net fishing for home use. Arnold (1997) described the pressures on Tlingit people to assimilate during the first decades of the 20th century, and analyzed their adaptations to the new economic realities:

Commercial-minded and more conservative Tlingits renegotiated their cultural identities by asserting their power as producers, workers, and subsistence harvesters. If this process sometimes departed from “traditional” Tlingit culture, it by no means entailed the erasure of cultural traditions or the reinvention of “Tlingit identity.” (Arnold 1997:137–138)

In Wrangell, local people worked through the Alaska Native Brotherhood and the unions to promote their economic rights.⁴

After statehood, bag and size limits and gear restrictions were implemented in personal use salmon fisheries at some Southeast streams, and on recreational marine fisheries targeting Chinook salmon. In 1960, the personal use fishery was changed to a subsistence fishery, and the permit system was initiated as a management tool (Bosworth 1991:34).

The information presented under the heading Local knowledge, harvest patterns, and community uses of salmon in Wrangell, Alaska is only portion of the report by Paige et al. (2009). The complete report can be found at <https://www.adfg.alaska.gov/techpap/TP%20323.pdf>.

PRESENT DAY

In addition to Tahltan First Nations harvest, Stikine River sockeye salmon returning to spawn in British Columbia, Canada are also harvested in commercial fisheries in marine waters of Southeast Alaska (Figure 1) and in U.S. subsistence and Canadian commercial fisheries in the Stikine River.

⁴ See Scott (1953) for further discussion of the social and economic processes of assimilation in 1940s Wrangell.

During the period 1985–2020, the annual average harvest of Stikine River sockeye salmon in commercial fisheries was 84,800 fish, of which 48,400 fish were harvested in the U.S. District 106 and 108 fisheries, 35,600 fish were harvested in the Canadian lower river commercial fishery, and 800 fish were harvested in the Canadian Upper River commercial fishery (TTC 2022). The average (2004–2020) harvest of Stikine River fish in the U.S. subsistence fishery was 1,200 fish (TTC 2022). Also, Stikine River sockeye salmon have been sacrificed for otolith recoveries, and have been harvested in various assessment fisheries.

Stikine River sockeye salmon are managed jointly by Canada and the U.S. under provisions of Chapter 1, Annex IV of the Pacific Salmon Treaty (PST). Stikine River sockeye salmon have been subdivided into four stock groups for research, management, and monitoring purposes: 1) the wild Tahltan stock, which are those fish originating from naturally spawning sockeye salmon in Tahltan Lake; 2) the enhanced Tahltan stock, which are those fish originating from broodstock collected at Tahltan Lake and subsequently back-planted as fry into Tahltan Lake; 3) the Tuya stock, which are those fish originating from broodstock collected at Tahltan Lake and subsequently planted as fry into Tuya Lake; and 4) the mainstem stock, which are all other natural sockeye salmon populations in the Stikine River. For management purposes, collective wild and enhanced Tahltan Lake stocks are referred to as “total Tahltan stock”, or sometimes, just “Tahltan stock”.

Enhancement of the Tahltan Lake sockeye salmon stock commenced with an initial egg take in 1989 under a PST joint Canada/U.S. enhancement program, with the first fry back-planted into Tahltan Lake in 1990 (TTC 2022). Broodstock collection from Tahltan Lake for subsequent planting into Tuya Lake occurred from 1991 to 1999 and from 2002 to 2013 (TTC 2022). Fry plants to Tuya Lake were discontinued after 2013 and consequently 2018 is the last year with Tuya returns (TTC 2022). Although not explicitly considered in the escapement goal review, Tuya-origin sockeye salmon are introduced here as they were harvested by Stikine River fisheries but removed from Tahltan-origin harvest totals.

INTRODUCTION

The original escapement goals, established in 1987 by the Transboundary Technical Committee (TTC), for the Stikine River Tahltan and the mainstem sockeye salmon stocks were largely based on professional judgment regarding stock productivity, the ability of existing systems to manage to them, precision and accuracy of estimates of stock assessment abundance estimates, and the degree of risk considered acceptable (TTC 1987; TTC 1993). The original 1987 Tahltan stock escapement goal range was 20,000 to 40,000 sockeye salmon with a management objective of 30,000 fish (unpublished Wood et al. 1993 report⁵). This escapement goal was revised in 1993, using additional data that was collected as part of the study to evaluate the enhancement program. The revised (and currently accepted) Tahltan stock escapement goal range is 18,000 to 30,000 sockeye salmon with a management objective of 24,000 fish. It accounts for 20,000 naturally spawning fish and up to 4,000 fish needed for broodstock to meet the objectives of the Canada/U.S. Stikine River enhancement program (TTC 1993; unpublished Wood et al. 1993 report⁵). The original 1987 mainstem escapement goal range was 20,000 to 40,000 with a management objective

⁵ Wood, C. C., R. B. Morely, M. R. S. Johannes, R. A. C. Johnston, and P. Etherton. 1993. Review of spawning escapement target for Tahltan Lake sockeye salmon. Department of Fisheries and Oceans Canada, Pacific Stock Assessment Review Committee Working Paper, S93-1. *Not citable.*

of 30,000 fish (TTC 1987; unpublished Wood and Johnston 1990 report⁶). This goal has remained in place as the current escapement goal and management objective for the mainstem stock.

STUDY SITE

The Tūdeṣe (Stikine River) is the largest of the transboundary rivers which flows from northern British Columbia Canada through Southeast Alaska to the Pacific Ocean. The river drains an area of approximately 52,000 km²; the majority of the drainage is located within Canada (Figure 2). The headwaters of the Tūdeṣe (Stikine River) are in the Stikine Plateau and Skeena and Cassiar Mountain Ranges; the river flows in a southwesterly direction for approximately 640 km, discharging into the ocean about 20 km north of Wrangell, Alaska (Figure 1; Figure 2).

The Tūdeṣe (Stikine River) produces one of the largest runs of sockeye salmon in northern British Columbia and Southeast Alaska. Sockeye salmon only spawn in a small part of the drainage because of numerous hydraulic velocity barriers, such as the Grand Canyon of the Tūdeṣe (Stikine River), located upstream of Telegraph Creek and the Forrest Kerr Canyon located on the largest tributary of the Tūdeṣe (Stikine River) the Iskut River.

OBJECTIVES

On 18 February 2020, pursuant to Chapter 1 (1)(a) and consistent with the recommendations of the Transboundary Panel Strategic Plan (TTC 2019), the Transboundary Panel directed the Transboundary Technical Committee (TTC) to complete a review of current spawning objectives for Tahltan Lake and Stikine River mainstem sockeye salmon stocks such that:

- The Parties develop a joint technical report to be submitted through the Parties' respective review mechanisms with the intention of establishing revised bilaterally approved maximum sustainable yield (S_{MSY}) spawning objectives for Tahltan Lake and Stikine River mainstem sockeye salmon;
- The spawning objectives for Tahltan Lake and Stikine mainstem sockeye salmon will be MSY-based ranges;
- The recommended spawning objectives are available for review by the Transboundary Panel prior to December 2022 and recommended to the Parties by the 2023 fishing season.

METHODS

U.S. TERMINAL AREA FISHERIES & STOCK ASSESSMENT DATA

The mixed-stock U.S. commercial drift gillnet District 106 and District 108 fisheries has been sampled weekly for stock assessment data, since 1983. The mixed stock analysis was based on scale pattern analysis from 1983 to 2011 (Marshall et al. 1984, Oliver and Walls 1985, and Wilcock et al. 2011). The results were used to estimate final contributions of All Tahltan, enhanced Tahltan, enhanced Tuya, and mainstem sockeye salmon stocks to the weekly harvests in District 108 and Subdistricts 106-41/42 and 106-30. The wild Tahltan was the difference between All Tahltan and enhanced Tahltan, which sometimes resulted in negative values due to the assumptions of the age

⁶ Wood, C. C., and R. A. C. Johnston. 1990. Stock Status of Stikine Sockeye. Pacific Stock Assessment Review Committee Working Paper S90-7. *Not citable*.

composition data. Since 2012, stock composition of harvest has been estimated as weekly contributions of wild and enhanced sockeye salmon stocks in the District 106 and District 108 drift gillnet fisheries using paired otolith, scale, and genetic samples. This postseason analysis is a mark-and-age-enhanced genetic mixed-stock analysis (MAGMA) model, which is an extension of the Pella-Masuda GSI model (Pella and Masuda 2001) that incorporates paired otolith mark and scale-age data into the genetic stock composition analysis. The MAGMA results were used to estimate final contributions of each stock to the weekly harvests in each fishery. Additionally, the MAGMA analysis provided seasonal estimates of age-specific stock composition for all major contributing age classes (>5%) used in brood tables. Age-specific stock composition estimates are only provided at the annual level because weekly sample sizes are not sufficient to meet precision standards.

The inriver subsistence fishery for sockeye salmon was established in 2004 and the annual harvest through 2020 averaged 1,200 fish. Individual stocks and ages are determined using the proportions from the inriver run analysis. From the late 1980s to mid-1990s, the U.S. conducted commercial test fisheries in the mixed-stock U.S. District 106 and District 108 fisheries; all fisheries combined annual harvest was 1,000 fish (TTC 2022). Scale pattern analysis was used to determine stock composition.

CANADIAN FISHERIES & STOCK ASSESSMENT DATA

Age and Otolith Analysis

Scale samples were analyzed by Fisheries and Oceans Canada (DFO) Sclerochronology Lab (Pacific Biological Station, Nanaimo, British Columbia) and otoliths were analyzed by Alaska Department of Fish and Game (ADF&G) Mark, Tag, Age Lab (Juneau, Alaska) or DFO Whitehorse lab (Whitehorse, Yukon Territory). Age composition of the Tahltan Lake escapement was derived by expanding the age composition of samples to weir counts or stock specific harvest within each statistical week, summing the expanded age composition of the counts across statistical weeks, and recalculating the annual weighted proportional age composition (Pestal et al. 2024). In the lower river fisheries samples, since egg diameter was used to assign unmarked fish to either wild or mainstem stocks, only females were used in the analyses, and age composition were expanded as such (Pestal et al. 2024).

Lower River Commercial Fishery

The Canadian lower river commercial fishery has been operating since 1979, with the exception of 1984 when there was no commercial fishery as a result of low anticipated returns. The fishing area includes the portion of the Stikine River, from the U.S./Canadian international border (border) upstream to the boundary signs located approximately 2 km above the Stikine River confluence with the Flood River, and the portion of the Iskut River from its confluence with the Stikine River to fishing boundary signs located approximately 10 km upstream, excluding any other tributaries of the Stikine or Iskut Rivers. All harvest in the commercial fishery is by set or drift gillnet.

Harvest and stock assessment data are collected and analyzed by statistical week. To estimate stock composition, only samples originating from below the confluence of the Iskut River with the Stikine River are used. A portion of the commercial harvest is sampled for matched age (scales), sex, length (ASL data; fork length (i.e., length of fish from tip of snout to fork of tail; Shaw 1994)), egg diameter, and otolith samples. Historically, harvest sampling was biased towards females (i.e.,

150 females and 50 males per statistical week), but in recent years, harvest sampling has been random (Pestal et al. 2024). Egg diameter is used to assign stock of origin (i.e., Tahltan or mainstem; Craig 1985; TTC 2022) and specific thermal marks on otoliths are used to apportion wild and enhanced fish and confirm origin and brood year. Average lower river commercial harvest is 33,200 sockeye salmon (1979–2020; range 6,100 to 95,800 fish) (TTC 2022).

Lower River Assessment (Test) Fishery

The lower river assessment (test) fishery has been operating upstream of the border and below the confluence of the Stikine and Iskut Rivers (Figure 2) near a location known as Boundary House. From 1985 to 2020 (excluding 2019 when no assessment fishery occurred due to low anticipated returns), the assessment fishery operated as a lethal fishery. The assessment fishery followed standardized protocols (similar gear, location, effort; Pestal et al. 2024) to gather information during the sockeye salmon migration period. It supplemented information collected in lower river commercial fisheries, but did not overlap with it. The entire assessment fishery harvest has been, in general, sampled for matched age (scales), sex, length (i.e., tip of nose to fork of tail length, postorbital hypural length, mid eye to fork of tail length; Shaw 1994) egg diameter, and otolith samples. Egg diameter is used to assign stock of origin (i.e., Tahltan or mainstem; Craig 1985; TTC 2022) and specific thermal marks on otoliths are used to apportion wild and enhanced fish and confirm origin and brood year. Average harvest in the assessment fishery (1985–2020) is 1,940 sockeye salmon (TTC 2022).

Upper River Commercial Fishery

The upper river commercial gillnet fishery occurs between the Chutine and Tuya Rivers (Figure 2). Historically, the fishery was initiated at the request of local residents to serve local markets in the communities of Telegraph Creek, Dease Lake, Cassiar, and Watson Lake (unpublished Wood and Johnston 1990 report⁴), and harvest has been recorded since 1975 (TTC 2022). Fishery openings are generally based on the lower river commercial fishery openings, lagged by one week. Average (1985–2020) annual sockeye salmon harvest in the upper river commercial fishery is 841 fish (TTC 2022). As upper river commercial and First Nation fishing areas overlap and use similar gear, biological data from each fishery is pooled for analysis (see First Nation Fishery section below; Pestal et al. 2024).

First Nation Fishery

The First Nation fishery predominantly occurs in the Telegraph Creek area, and harvest has been documented since 1972 (TTC 2022). Fishing for sockeye salmon generally occurs from mid-June through early August with most fishing activity completed by late August. Although harvest from the First Nation fishery is discretely recorded, biological samples are combined with the upper river commercial fishery for analysis. Although sampling protocols have shifted over time (Pestal et al. 2024), matched length (i.e., tip of nose to fork of tail length, postorbital hypural length, mid eye to fork of tail length; Shaw 1994), weight, age (scales), sex, otoliths, and egg diameters have generally been recorded. Historically, egg diameter was used to assign stock of origin (i.e., Tahltan or mainstem; Craig 1985; TTC 2022), however in recent years a stock composition of 98% Tahltan and 2% mainstem has been applied to harvest in all statistical weeks. Prior to analysis for the escapement goal review, all upper river commercial and First Nation fishery data were revised to apply these stock proportions. Specific thermal marks on otoliths are used to apportion wild and

enhanced fish and confirm origin and brood year. The average (1972–2020) annual harvest of sockeye salmon in the First Nation fishery is 5,200 fish, with a range of approximately 2,000 to 10,600 fish (TTC 2022).

Excess Salmon to Spawning Requirements (ESSR) and Assessment – Tahltan Lake and Tuya River

The intended purpose of Excess Salmon to Spawning Requirements (ESSR) fisheries is to facilitate the harvest of salmon deemed surplus to spawning escapement requirements. ESSR fisheries have occurred at Tahltan Lake from 1993 to 1996, when sockeye salmon numbers exceeded the upper end of the spawning escapement goal range. In 1996, for example, ESSR harvest exceeded 14,300 sockeye salmon (TTC 2022). No ESSR harvest has occurred in other years where returns exceeded escapement requirements.

Sockeye salmon entering the Tuya River were considered to be excess as they were blocked from accessing potential spawning grounds of Tuya Lake by natural barriers located in the lower reaches of Tuya River. ESSR fisheries were conducted on the Tuya River below the first barrier for enhanced sockeye salmon from 1996 to 2000, and again in 2003 and 2004 (TTC 2022). Additional harvest and lethal sampling occurred annually in the Tuya River from 1996 to 2014, and a Tuya assessment project operated in the mainstem Stikine River between 2018 and 2014 (average harvest: 2,157 sockeye salmon; TTC 2022).

ESCAPEMENT AND ABOVE BORDER RUN

Tahltan Lake Spawning Escapement:

Sockeye salmon spawning escapement to Tahltan Lake has been monitored since 1959 using a weir at the lake outlet. The average (1959–2020) annual escapement to the lake is 24,477 fish (TTC 2022). The enumeration and sampling project at Tahltan Lake was conducted by ADF&G from 1959 to 1976, and conducted jointly by DFO and Tahltan Central Government (TCG) from 1977 to present day. The project generally operates from the beginning of July through the beginning of September, or mid to late September if monitoring is extended throughout the broodstock collection program (initiated in 1989). In 1965 and 2014, landslides in the lower Tahltan River delayed and/or impeded returns to Tahltan Lake. In 2018, returns to the lake were estimated (based on run timing) as forest fires in the area required evacuation of field staff. As a result, limited biological data are available in those years.

Although sampling protocols have shifted over time (Pestal et al. 2024), length (i.e., tip of nose to fork of tail length, postorbital hypural length, mid eye to fork of tail length; Shaw 1994), age (scales), sex, and otoliths have generally been collected in proportion to anticipated weekly run strength. Specific thermal marks on otoliths are used to apportion wild and enhanced fish and confirm origin and brood year.

Stikine River Above Border Run and Escapement

The Stikine River above border run is the Tahltan above border run estimate divided by the above border proportion of Tahltan fish (Craig 1985). This was generated through a smoothing curve analysis of the paired age, sex, length, egg diameter, and otolith samples on the lower river commercial fishery and sometimes assessment fisheries. In 2019, due to limited data it was based on the 10-year (2009–2018) average of the above border stock proportions. Stikine River sockeye

salmon escapement is the difference between the Stikine River above border run estimate and Stikine River above border harvest and removals.

Mainstem Above Border Run and Escapement

The mainstem above border estimate is calculated from the difference between Tahltan and Tuya above border estimates to the Stikine River above border estimate. Mainstem escapement is calculated as the difference between mainstem above border estimate and the mainstem above border harvest and removals. Age distributions are calculated based on mainstem escapement where age proportions are assumed to be equivalent to the Canadian harvest.

DATA ANALYSIS

Brood Tables

Tahltan natural stock: This broodtable links total natural spawners (including wild and enhanced spawners but excludes broodstock take) to total unmarked (wild) returns (including all offspring of natural spawners). This covers all fish spawning naturally in Tahltan Lake. Estimates are available since 1959 and match the wild spawner time series until 1993 when enhanced fish first started to be tracked (Table 1). Since 1993, the natural spawner series is the sum of wild and enhanced spawners, excluding broodstock take. Data is up to and including year 2020 and brood years 1983 through 2014.

Mainstem stock: This broodtable links spawners to returns. This covers all fish spawning naturally in the mainstem. Spawner estimates are available since 1979 (Table 2). Mainstem stock spawner estimates are calculated as the difference between mainstem above border estimate (calculated from the difference between the Tahltan and Tuya stock above border estimates to the Stikine River above border estimate) and the mainstem removals (Craig 1985). Data is up to and including year 2020 and brood years 1983 through 2014.

Spawner-Recruit Models

Basic Ricker Model and Extensions

Returns R of Stikine River sockeye salmon originating from spawners in brood years $y = 1983$ to 2014 were modeled as a function of spawning escapements S using a linearized Ricker (1954) spawner-recruit function (i.e., basic Ricker model),

$$\ln(R_y) = \ln(S_y) + \ln(\alpha) - \beta S_y + \varepsilon_y, \quad (1)$$

where α is the productivity parameter, and β is the inverse capacity parameter (density-dependence). Two extensions of the basic Ricker models were also investigated, the linearized Ricker spawner-recruit function with an autoregressive lognormal process error with a lag of one year (Noakes et al. 1987; AR1 Ricker model), and the time variant alpha model. In the AR1 Ricker model,

$$\ln(R_y) = \ln(S_y) + \ln(\alpha) - \beta S_y + \phi v_{y-1} + \varepsilon_y, \quad (2)$$

ϕ is the lag-1 AR coefficient, and v_y are the model residuals,

$$v_y = \ln(R_y) - \ln(S_y) - \ln(\alpha) + \beta S_y = \phi v_{y-1} + \varepsilon_y, \quad (3)$$

where $\varepsilon_y \sim N(0, \sigma_\varepsilon^2)$. The basic Ricker model was only investigated if the 95% credible interval of the posterior distribution of the ϕ parameter (of the AR1 Ricker model) included 0, suggesting that the parameter is not statistically different than zero. Otherwise, the AR1 Ricker model was used in the spawn-recruit analysis.

The time variant alpha model was investigated to look at patterns in changes in productivity over time. This model assumes that the alpha parameter takes a random walk process,

$$\ln(\alpha)_y = \ln(\alpha)_{y-1} + \omega_t, \quad (4)$$

where $\omega_t \sim N(0, \sigma_\omega^2)$; (e.g., Peterman et al. 2003; Peterman and Dorner 2012; Holt and Michielsens 2020). To determine a change in regime shift (i.e., a change in productivity), the Sequential t -Test Analysis of Regime Shifts (STARS) algorithm (Rodionov 2004; Rodionov and Overland 2005) was used.

Model Fitting

An interactive online application that allows users to load in a data set, explore alternative spawner-recruit model fits, and then explore alternative probability profiles was used for the escapement goal analysis (Hamazaki 2022; hereafter referred to as the *Hamazaki App*). Within the *Hamazaki App*, MCMC methods, to generate the joint posterior probabilities of the unknown quantities, are employed to provide a more realistic assessment of uncertainty than is possible with traditional spawner-recruit methods. The *R2jags* package (Su and Yajima 2015) provides the interface between the R (R Core Team 2021) environment and the Bayesian data analysis software JAGS ([JAGS - Just Another Gibbs Sampler \(sourceforge.io\)](https://www.jags.org/)), while the *Shiny* package (Chang et al. 2022) creates the interactive interface of the application. The *Hamazaki App* was used for model fitting, diagnostics, and calculation of the biological benchmarks.

Model parameters and priors

Parameter priors were set to be flat, uninformative, and within a reasonable range seen in salmon stock assessments (Hamazaki 2022; Table 3).

Diagnostic Tools for Assessing Mixing and Convergence

Three MCMC chains were initiated. After a 10,000 sample burn-in period was discarded, 6,000 samples (200,000 iterations, thinned by 100; 2000 samples per chain) were retained for analysis to estimate posterior medians, means, standard deviations, and percentiles. A variety of diagnostic tools were used to assess mixing and convergence including: time series plots (plot of the sampled value against its number on the chain to check for adequate mixing in visual assessment of overlaid

chains; Toft et al. 2007), autocorrelation plots (the correlation between the samples i iterations apart in the chain to determine adequate mixing and assessing whether a chain needs further thinning; Toft et al. 2007), density plots, between and within variances of multiple chains (\hat{R}), and the effective sample size for each parameter. The density plots of the posterior distribution of the parameters should be smooth and should not reach the bounds of the priors. To determine convergence, two criteria were used; the Gelman-Rubin convergence diagnostic, also called the \hat{R} value (Brooks and Gelman 1998; Gelman and Rubin 1992), which compares the first half of each chain to the second half to determine lack of convergence within each chain, and the rank-normalized effective sample size. Vehtari et al. (2021) have suggested if a threshold of 1.01 ($\hat{R} < 1.01$) is used for each parameter, one can be fairly confident that convergence has been reached. In addition, the effective sample size should be > 400 for each parameter (Vehtari et al. 2021). An effective sample size > 400 should be sufficient to attain a stable estimate of the Monte Carlo standard error (i.e., an estimate of the difference between the mean of the sampled values (the posterior mean) and the true posterior mean).

Biological Benchmark Estimation for Management

The fundamental step of the analysis was to fit a biological production model and estimate population parameters relating to productivity and capacity based on the shape of the fitted model. Biological benchmarks (e.g., S_{MSY}) were then derived from the productivity and capacity parameters of the fitted model. The biological benchmarks in this report have widely accepted technical definitions and can be calculated independently of any management considerations. Using two frames of reference, Canada’s Precautionary Approach and Wild Salmon Policy (e.g., Grant et al. 2011; Holt 2009; Holt et al. 2009) and the Alaska Sustainable Salmon Fisheries Policy (Munro 2019), the following biological benchmarks were calculated:

- S_{MSY} : spawner abundance that maximizes sustained yield;
- S_{MAX} : spawner abundance that maximizes the number of recruits;
- S_{EQ} : spawner abundance that results in long-term equilibrium, whereby spawners equal the number of recruits;
- U_{MSY} : harvest rate (the proportion of the total run that is harvested) at maximum sustained yield;
- S_{GEN} : spawner abundance with a high probability of rebuilding to S_{MSY} in one generation in the absence of harvest; and
- $80\%S_{MSY}$: spawner level that is 80% of the spawner level that produces maximum sustained yield.

Biological benchmarks were calculated for each individual MCMC sample and the median across all the posterior samples was reported as the point estimate. Spawning abundance at MSY, S_{MSY} , was approximated by Hilborn (1985)

$$S_{MSY} \cong \frac{\ln(\alpha)}{\beta} [0.5 - 0.07 \ln(\alpha)], \quad (5)$$

Sustained yield at a specified level of S was obtained by subtracting spawning escapement from recruitment,

$$Y_S = R - S = S e^{(\ln(\alpha) - \beta S)} - S. \quad (6)$$

Spawning escapement at maximum sustained return, S_{MAX} , was calculated as $1/\beta$ and equilibrium spawning abundance in the absence of fishing (recruitment that exactly replaces spawners) as

$$S_{EQ} = \frac{\ln(\alpha)}{\beta}. \quad (7)$$

Harvest rate leading to MSY, U_{MSY} , was approximated by Hilborn (1985)

$$U_{MSY} \cong \ln(\alpha) [0.5 - 0.07 \ln(\alpha)]. \quad (8)$$

The biological benchmark S_{GEN} was calculated using the Connors et al. (2022) version of the S_{GEN} optimizer within the *Hamazaki App*. The biological benchmark $80\%S_{MSY}$, based on Hilborn (1985), was calculated based on posterior samples of $\ln(\alpha)$ and β .

Model parameters based on expected mean and expected median recruits

Under the assumption of lognormal distribution of recruits (R), $R \sim LN(\ln(\mu), \sigma^2)$ or $\ln(R) \sim N(\ln(\mu), \sigma^2)$, μ is the expected median recruit, and the expected mean recruitment is $\mu = \exp(\ln(\mu) + \sigma^2/2)$. Therefore, no bias-correction is applied for the expected median. The expected mean recruit $E(R)$ of the basic Ricker at a given spawner is

$$\ln(E(R)) = \ln(S) + \ln(\alpha) - \beta S + \sigma^2/2 \text{ or } \ln(E(R)) = \ln(S) + \ln(\alpha') - \beta S, \quad (9)$$

where $\ln(\alpha') = \ln(\alpha) + \sigma^2/2$ and $\alpha' = \alpha e^{\frac{\sigma^2}{2}}$ and is $\ln(\alpha') = \ln(\alpha) + \frac{\sigma^2}{2(1-\phi^2)}$ and $\alpha' = \alpha e^{\frac{\sigma^2}{2(1-\phi^2)}}$ for the AR1 Ricker model (Subbey et al. 2014). For the expected mean, the statistical bias-corrected alpha parameters,

$$\ln(\alpha') = \ln(\alpha) + \frac{\sigma^2}{2(1-\phi^2)}, \quad (10)$$

instead of $\ln(\alpha)$, are used in equations 5 through 8 for the AR1 Ricker, and the statistical bias-corrected alpha parameters,

$$\ln(\alpha') = \ln(\alpha) + \frac{\sigma^2}{2}, \quad (11)$$

instead of $\ln(\alpha)$, are used in equations 5 through 8 for the basic Ricker and time variant alpha models to calculate the biological benchmarks; $S_{MSY,c}$, $S_{EQ,c}$, $U_{MSY,c}$.

There has not been consistency in the literature (Subbey et al. 2014), or among agencies, projects, or regions as to whether a log-normal bias correction is applied or is not applied to the productivity parameter before calculating biological benchmarks. Guidelines from Subbey (et al. 2014) suggest that when the target is mean annual recruitment log-normal bias correction should be applied, whereas log-normal bias correction should not be applied when the target is median annual recruitment. This is a separate issue as to whether the posterior mean or posterior median is reported in regard to the log normal bias or to the non-bias corrected productivity parameter. ADF&G analyses typically apply a bias correction to the productivity parameter before calculating biological benchmarks (e.g., Bernard et al. 2000, McPherson et al. 2010, Fleischman and Evenson 2010, Eggers and Bernard 2011, Fleishman et al. 2011, Hamazaki et al. 2012, Fleischman and Reimer 2017, Brenner et al. 2018, Joy et al. 2021). Prior analyses of transboundary stocks, both solely by ADF&G, and jointly with ADF&G and DFO personnel, have applied a bias correction to the productivity parameter before calculating the biological benchmarks (e.g., McPherson et al. 2010 for Taku River Chinook salmon, Bernard et al. 2000 for Stikine River Chinook salmon, Bernard and Jones III 2010 for Alsek Chinook salmon, Eggers and Bernard 2011 for Alsek sockeye salmon, Pestal et al. 2016 for Little Tahltan Chinook salmon on the Stikine River, Miller and Pestal 2020 for Taku River sockeye salmon, Connors et al. 2022 for the Yukon River Mainstem Chinook salmon stock) or presented both biological benchmarks, with and without the log-normal bias correction, but presented the bias-corrected version as the base case (Pestal and Johnston 2015 for Taku River coho salmon). The bias correction, applied to the productivity parameter before calculating biological benchmarks, has not typically been applied for the wild salmon policy (WSP) benchmarks (e.g., Grant et al. 2011 and 2020 for Fraser River sockeye salmon, Holt et al. 2018 for chum salmon in Southern British Columbia, DFO 2015 for Fraser River coho salmon, DFO 2016 for Southern British Columbia Chinook salmon, Korman et al. 2019 and Arbeider et al. 2020 for Fraser River coho salmon, Ramshaw et al. 2019 for

Sakinaw Lake sockeye salmon, general WSP benchmarks referenced in Holt 2009, Holt et al. 2009, Holt and Bradford 2011) and is not part of the WSP Software toolkit (Holt and Ogden 2013). Following the WSP (WSP; Holt 2009), when calculating the biological benchmarks for Stikine River sockeye salmon, the expected median (log normal non-bias corrected productivity parameter) was reported as the base case (Table 4 and Table 5). The expected mean (log normal bias-corrected productivity parameter) was also reported for completeness (Table 4 and Table 5).

MSY Profile (Optimal Yield Profile)

The MSY Profile calculates the probability of a given escapement producing yields that are above $q\%$ of MSY. The MSY profile is calculated in the following steps. In each Bayesian sample of the spawner recruit parameters (j) and given spawner range (S_i),

- Calculate the expected yield $Y_j(S_i)$ and find the maximum yield (MSY) $Max(Y_j)$.
- Assign $X_{i,j}$ to 1 if the expected yield is above the minimum $q\%$ of the $Max(Y_j)$ and 0 if otherwise.

Then, for each spawner (S_i) calculate the mean of $X_{i,j}$ of all samples (j); profile probability of achieving yield above $q\%$ of MSY. The MSY Profile Range S_{MSY} is a range of spawners such that the profile probability is above the target probability of $p\%$. This is written as the MSY based spawner profile,

$$P(S_{i,j}) = \frac{\sum_{j=1}^n X_{i,j}}{n} \text{ where } X_{i,j} = \begin{cases} 1 & \text{if } Y_j(S_i) \geq q \cdot \text{Max}(Y_j) \\ 0 & \text{otherwise} \end{cases}. \quad (12)$$

The MSY based escapement goal range is a range of S where $P(S)$ is equal to or greater than the predefined p ,

$$\{S_{MSY} \leftarrow [S_l, S_u] | P(S) \geq p\}. \quad (13)$$

Expected Sustained Yield

Expected sustained yield, or the numbers of fish over and above those necessary to replace spawners averaged over the brood years from 1983 to 2014, is maximized near S_{MSY} .

RESULTS

FITTED MODEL

The long-term average productivity scenario (i.e., the entire time series; brood years 1983 through 2014 and total returns of ages 3 through 6) and the AR1 Ricker model were used in the following analyses. As the 95% credible interval of the posterior distribution of the ϕ parameter (of the AR1 Ricker model) did not include 0 for either spawner recruit model (i.e., Tahltan natural or mainstem stock model), the AR1 Ricker model, which corrects for the patterns in the time-series (i.e., residuals), was the preferred model over the basic Ricker model for both stocks. In addition, explorations of changes in productivity, based on the time variant alpha model by stock, revealed a trend towards a lower productivity regime in recent brood years (brood years 2007–2014 for the Tahltan natural stock; brood years 2002–2014 for the mainstem stock; Figure 3; Table 6). As the changes were most pronounced in the most recent years of the time series, and productivity fluctuates over the time series, the long-term average productivity scenario, based on the entire time series, was used for the calculation of biological benchmarks.

DIAGNOSTIC TOOLS FOR ASSESSING MIXING AND CONVERGENCE

Given the data and model structure for each stock, no major problems were encountered for either stock based on the diagnostics. The time series plots for key model parameters were centered around a mean and the three chains were indistinguishable, suggesting that the chains had each converged and had converged to similar values. To improve mixing of the chain and prevent autocorrelation, samples were thinned (every 100th iteration). The Gelman-Rubin convergence diagnostic was < 1.01 for all model parameters ($(\ln(\alpha), \beta, \phi, \sigma)$; Brooks and Gelman 1997) for the Tahltan natural stock and < 1.01 for all model parameters for the mainstem stock. The effective sample size was > 400 for each parameter (i.e., effective sample sizes were ≥ 3000 for each parameter for the Tahltan natural stock and ≥ 2900 for each parameter for the mainstem stock) suggesting that all chains converged to the same posterior distribution. Ten thousand iterations

were discarded at the beginning of the chain (burn-in period) to ensure that the first and last part of the chain had the same distribution. As the diagnostic tools suggested that there was adequate mixing and convergence of the MCMC chains, interval estimates were constructed from the percentiles of samples of the posterior distribution.

STOCK PRODUCTIVITY, CAPACITY, AND YIELD

Tahltan natural stock

Posterior medians, posterior means, and 95% credible intervals for key model parameters and biological benchmarks are summarized in Table 4. The mean point estimate of $\ln(\alpha)$ is 1.85 corresponding to a high productivity stock, $\alpha = 6.81$ (high productivity stocks have an $\alpha \geq 4$; Su and Peterman 2012) and the mean point estimate of the density dependent parameter β is 3.78×10^{-5} . Uncertainty about β is reflected in variability in the values of S leading to maximum recruitment $S_{MAX} = 1/\beta$, and uncertainty about equilibrium abundance, S_{EQ} is reflected by variability in the values of S where the curves intersect the replacement line. The contrast in the spawner data used in the spawner-recruit analysis (brood years 1983–2014) is high (26.5; maximum escapement divided by the minimum escapement in Table 1; > 8 is considered high contrast; Clark et al. 2014). The estimated AR(1) parameter ϕ is 0.42, suggesting a positive lag-1 serial correlation in residuals. Stock productivity, $\ln(R/S)$ was strongly cyclic ranging from -1.10 to 3.39 (R/S ranged from 0.33 to 29.57). The Ricker recruitment residuals in Figure 4a are deviations in recruitment from that predicted by the AR1 Ricker spawner-recruit relationship (Figure 5a), reflecting time-varying changes in productivity after controlling for density-dependent effects. No patterns in the residuals were observed.

To incorporate uncertainty about the plausible spawner-recruit relationships, the success or failure of a given number of spawners to achieve biological reference points across plausible spawner-recruit relationships were tallied to create optimal yield profiles (Figure 6a). Optimal yield profiles show the probability of a given number of spawners achieving at least 70%, 80%, or 90% of MSY. These probabilities, which are highest near $S_{MSY} = 18,100$ fish (Table 4) can be used to quantify the yield performance of prospective escapement goals taking into consideration uncertainty about the true abundance and productivity of the stock (Figure 7a).

Mainstem stock

Posterior medians, posterior means, and 95% credible intervals for key model parameters and biological benchmarks are summarized in Table 5. The mean point estimate of $\ln(\alpha)$ is 1.49 corresponding to a moderately high productivity stock, $\alpha = 4.60$ (high productivity stocks have an $\alpha \geq 4$; Su and Peterman 2012) and the mean point estimate of the density dependent parameter β is 2.81×10^{-5} . Uncertainty about β is reflected in variability in the values of S leading to maximum recruitment $S_{MAX} = 1/\beta$, and uncertainty about equilibrium abundance, S_{EQ} is reflected by variability in the values of S where the curves intersect the replacement line. The contrast in the spawner data used in the spawner-recruit analysis (brood years 1983–2014) is high (14.9; maximum escapement divided by the minimum escapement in Table 2; > 8 is considered high contrast; Clark et al. 2014). The estimated AR(1) parameter ϕ is 0.52, suggesting a positive lag-1 serial correlation in residuals. Stock productivity, $\ln(R/S)$ was cyclic ranging from -0.92 to 2.28 (R/S ranged from 0.40 to 9.79). The Ricker recruitment residuals in Figure 8a are deviations in

recruitment from that predicted by the AR1 Ricker spawner-recruit relationship (Figure 5b), reflecting time-varying changes in productivity after controlling for density-dependent effects. No patterns in the residuals were observed.

To incorporate uncertainty about the plausible spawner-recruit relationships, the success or failure of a given number of spawners to achieve biological reference points across plausible spawner-recruit relationships were tallied to create optimal yield profiles (Figure 6b). Optimal yield profiles show the probability of a given number of spawners achieving at least 70%, 80%, or 90% of MSY. These probabilities, which are highest near $S_{MSY} = 21,000$ fish (Table 5) can be used to quantify the yield performance of prospective escapement goals taking into consideration uncertainty about the true abundance and productivity of the stock (Figure 7b).

BIOLOGICAL BENCHMARKS

Tahltan natural stock

Using the brood year data from 1983 to 2014, the estimated (posterior median) biological benchmarks with the 2.5th and 97.5th percentiles of the posterior distribution (capturing the central 95% of parameter samples; Table 4) were:

- Spawner level that produces maximum sustained yield (S_{MSY}) estimated at 18,100 spawners (13,600 to 25,600 spawners);
- Spawner level that produces the maximum adult recruits (S_{MAX}) estimated at 28,100 spawners (18,800 to 41,800 spawners);
- Equilibrium spawner level in the absence of fishing (S_{EQ}) estimated at 50,500 spawners (36,000 to 69,300 spawners);
- Spawner level with a high probability of rebuilding to S_{MSY} in one generation in the absence of harvest (S_{GEN}) estimated at 3,700 spawners (1,800 to 6,900 spawners).
- Spawner level that is 80% of that needed to produce maximum sustained yield ($80\%S_{MSY}$) estimated at 14,900 spawners (10,900 to 20,400 spawners).

Mainstem stock

Using the brood year data from 1983 to 2014, the estimated (posterior median) biological benchmarks with the 2.5th and 97.5th percentiles of the posterior distribution (capturing the central 95% of parameter samples; Table 5) were:

- Spawner level that produces maximum sustained yield (S_{MSY}) estimated at 21,000 spawners (16,700 to 26,300 spawners);
- Spawner level that produces the maximum adult recruits (S_{MAX}) estimated at 36,600 spawners (27,800 to 48,300 spawners);
- Equilibrium spawner level in the absence of fishing (S_{EQ}) estimated at 53,800 spawners (40,500 to 67,800 spawners);
- Spawner level with a high probability of rebuilding to S_{MSY} in one generation in the absence of harvest (S_{GEN}) estimated at 5,700 spawners (3,500 to 8,600 spawners).

- Spawner level that is 80% of that needed to produce maximum sustained yield (80% S_{MSY}) estimated at 17,000 spawners (13,400 to 21,000 spawners).

DISCUSSION

CONSIDERATIONS FOR CHOOSING A SPAWNING ESCAPEMENT GOAL

Time-variant alpha model

While the AR1 and basic Ricker models assume that the alpha and beta parameters are constant over the time series, the time-variant alpha model can be used to explore changes in alpha over time. For both stocks, the time-variant alpha model shows annual variations in productivity, but the STARS algorithm (Rodionov 2004; Rodionov and Overland 2005) only identifies the most recent available brood years as having switched to the lowest, most pronounced, productivity regime of the time series. The Tahltan natural stock showed two productivity regimes (1983–2006, 2007–2014); the natural logarithm of alpha decreased from 2.09 in the first regime to 1.43 in the second regime (equivalent to alpha values of 8.08 to 4.16, respectively). The mainstem stock showed three productivity regimes (1983–2001, 2002–2012, 2013–2014); the natural logarithm of alpha decreased from 1.77 in the first regime, to 1.33 in the second regime, and then to 0.70 in the third regime (equivalent to alpha values of 5.88, 3.77, and 2.02, respectively). Although the pattern in the reduction in productivity held for both stocks, the selected breaks in the regime were sensitive to rerunning the analysis and the resultant MCMC samples (i.e., the STARS algorithm uses the posterior mean across the MCMC samples to determine the regime shifts based on the changes in the natural logarithm of alpha by year). For example, the regime shift (change in productivity) for the Tahltan natural stock fluctuated between 2006 and 2007, and 2012 and 2013. In addition, simulations have shown that when the true underlying productivity in the most recent year is decreasing, productivity estimates are less biased with the time-varying model (compared to the standard model), but more imprecise (Holt and Michielsens 2020).

Given the cyclic pattern of temporal productivity seen in these stocks, and the sensitivity to changes in productivity at the end of the time series, it may be more effective and appropriate to adopt management policies that are robust to this uncertainty in productivity until it can be shown what underlying mechanisms are causing these declines in productivity, and if the recent downturn in productivity persists for these stocks (Holt and Michielsens 2020). As declining productivity has been observed in many Pacific salmon stocks (Peterman and Dorner 2012; Ruggerone and Connors 2015), productivity estimates (and hence biological benchmarks) for Stikine River sockeye salmon stocks should be updated regularly to identify signs of a persistent downturn.

SOURCES OF UNCERTAINTY

Uncertainties in data

Unreported harvest and incidental fishing mortality such as escape mortality (mortality of fish that actively escape after contact with fishing gear such as a hook or gillnet prior to landing), depredation (fish that die as a result of predators directly removing fish from fishing gear during the capture process; not including predation of released fish), and fishery dropout (fish that die and dropout of fishing gear such as gillnets prior to landing) were not accounted for in this analysis (Patterson et al. 2017). This unaccounted harvest can bias available harvest estimates. Second, total fish numbers from the U.S. commercial fisheries are based on total weight converted to

numbers of fish. Third, an unknown number of Stikine River sockeye salmon are harvested in nondirected interception fisheries in Southeast Alaska outside of the terminal area (defined as District 106 and 108). Pursuant to the February 2022 version of the Pacific Salmon Treaty, Chapter 1, Annex IV, paragraph 3(a)(i), this analysis only included directed harvest of Stikine River sockeye salmon in terminal areas. Therefore, run abundance and return only encompass Stikine River sockeye salmon inside the Stikine River drainage and in the terminal areas adjacent to the outlet. Future analyses could include harvest in nonterminal areas to better represent the total run abundance and total return of Stikine River sockeye salmon. Fourth, as the analysis is stock-specific, Canadian data relies heavily on egg diameter to assign a record (i.e., fish) to a wild stock (i.e., Tahltan or mainstem; see the Lower River Commercial Fishery in the Methods section). As a result, a significant number of records were excluded from the analysis. For example, about 71% (77,000 of 108,300) of the records from the Lower River Commercial Fishery were excluded because data were not ‘matched’ (i.e., records did not have age (scales), sex (egg diameter), stock, otoliths, and/or statistical week). Finally, the mainstem stock is dependent on the Tahltan estimate and is a calculated value (see Mainstem Spawning Escapement in the Methods section).

CONCLUSIONS

BIOLOGICAL BENCHMARKS

Tahltan natural stock

Based on the analyses from the first-order autoregressive Ricker model for the Tahltan natural stock of the Stikine River sockeye salmon (brood years 1983–2014), the median spawner level that produces maximum sustained yield (S_{MSY}) is estimated at 18,100 spawners. The possible lower and upper biological escapement goal ranges are listed in Table 7.

Mainstem stock

Based on the analyses from the first-order autoregressive Ricker model for the mainstem stock of the Stikine River sockeye salmon (brood years 1983–2014), the median spawner level that produces maximum sustained yield (S_{MSY}) is estimated at 21,000 spawners. The possible lower and upper biological escapement goal ranges are listed in Table 7.

FUTURE DATA REQUIREMENTS AND RECOMMENDATIONS

To be able to update the broodtable and spawner recruit analysis, we recommend that the following data continue to be collected.

U.S. Data

- U.S. Subsistence fishery (harvest)
- District 106 commercial fishery data (ASL data, harvest, weekly stock proportions, enhanced contribution)
- District 108 commercial fishery data (ASL data, harvest, weekly stock proportions, enhanced contribution)

Canadian Data

- The lower Stikine River assessment project is no longer a lethal fishery (as of 2021) but age, sex, and length data are collected; data collected informs run timing for inseason (fishery) management, postseason run reconstruction, and age composition of the run but does not currently contribute to broodtable or spawner recruit analysis.
- Lower Stikine River commercial fishery sample data (ASL data, weekly stock proportions, harvest, enhanced contribution)
- Upper Stikine River commercial fisheries (ASL data, weekly stock proportions, harvest, enhanced contribution)
- Canadian First Nation fishery sample data (ASL, harvest)
- Tahltan Lake weir data (ASL data, weir counts, broodstock, natural spawners, enhanced contribution)

In addition, we recommend evaluating and updating Canadian fishery sampling projects to include the use of genetic stock identification rather than egg diameter to assist in stock identification; this change may increase the number of matched records available for future spawner recruit analysis.

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TABLES

Table 1. Estimated escapement and brood year returns of the Tahltan natural stock of Stikine River sockeye salmon by age. The statistics (average, minimum, maximum) only pertain to brood years 1983 through 2014. Since 1993, the natural spawner series (i.e., escapement column) is the sum of wild and enhanced spawners, excluding broodstock take. The enhanced spawners column is the last column in the table. A column of wild spawners is not shown.

Brood year	Escapement	Estimated returns by age						Total return (ages 3–6)	Spawners (enhanced)
		Age2	Age3	Age4	Age5	Age6	Age7		
1959	4,311	---	---	---	---	---	---	---	---
1960	6,387	---	---	---	---	---	---	---	---
1961	16,519	---	---	---	---	---	---	---	---
1962	14,508	---	---	---	---	---	---	---	---
1963	0	---	---	---	---	---	---	---	---
1964	18,353	---	---	---	---	---	---	---	---
1965	1,471	---	---	---	---	---	---	---	---
1966	21,580	---	---	---	---	---	---	---	---
1967	38,802	---	---	---	---	---	---	---	---
1968	19,726	---	---	---	---	---	---	---	---
1969	11,805	---	---	---	---	---	---	---	---
1970	8,430	---	---	---	---	---	---	---	---
1971	18,523	---	---	---	---	---	---	---	---
1972	52,454	---	---	---	---	---	---	---	---
1973	2,864	---	---	---	---	---	---	---	---
1974	8,101	---	---	---	---	---	---	---	---
1975	8,159	---	---	---	---	---	---	---	---
1976	24,111	---	---	---	---	---	---	---	---
1977	42,960	---	---	---	---	---	---	---	---
1978	22,788	---	---	---	---	---	---	---	---
1979	10,211	---	---	---	---	---	0	---	---
1980	11,018	---	---	---	---	1,927	10	---	---
1981	50,790	---	---	---	27,309	2,129	3	---	---
1982	28,257	---	---	391	11,402	881	0	---	---
1983	21,256	---	0	471	5,123	1,489	5	7,082	---
1984	32,777	0	3	2,408	10,864	2,515	3	15,790	---
1985	67,326	0	0	2,145	19,363	2,839	7	24,347	---
1986	20,280	0	0	4,357	77,877	9,826	52	92,059	---
1987	6,958	0	0	8,151	86,387	13,307	77	107,846	---
1988	2,536	0	25	8,269	51,090	5,236	8	64,621	---
1989	6,106	0	38	56,511	94,701	9,148	98	160,398	---
1990	11,625	0	0	10,755	44,363	6,297	24	61,415	---

-continued-

Table 1. Page 2 of 2.

Brood year	Escapement	Estimated returns by age						Total return (ages 3-6)	Spawners (enhanced)
		Age2	Age3	Age4	Age5	Age6	Age7		
1991	46,583	0	70	16,834	194,860	9,478	9	221,242	
1992	56,213	0	1	3,635	45,374	1,227	56	50,237	---
1993	47,104	0	0	5,755	22,973	4,068	73	32,796	1,030
1994	36,133	0	0	7,030	42,038	1,606	86	50,673	6,172
1995	26,675	0	5	4,031	11,760	1,863	2	17,660	10,084
1996	33,759	0	-17 ^a	1,718	16,759	829	39	19,289	3,936
1997	9,811	0	19	832	10,873	4,572	275	16,296	1,982
1998	9,169	0	3	9,134	40,763	4,723	75	54,622	616
1999	7,449	0	4	16,101	74,479	15,864	380	106,447	497
2000	3,953	0	3	43,423	66,703	6,753	12	116,882	801
2001	12,375	0	167	4,799	44,293	10,583	76	59,841	4,900
2002	14,289	0	4	37,194	43,001	1,280	11	81,479	3,799
2003	49,587	0	-137 ^a	3,021	15,194	4,460	83	22,536	21,694
2004	58,709	0	3	10,489	64,028	2,516	62	77,035	29,994
2005	39,622	0	12	6,080	25,203	6,856	25	38,151	16,420
2006	50,052	0	5	16,041	56,438	1,900	92	74,384	24,126
2007	18,035	0	17	2,203	14,054	1,918	126	18,192	7,673
2008	8,052	0	9	3,776	14,318	1,778	182	19,882	4,143
2009	27,313	0	10	5,979	24,655	2,503	8	33,147	4,041
2010	18,218	0	63	15,679	22,950	1,351	84	40,043	7,789
2011	29,689	0	5	18,093	95,573	6,848	43	120,520	10,248
2012	9,514	0	1	10,648	32,285	469	2	43,402	3,928
2013	12,632	0	116	1,689	5,484	251	0	7,541	6,383
2014	36,864	0	0	13,289	21,094	485	---	34,869	17,376
2015	29,288	0	48	6,054	7,630	---	---	---	14,312
2016	34,146	0	1	3,916	---	---	---	---	13,245
2017	16,332	0	20	---	---	---	---	---	8,525
2018	14,472	17	---	---	---	---	---	---	7,210
2019	33,208	---	---	---	---	---	---	---	19,037
2020	10,774	---	---	---	---	---	---	---	6,254
Average	25,958	0.00	13	10,954	43,591	4,526	67	59,085	8,529
Minimum	2,536	0.00	-137 ^a	471	5,123	251	0	7,082	497
Maximum	67,326	0.00	167	56,511	194,860	15,864	380	221,242	29,994

^a The wild Tahltan was the difference between All Tahltan and enhanced Tahltan, which sometimes resulted in negative values due to the assumptions of the age composition data.

Table 2. Estimated escapement and brood year returns of the mainstem stock of Stikine River sockeye salmon by age. The statistics (average, minimum, maximum) only pertain to brood years 1983 through 2014.

Brood year	Escapement	Estimated returns by age						Total return (ages 3–6)
		Age2	Age3	Age4	Age5	Age6	Age7	
1979	16,608	---	---	---	---	---	0	---
1980	30,806	---	---	---	---	2,270	0	---
1981	61,072	---	---	---	33,570	1,865	0	---
1982	19,964	---	---	5,069	18,751	963	14	---
1983	29,307	---	18	8,007	21,930	3,172	41	33,127
1984	38,107	0.00	444	11,567	54,753	3,465	46	70,229
1985	90,617	0.00	1,128	16,621	32,979	3,569	18	54,297
1986	30,910	0.00	29	4,335	44,862	7,259	49	56,485
1987	21,023	0.00	33	13,272	99,025	6,931	12	119,261
1988	22,841	0.00	312	20,375	109,960	1,525	8	132,173
1989	45,103	0.00	235	39,540	57,765	8,216	4	105,756
1990	22,638	0.00	81	6,169	54,262	670	3	61,182
1991	44,880	0.00	66	17,809	57,828	2,389	7	78,091
1992	65,392	0.00	1,141	32,136	63,641	1,896	19	98,814
1993	71,792	0.00	526	10,736	33,563	1,914	13	46,738
1994	34,636	0.00	31	1,908	23,994	687	11	26,621
1995	42,850	0.03	75	6,523	17,289	2,641	3	26,528
1996	45,852	0.00	87	5,575	49,553	1,276	337	56,491
1997	37,436	0.00	335	6,412	24,221	3,078	30	34,045
1998	19,175	0.00	115	11,116	83,969	978	37	96,178
1999	6,071	0.00	342	13,513	41,634	3,941	36	59,430
2000	10,132	0.00	1,441	39,026	57,930	773	9	99,169
2001	40,855	0.00	970	16,179	32,401	1,959	24	51,508
2002	27,154	0.00	36	10,754	27,067	617	63	38,474
2003	57,972	0.00	62	6,283	15,822	941	51	23,109
2004	36,728	0.00	398	14,635	27,827	2,006	30	44,866
2005	34,788	0.00	23	11,621	33,633	6,590	29	51,866
2006	27,603	0.00	109	9,299	50,038	2,326	141	61,772
2007	20,865	0.00	43	6,759	47,319	3,632	16	57,753
2008	16,178	0.00	49	11,448	37,723	1,757	10	50,977
2009	17,148	0.00	273	13,311	26,103	3,069	110	42,755
2010	24,831	0.00	301	7,104	36,841	1,381	11	45,627
2011	29,393	0.00	223	11,004	43,372	1,925	235	56,523
2012	33,812	0.00	285	10,868	20,266	1,749	1	33,168
2013	27,091	0.04	116	3,464	13,615	579	0	17,774
2014	19,691	0.00	105	7,824	17,648	647	---	26,223

-continued-

Table 2. Page 2 of 2.

Brood year	Escapement	Estimated returns by age						Total return (ages 3–6)
		Age2	Age3	Age4	Age5	Age6	Age7	
2015	26,432	0.00	757	12,157	6,624	---	---	---
2016	28,646	0.00	308	3,622	---	---	---	---
2017	11,678	0.00	78	---	---	---	---	---
2018	13,762	0.81	---	---	---	---	---	---
2019	23,174	---	---	---	---	---	---	---
2020	7,126	---	---	---	---	---	---	---
Average	34,152	0.00	295	12,662	42,463	2,611	45	58,032
Minimum	6,071	0.00	18	1,908	13,615	579	0	17,774
Maximum	90,617	0.04	1,441	39,540	109,960	8,216	337	132,173

Table 3. Prior distributions for the model parameters. The different models are the basic Ricker, the first-order autoregressive Ricker model (AR1 Ricker), and the time-variant alpha model (TVA).

Parameter	Prior	Model(s)
$\ln(\alpha)$	$U(0,10)$	Basic Ricker, AR1 Ricker, TVA
β	$U(0,10)$	Basic Ricker, AR1 Ricker, TVA
σ	$U(0,10)$	Basic Ricker, AR1 Ricker, TVA
ϕ	$U(-1,1)$	AR1 Ricker
ε_0	$N(0,100)$	AR1 Ricker
σ_w	$U(0,10)$	TVA

Table 4. Parameter estimates (posterior medians, posterior means, the 95% credible intervals, the coefficients of variation (CVs)) from the first-order autoregressive Ricker model for the Tahltan natural stock of Stikine River sockeye salmon in brood years 1983–2014. The median is the point estimate of the expected mean (bias-corrected; $S_{MSY.c}$, $S_{EQ.c}$, $U_{MSY.c}$) and the median is the point estimate of the expected median (S_{MSY} , S_{EQ} , U_{MSY}). The posterior CVs are the posterior standard deviations divided by the posterior means. Outliers were removed.

Parameter	SD	5%	Median	95%	Mean	CV
α	2.38	3.34	6.54	11.26	6.81	0.35
α'	4.15	5.87	10.78	19.72	11.48	0.36
β	8.91E-06	2.39E-05	3.72E-05	5.33E-05	3.78E-05	0.24
$\ln(\alpha)$	0.37	1.21	1.88	2.42	1.85	0.20
$\ln(\alpha')$	0.36	1.77	2.38	2.98	2.38	0.15
ϕ	0.17	0.12	0.43	0.69	0.42	0.41
σ	0.12	0.71	0.87	1.10	0.88	0.13
S_{MSY}	3,675	13,572	18,053	25,560	18,611	0.20
$S_{MSY.c}$	4,666	15,515	20,894	30,723	21,750	0.21
S_{MAX}	6,936	18,767	26,873	41,797	28,059	0.25
S_{EQ}	10,148	35,951	49,275	69,289	50,462	0.20
$S_{EQ.c}$	13,928	47,307	62,673	92,206	65,325	0.21
U_{MSY}	0.09	0.50	0.69	0.80	0.68	0.14
$U_{MSY.c}$	0.06	0.67	0.79	0.87	0.78	0.08
S_{GEN}	1,568	1,785	3,355	6,854	3,714	0.42
$S_{GEN.c}$	1,109	1,911	3,008	5,521	3,248	0.34
$S_{MSY\ 80\%}$	2,940	10,857	14,442	20,448	14,888	0.20
MSY	17,418	17,272	42,140	74,385	43,733	0.40

Table 5. Parameter estimates (posterior medians, posterior means, the 95% credible intervals, the coefficients of variation (CVs)) from the first-order autoregressive Ricker model for the mainstem stock of Stikine River sockeye salmon in brood years 1983–2014. The median is the point estimate of the expected mean (bias-corrected; $S_{MSY.c}$, $S_{EQ.c}$, $U_{MSY.c}$) and the median is the point estimate of the expected median (S_{MSY} , S_{EQ} , U_{MSY}). The posterior CVs are the posterior standard deviations divided by the posterior means. Outliers were removed.

Parameter	SD	5%	Median	95%	Mean	CV
α	1.14	2.87	4.51	6.67	4.60	0.25
α'	1.45	3.62	5.51	8.47	5.69	0.25
β	4.60E-06	2.07E-05	2.79E-05	3.60E-05	2.81E-05	0.16
$\ln(\alpha)$	0.25	1.05	1.51	1.90	1.49	0.17
$\ln(\alpha')$	0.25	1.29	1.71	2.14	1.71	0.15
ϕ	0.18	0.21	0.53	0.80	0.52	0.34
σ	0.07	0.41	0.51	0.64	0.51	0.14
S_{MSY}	2,890	16,694	21,048	26,308	21,199	0.14
$S_{MSY.c}$	3,195	18,864	23,015	29,307	23,383	0.14
S_{MAX}	6,139	27,774	35,907	48,309	36,623	0.17
S_{EQ}	8,047	40,480	53,619	67,781	53,790	0.15
$S_{EQ.c}$	9,097	48,811	60,580	78,653	61,609	0.15
U_{MSY}	0.07	0.45	0.59	0.70	0.59	0.13
$U_{MSY.c}$	0.07	0.53	0.65	0.75	0.65	0.10
S_{GEN}	1,577	3,453	5,497	8,647	5,706	0.28
$S_{GEN.c}$	1,510	2,911	4,803	7,871	5,031	0.30
$S_{MSY\ 80\%}$	2,312	13,356	16,838	21,047	16,959	0.14
MSY	10,860	15,389	31,870	51,403	32,441	0.33

Table 6. Estimates of alpha by year (posterior means, standard deviation, the 95% credible intervals, and the alpha by regime) from the time-variant Ricker model for the Tahltan natural stock and for the mainstem stock of Stikine River sockeye salmon in brood years 1983–2014.

Year	Tahltan natural					Mainstem				
	Mean	SD	5%	95%	Regime	Mean	SD	5%	95%	Regime
1983	2.23	1.96	0.58	8.16	---	4.08	1.55	1.63	9.12	---
1984	2.78	1.74	0.99	8.35	8.08	5.46	1.33	3.17	9.86	5.88
1985	5.36	1.68	1.95	14.90	8.08	6.94	1.47	3.46	15.02	5.88
1986	9.45	1.57	3.89	22.79	8.08	5.44	1.36	3.30	10.52	5.88
1987	15.46	1.59	5.74	36.88	8.08	9.11	1.27	5.36	13.92	5.88
1988	20.32	1.63	7.12	48.31	8.08	9.90	1.28	5.69	15.53	5.88
1989	21.05	1.65	6.94	49.13	8.08	8.12	1.31	4.96	13.76	5.88
1990	13.10	1.56	5.71	32.80	8.08	5.90	1.31	3.78	10.67	5.88
1991	16.47	1.72	5.84	49.46	8.08	6.42	1.33	3.82	11.65	5.88
1992	9.26	1.70	3.36	27.04	8.08	7.88	1.41	4.13	15.58	5.88
1993	6.03	1.67	2.22	16.94	8.08	4.90	1.42	2.60	9.86	5.88
1994	5.16	1.62	2.02	13.29	8.08	2.65	1.47	1.49	6.23	5.88
1995	3.14	1.71	1.16	9.10	8.08	2.58	1.45	1.43	5.91	5.88
1996	3.11	1.70	1.11	8.84	8.08	4.11	1.32	2.40	6.88	5.88
1997	3.89	1.59	1.59	9.73	8.08	3.44	1.40	1.95	6.74	5.88
1998	7.69	1.49	3.49	16.99	8.08	7.46	1.27	4.38	11.45	5.88
1999	13.39	1.59	5.35	32.15	8.08	9.78	1.32	4.93	14.86	5.88
2000	17.09	1.69	5.94	43.29	8.08	9.95	1.36	4.83	15.21	5.88
2001	9.97	1.52	4.46	23.34	8.08	4.55	1.31	2.79	7.89	5.88
2002	8.80	1.53	3.81	20.23	8.08	3.36	1.31	2.11	6.15	3.77
2003	5.96	1.69	2.10	16.76	8.08	2.58	1.47	1.30	5.55	3.77
2004	8.62	1.70	3.15	25.82	8.08	3.50	1.30	2.16	5.89	3.77
2005	6.24	1.61	2.52	16.18	8.08	4.04	1.27	2.63	6.61	3.77
2006	6.78	1.63	2.67	18.18	8.08	4.69	1.25	3.02	7.31	3.77
2007	3.64	1.62	1.43	9.11	4.16	4.88	1.23	3.23	7.48	3.77
2008	3.81	1.55	1.59	8.97	4.16	4.77	1.23	3.14	7.28	3.77
2009	4.15	1.55	1.76	9.63	4.16	4.14	1.23	2.81	6.46	3.77
2010	5.03	1.52	2.14	11.46	4.16	3.81	1.25	2.51	6.13	3.77
2011	7.29	1.63	2.78	18.80	4.16	3.95	1.26	2.44	6.16	3.77
2012	5.07	1.51	2.22	11.25	4.16	2.65	1.29	1.69	4.58	3.77
2013	2.43	1.73	0.90	7.21	4.16	1.78	1.39	1.10	3.81	2.02
2014	3.48	1.68	1.23	9.39	4.16	2.29	1.28	1.42	3.99	2.02

Table 7. The optimal yield probabilities (probability of achieving at least X% of MSY in column two) are the probabilities (column three) that a given level of spawning escapement will produce average yields exceeding 70%, 80%, or 90% of MSY for each stock. The lower and upper bound columns show the possible lower and upper ends of the escapement goal range based on the probabilities.

Target	% of target	Probability of achieving	Lower bound	Upper bound	Stock
MSY	90	70	12,900	23,300	Tahltan natural
MSY	90	75	13,400	22,700	Tahltan natural
MSY	90	80	14,000	22,100	Tahltan natural
MSY	90	85	14,600	21,300	Tahltan natural
MSY	90	90	15,400	20,500	Tahltan natural
MSY	80	70	10,200	26,700	Tahltan natural
MSY	80	75	10,600	26,000	Tahltan natural
MSY	80	80	11,000	25,200	Tahltan natural
MSY	80	85	11,500	24,300	Tahltan natural
MSY	80	90	12,100	23,400	Tahltan natural
MSY	70	70	8,200	29,400	Tahltan natural
MSY	70	75	8,500	28,600	Tahltan natural
MSY	70	80	8,900	27,800	Tahltan natural
MSY	70	85	9,300	26,800	Tahltan natural
MSY	70	90	9,700	25,800	Tahltan natural
MSY	90	70	16,000	30,500	mainstem
MSY	90	75	16,300	29,800	mainstem
MSY	90	80	16,800	29,200	mainstem
MSY	90	85	17,300	28,600	mainstem
MSY	90	90	17,900	27,800	mainstem
MSY	80	70	12,600	34,600	mainstem
MSY	80	75	12,900	33,900	mainstem
MSY	80	80	13,200	33,200	mainstem
MSY	80	85	13,600	32,400	mainstem
MSY	80	90	14,100	31,600	mainstem
MSY	70	70	10,100	38,000	mainstem
MSY	70	75	10,400	37,300	mainstem
MSY	70	80	10,600	36,500	mainstem
MSY	70	85	10,900	35,700	mainstem
MSY	70	90	11,400	34,600	mainstem

FIGURES



Figure 1. U.S. District 106 and 108 fishing area.



Figure 2. Stikine River drainage and Canadian fishery areas.

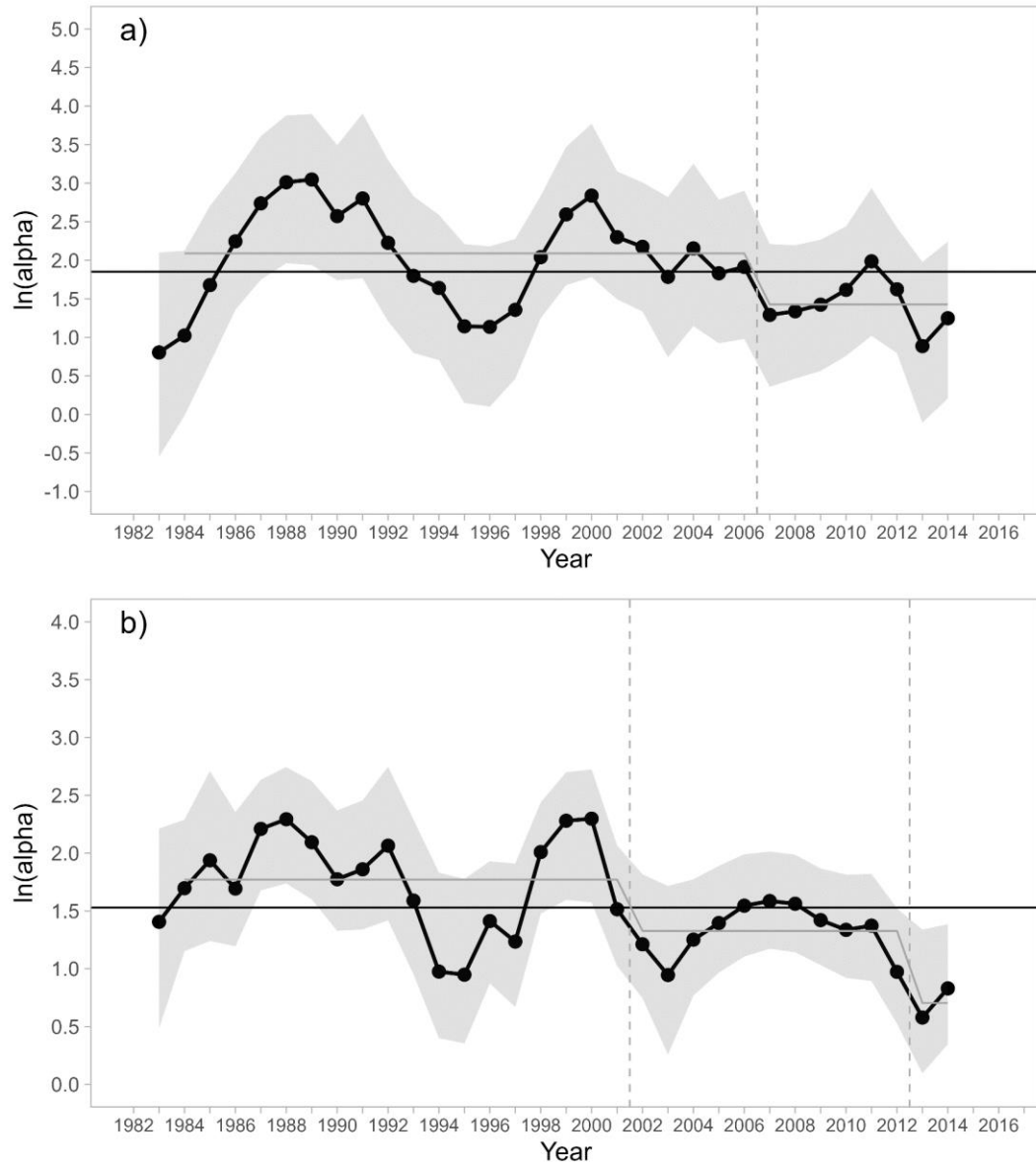


Figure 3. Estimates of $\ln(\alpha)$ with 95% credible intervals (shaded regions) based on the time-variant alpha models for the (A) Tahltan natural stock and the (B) mainstem stock of Stikine River sockeye salmon. The horizontal black lines in each figure represent the mean $\ln(\alpha)$ across all years, and the horizontal grey lines represent the $\ln(\alpha)$ parameter by regime. The Tahltan natural stock showed two productivity regimes (1983–2006, 2007–2014; dotted vertical line separates the regimes) with a break between 2006 and 2007. The mainstem stock showed three productivity regimes (1983–2001, 2002–2012; 2013–2014; dotted vertical lines separates the regimes) with a break between 2001 and 2002, and a break between 2012 and 2013.

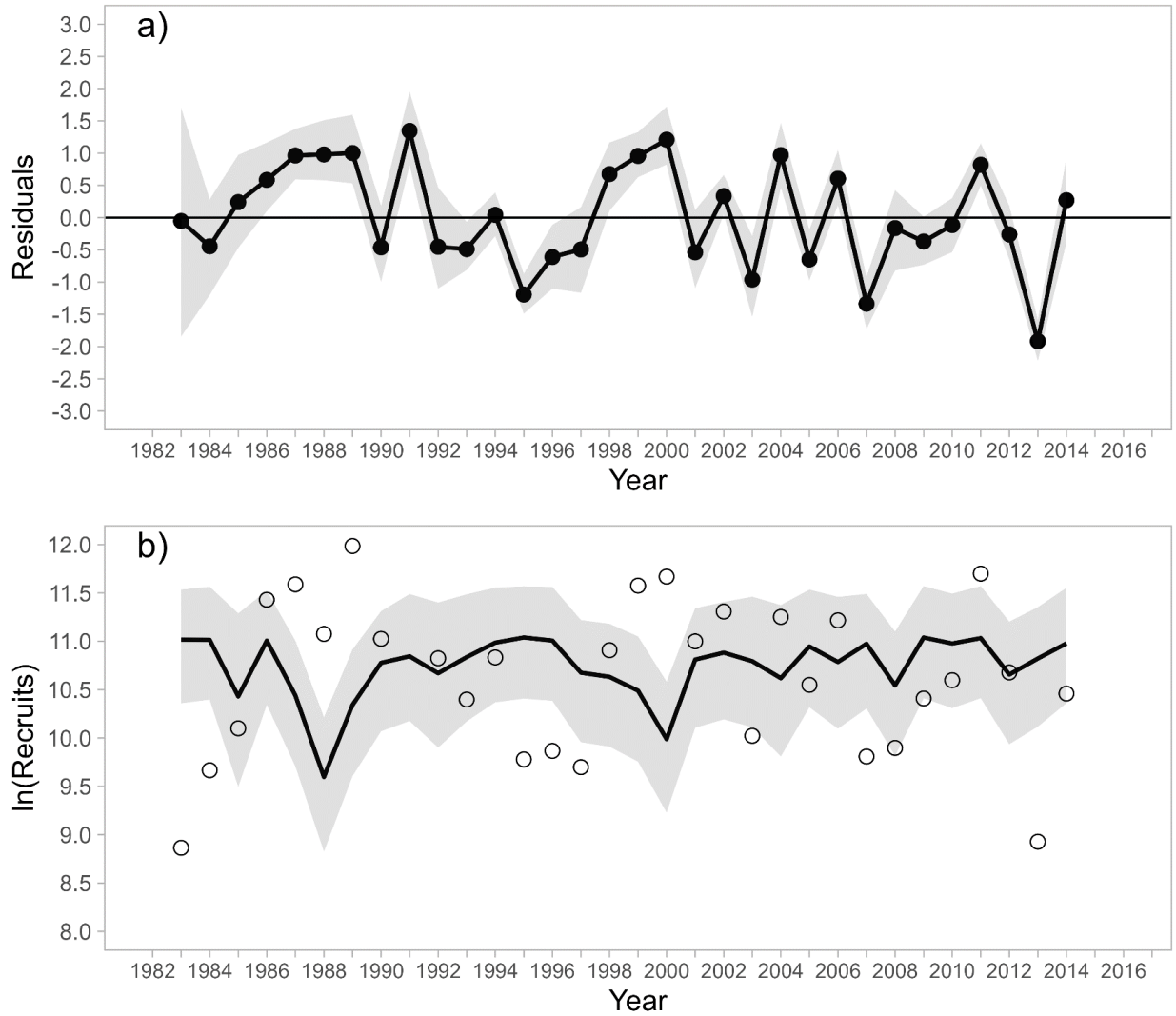


Figure 4. (A) Model residuals and (B) natural logarithms of recruits by brood year (1983–2014) from a first-order autoregressive Ricker model for the Tahltan natural stock of Stikine River sockeye salmon. In figure B, the line is the predicted recruits (natural logarithm) and the open circles are the observed recruits (natural logarithm). The shaded area is the 95% credible interval.

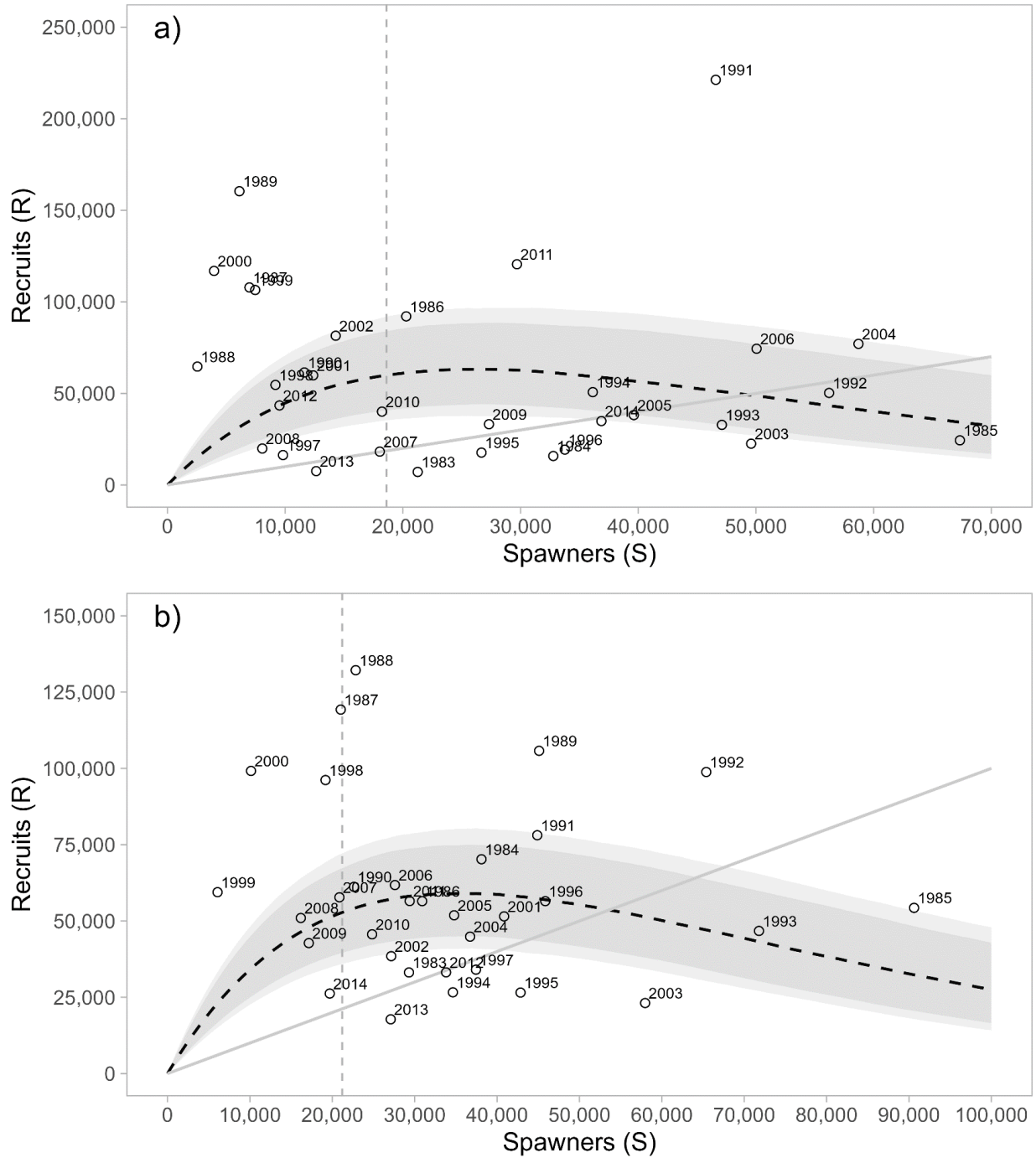


Figure 5. Spawner-recruit relationship (dashed line) with 90% and 95% credible intervals (shaded regions) for (A) the Tahltan natural stock of Stikine River sockeye salmon and (B) the mainstem stock of Stikine Ricker sockeye salmon stock as derived from a first-order autoregressive Ricker model for brood years 1983–2014. Recruits replace spawners on the solid, grey diagonal line. The point estimates of the expected median (non-bias corrected) of S_{MSY} are shown as a vertical dotted grey line in each figure.

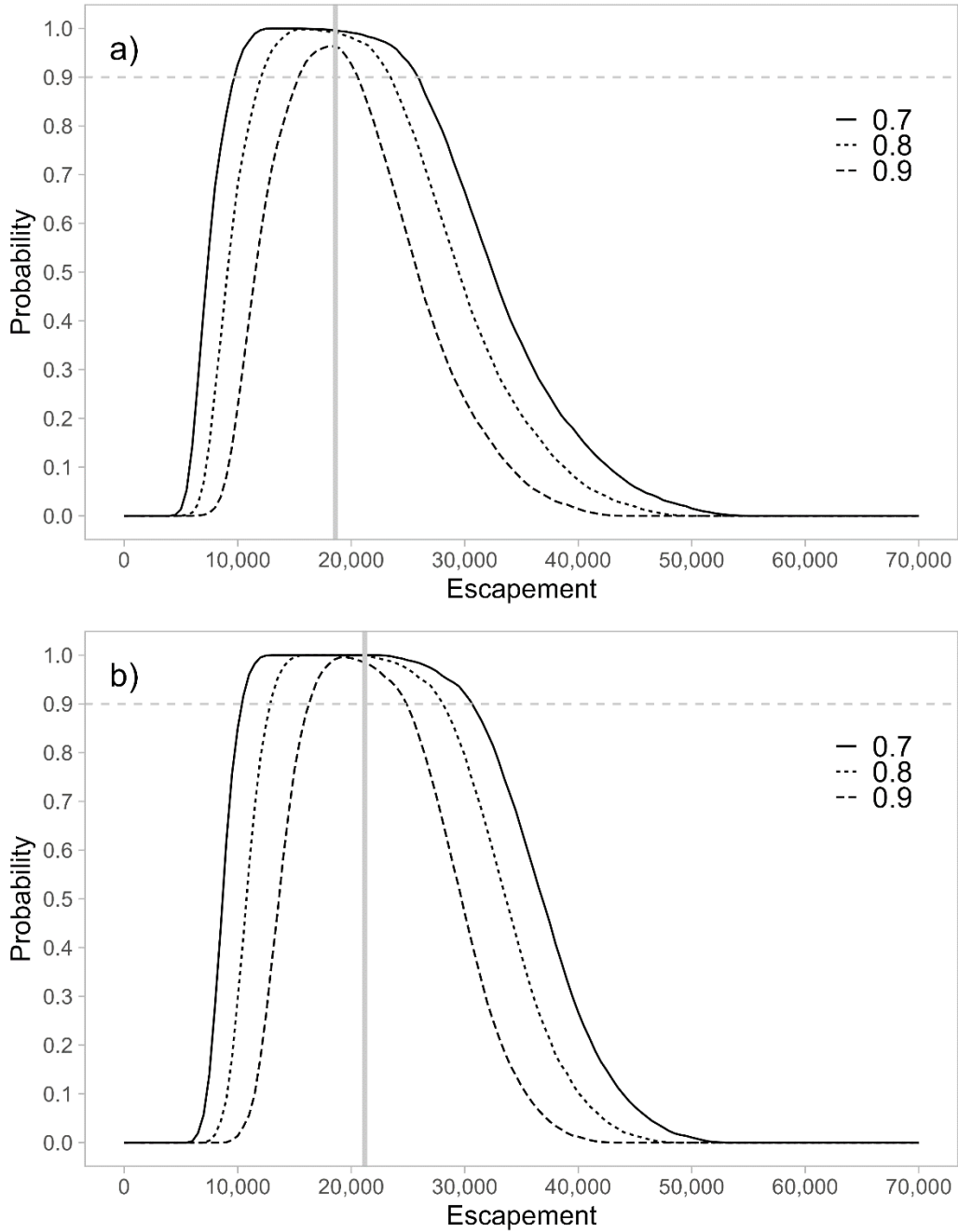


Figure 6. Optimal yield profiles (OYPs) for the (A) Tahltan natural stock of Stikine River sockeye salmon stock and the (B) mainstem stock of Stikine Ricker sockeye salmon stock as derived from a first-order autoregressive Ricker model for brood years 1983–2014. The OYPs show the probability that an escapement will result in specified fractions (0.70, 0.80, and 0.90 line) of maximum sustained yield. The vertical lines are the point estimate of S_{MSY} based on median (non-bias corrected) recruitment; 18,100 for the Tahltan natural stock and 21,000 for the mainstem stock. The dotted horizontal line is at 0.90 probability for reference.

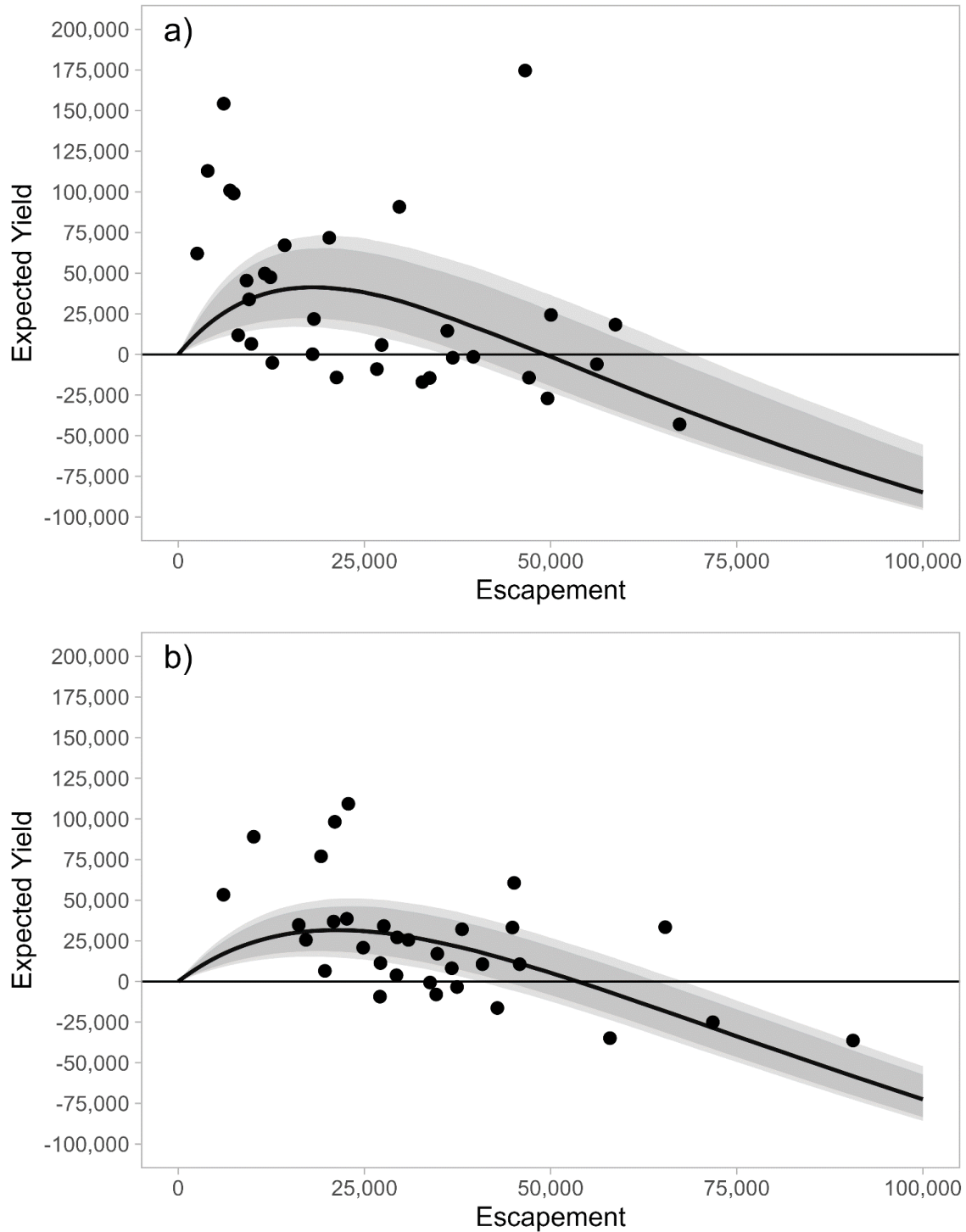


Figure 7. Expected sustained yield curve (based on median recruitment) with 90% and 95% Bayesian credible intervals (shaded regions) for the (A) Tahltan natural stock of Stikine River sockeye salmon and the (B) mainstem stock of Stikine Ricker sockeye salmon stock as derived from a first-order autoregressive Ricker model for brood years 1983–2014. The circles are the observed data.

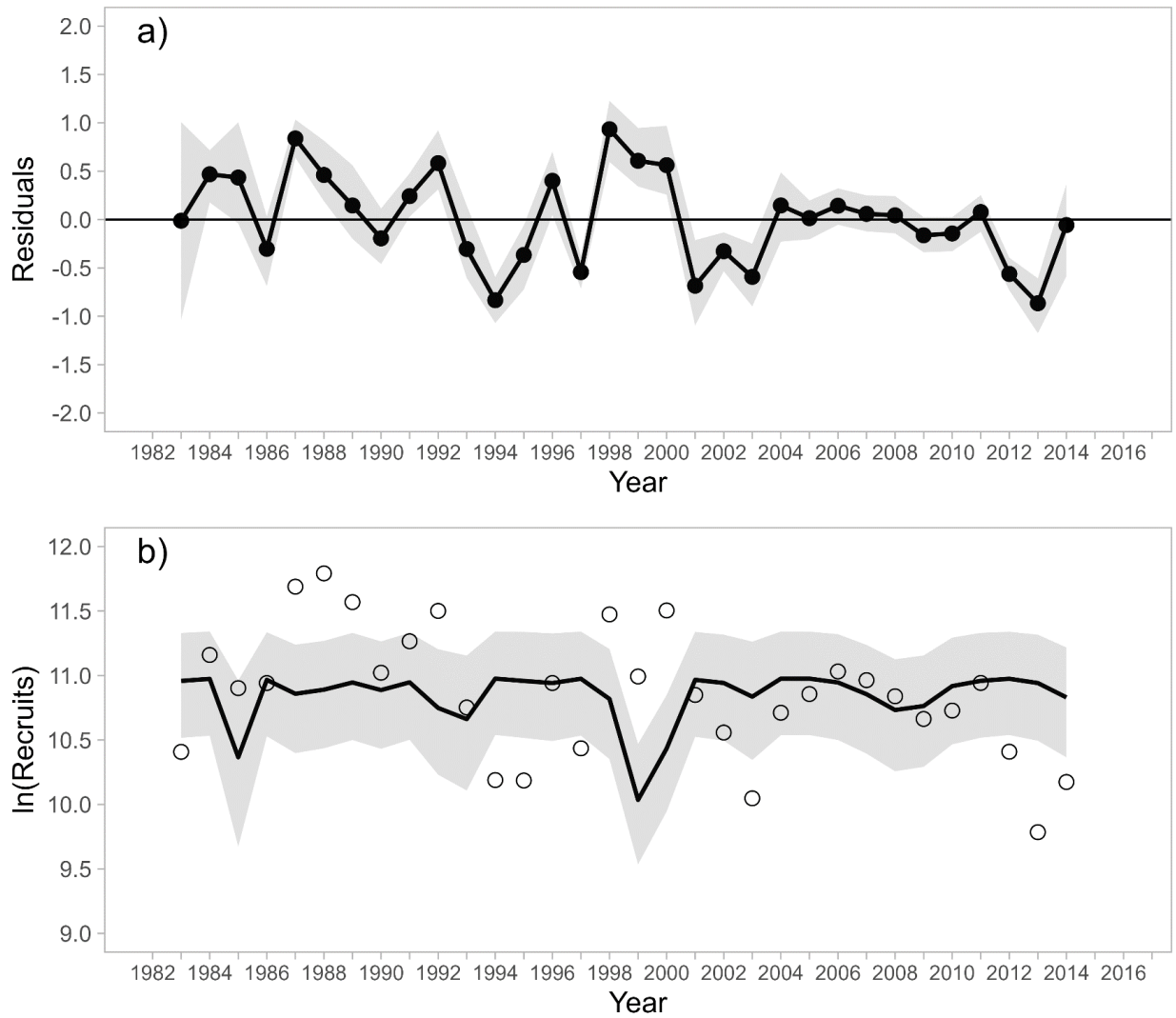


Figure 8. (A) Model residuals and (B) natural logarithms of recruits by brood year (1983–2014) from a first-order autoregressive Ricker model for the mainstem stock of Stikine River sockeye salmon. In figure B, the line is the predicted recruits (natural logarithm) and the open circles are the observed recruits (natural logarithm). The shaded area is the 95% credible interval.