ADVICE FROM THE ASSESSMENT OF THE RISK TO FRASER RIVER SOCKEYE SALMON DUE TO *TENACIBACULUM MARITIMUM* TRANSFER FROM ATLANTIC SALMON FARMS IN THE DISCOVERY ISLANDS AREA, BRITISH COLUMBIA

Net-pen along the coast of British Columbia (photo credit: DFO).

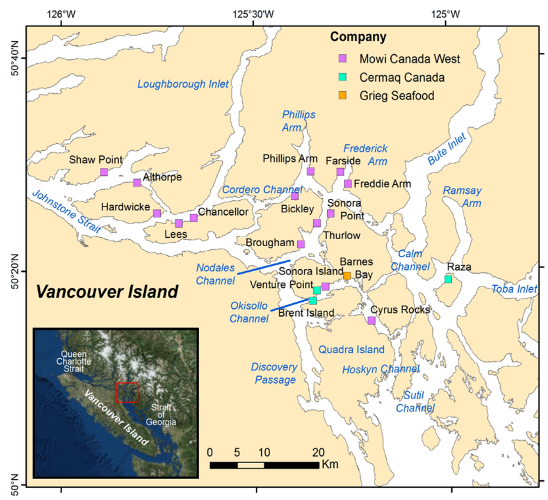

Figure 1. Location of the 18 Atlantic Salmon farms in the Discovery Islands area included in this risk assessment.

Context:

Fisheries and Oceans Canada (DFO), under the Sustainable Aquaculture Program, is committed to deliver environmental risk assessments to support science-based decision making related to aquaculture activities. The Aquaculture Science Environmental Risk Assessment Initiative was implemented to assess the risks of aquaculture activities to wild fish and the environment. The risks associated with each environmental stressor validated in the Pathways of Effects for finfish and shellfish aquaculture (DFO, 2010) will be assessed as per the Aquaculture Science Environmental Risk Assessment Framework ensuring a systematic, consistent and transparent process.

DFO's Aquaculture Management Directorate has requested CSAS advice on the risks to Fraser River Sockeye Salmon due to pathogen transfer from marine Atlantic Salmon (Salmo salar) farms located in the Discovery Islands area in British Columbia. This request supports DFO's role in the management of aquaculture in British Columbia and aligns with recommendations in the final report of the Commission of Inquiry into the Decline of Sockeye Salmon in the Fraser River, including recommendations 18 and 19 on risks to wild fish populations related to pathogen transfer from finfish farms (Cohen, 2012).

The advice is provided through a series of pathogen transfer risk assessments; this eighth risk assessment is focusing on Tenacibaculum maritimum*. The risks associated with other pathogens also* *known to cause disease on marine Atlantic Salmon farms in the Discovery Islands area will be assessed in subsequent processes.*

This Science Advisory Report is from the December 3-5, 2019 National Peer Review Meeting on the Assessment of the risk to Fraser River Sockeye Salmon due to bacteria causing erosive lesions transfer from Atlantic Salmon farms located in the Discovery Islands area, British Columbia. Additional publications from this meeting will be posted on the [Fisheries and Oceans Canada (DFO) Science Advisory Schedule] as they become available.

SUMMARY

Tenacibaculum maritimum Transfer Risk Assessment

- *Tenacibaculum maritimum* released from Atlantic Salmon (*Salmo salar*) farms operating in the Discovery Islands area was assessed to pose minimal risk to Fraser River Sockeye Salmon (*Oncorhynchus nerka*) abundance and diversity under current farm practices.
- The assessment relied on 2002 to 2018 fish health data on salmon farms; and the current state of knowledge of *T. maritimum,* including fish health data surveys and studies from enhanced and wild salmon in British Columbia.
- Between 2002 and 2018, clinical signs of the disease mouthrot (yellow mouth) have been reported on Atlantic Salmon farms in the Discovery Islands area 13 of 17 years through the Fish Health Audit Surveillance Program and/or as a Fish Health Event.
- Susceptibility of Sockeye Salmon is unknown, therefore it was assumed for the risk assessment that Sockeye Salmon are susceptible to *T. maritimum* infection.
- The overall likelihood assessment concluded that Fraser River Sockeye Salmon would become infected with *T. maritimum* released from Atlantic Salmon farms in the Discovery Islands area is unlikely for juveniles and very unlikely for adults. The uncertainties for the different steps ranged from high uncertainty to high certainty.
- The consequence assessment concluded that the potential magnitude of impacts on the abundance and diversity of Fraser River Sockeye Salmon is negligible given that mortality attributable to *T. maritimum* infection from Atlantic Salmon farms was estimated to be less than 1%. This conclusion was made with reasonable uncertainty.
- The main sources of uncertainties, the approach taken to address each of them, and their potential impacts on the results/rankings and the final risk estimates were included in the risk assessment. The most conservative assumptions and estimates (e.g., plausible worst-case scenarios) were applied to the final rankings/conclusions wherever possible.

This risk assessment was informed by a summary of the current state of knowledge on *Tenacibaculum maritimum* and mouthrot (Wade and Weber, 2020). The key elements of this review are summarized below.

Characterization of *Tenacibaculum maritimum* and mouthrot

- *Tenacibaculum maritimum* has a global distribution. It is a naturally occurring member of the marine bacterial community. This species had been found in association with fish (i.e., on the surfaces of fish) with and without signs of disease. It is considered to be an opportunistic pathogen of marine fishes.

- Mouthrot (yellow mouth) is a disease of juvenile farmed salmonids in British Columbia (BC) and the United States (US) Pacific Northwest. Clinical signs of this disease are yellow plaques in the mouth. This disease is caused by infection with *Tenacibaculum maritimum.*
- Mouthrot has not been reported in any wild salmon species in BC or Washington State. However, it has been rarely observed in farmed Chinook Salmon.
- Genetic material of *T. maritimum* was detected in samples from 5 of 2,006 wild juvenile Fraser River Sockeye Salmon. Note that this detection does not necessarily indicate infection or disease.
- Mouthrot is usually diagnosed in juvenile Atlantic Salmon in the first few months after seawater entry. Mouthrot has not been diagnosed in farmed salmonids after the first year at sea.
- The mechanisms by which juvenile Atlantic Salmon die from *T. maritimum* infection are unknown.
- *Tenacibaculum maritimum* causing mouthrot has been demonstrated to transfer between fish in a laboratory experiment. However, neither the timing of shedding nor the rate of shedding during infection have been described.
- There is no commercially available vaccine for *T. maritimum* in Atlantic Salmon. Treatment of mouthrot is the largest use of antimicrobials by the BC salmon farming industry and it is used with success.

INTRODUCTION

This risk assessment was conducted under the DFO Aquaculture Science Environmental Risk Assessment Initiative, implemented as a structured approach to provide risk-based science advice to further support sustainable aquaculture in Canada. Risk assessments conducted under this initiative follow a Framework adapted from international and national risk assessment frameworks (GESAMP, 2008; ISO, 2009; Mandrak et al., 2012). Details about the initiative and the framework are available on the DFO Aquaculture Science Environmental Risk Assessment Initiative webpage. Risk assessments conducted under the Initiative do not include socio-economic considerations.

This advisory report summarizes the consensus advice developed during the December 3-5, 2019 Canadian Science Advisory Secretariat (CSAS) scientific peer-review meeting that included international and national scientific experts. The information and current scientific knowledge about *Tenacibaculum maritimum* and mouthrot and the risk assessment were presented in the following documents:

- Characterization of *Tenacibaculum maritimum* and mouthrot to inform pathogen transfer risk assessments in British Columbia (Wade and Weber, 2020).
- Assessment of the risk to Fraser River Sockeye Salmon due to *Tenacibaculum maritimum* on Atlantic Salmon farms in the Discovery Islands area, British Columbia (Mimeault et al., 2020).

The two supporting research documents were reviewed and used to meet the remaining objectives of the meeting, specifically:

- review the qualitative assessments of the risk to Fraser River Sockeye Salmon abundance and diversity due to *Tenacibaculum maritimum* transferred from Atlantic Salmon farms located in the Discovery Islands area;
- review the uncertainties associated with the estimation of the risk to Fraser River Sockeye Salmon abundance and diversity; and
- if risk assessment outcomes warrant, provide advice on additional measures that would reduce the risk to Fraser River Sockeye Salmon abundance and diversity due to *Tenacibaculum maritimum* transferred from Atlantic Salmon farms in the Discovery Islands area.

ANALYSIS

Characterization of *Tenacibaculum maritimum* and mouthrot

The following summary highlights the key aspects of *Tenacibaculum maritimum* and mouthrot relevant to the risk assessment; for more details refer to Wade and Weber (2020).

The genus *Tenacibaculum* includes several species pathogenic to marine fish. To date, three species (*Tenacibaculum dicentrarchi*, *Tenacibaculum finnmarkense*, and *Tenacibaculum maritimum*) have been associated with tenacibaculosis in Atlantic Salmon globally. However, on the Pacific Coast of North America, the clinical presentation of *T. maritimum* infection in Atlantic Salmon differs from tenacibaculosis and is referred to as mouthrot or yellow mouth (summarised in Frisch et al. (2018a)). Treatment of *Tenacibaculum maritimum* infection is the largest use of antimicrobials by the industry in BC (Morrison and Saksida, 2013) as there is no commercially available vaccine. This analysis focuses on *T. maritimum* causing mouthrot.

Tenacibaculum maritimum (formerly *Flexibacter maritimus)* is an aerobic, gram-negative, gliding, filamentous bacterium (Wakabayashi et al., 1986; Suzuki et al., 2001; Avendaño-Herrera et al., 2006). Clinical signs of mouthrot in Atlantic Salmon include: lethargy, weakness and anorexia, and some fish may exhibit head shaking or flashing (Kent, 1992). Early in the infection, yellow bacterial mats are present around the palate, teeth and vomer (Kent, 1992). As disease progresses, fish develop multiple ulcers in the mouth with large yellow bacterial mats (Kent, 1992; Frelier et al., 1994).

Phylogenetic analyses of *T. maritimum* isolates sampled from fish with clinical mouthrot demonstrated that the Western Canadian isolates belong to distinct sequence types (Frisch et al., 2017), which are most closely related to the strain isolated from Norwegian Lumpfish and a strain isolated from Chilean Atlantic Salmon. Results from this study and previous analysis of *T. maritimum* by Habib et al. (2014) suggest that the distribution of the bacterial strains may be related to seawater temperature.

Mouthrot has been reported in farmed Atlantic Salmon in BC (Ostland et al., 1999) and Washington State (Frelier et al., 1994), in farmed Rainbow Trout in Washington State (Frelier et al., 1994) and in farmed Chinook Salmon (*O. tschawytscha*) in BC (summarized in Wade and Weber (2020)). To date, mouthrot has not been diagnosed in farmed Coho Salmon (*O. kisutch*) in BC (DFO, 2019a, b; Wade and Weber, 2020). Mouthrot has not been reported in any wild fish species in BC or Washington State. No references could be found describing the bacterial isolation or mouthrot in Sockeye Salmon. However, Nekouei et al. (2019) reported the molecular detection of *T. maritimum* in 5 of 2,006 juvenile Fraser River Sockeye Salmon screened using high-throughput microfluidics quantitative PCR. The samples used in this study were homogenates of five different tissues including gill and the screening test was not validated for diagnostic purposes; therefore, the authors emphasized that these detections are not necessarily indicative of infection with the bacterium.

Mouthrot is primarily considered a disease of concern for smolts. Mouthrot can usually be observed in smolts between three to eight weeks following seawater entry (Hicks, 1989; Frelier et al., 1994) and affects smolts in their first year at sea (Anonymous, 1996 in Ostland et al. (1999)). Some potential predisposing factors for Atlantic Salmon smolts to contract mouthrot include feeding on hard pellets, fish biting net surfaces and stress-induced lesions/abrasions in the mouth (Kent and Poppe, 1998). However, there is still little understanding of the mechanism of infection, and the mechanism of death in Atlantic Salmon smolts infected with *Tenacibaculum maritimum* in BC is still unknown (Frisch et al., 2018a).

Tenacibaculum maritimum isolates from outbreaks in Western Canada can induce mouthrot in Atlantic Salmon (Frisch et al., 2018b); however, there are virulence differences between different *T. maritimum* isolates. For example, while a 5-hour bath challenge with a Western Canadian isolate resulted in 100% mortality in Atlantic Salmon when exposed to concentrations of ~10^5 cells/mL and higher, exposure to a higher concentration (~10^7) of a different isolate did not induce mortality. When mortality was induced, first mortalities were observed 3 to 11 days post-exposure. The last observed mortalities occurred from 6 to 14 days post exposure. All of these experiments were concluded 21 days after exposure.

The only published paper describing outbreaks of mouthrot on salmonid farms without treatment (located in Puget Sound, Washington, USA) reported that cumulative pen-level mortalities in smolts with characteristic oral lesions varied between 5 and 10%, but occasionally reached as high as 30% (Frelier et al., 1994).

Horizontal transmission of *T. maritimum* (the spread from fish to fish) has been demonstrated through cohabitation experiments with 40 g Norwegian Atlantic Salmon smolts and isolates derived from BC Atlantic Salmon showing clinical signs of mouthrot (Frisch et al., 2018b). Although the horizontal transmission is consistent with shedding of *T. maritimum* from infected fish, to date, neither the timing of shedding nor the rate of shedding during infection have been described.

Clinical signs of mouthrot have been reported at temperatures ranging from approximately 8 to 15 °C and salinity ranging between 29 and 34 ppt (Frelier et al., 1994; Frisch et al., 2017).

The bacterium is adhesive and can create biofilms on hard surfaces (Declercq et al., 2013; Frisch et al., 2017; Frisch et al., 2018a; Frisch et al., 2018b). The kinetics of various *T. maritimum* strains tested (none from BC) suggest that the inert surfaces of aquaculture settings can harbour biofilms and serve as transient reservoirs for the bacteria (Levipan et al., 2019).

Occurrence on Atlantic Salmon farms in BC

Between 2002 and 2018, mouthrot was diagnosed at the farm-level in 106 of the 1459 (7.3%) audits conducted on Atlantic Salmon farms in BC through the Fish Health Audit Surveillance Program. In the same time period (excluding 2013 - 2015), 537 Fish Health Events were attributed to mouthrot on Atlantic Salmon farms in BC. Between 2011 and 2018, four mortality events were attributed to mouthrot on Atlantic Salmon farms in BC. Refer to Wade and Weber (2020) for more details.

Tenacibaculum maritimum Transfer Risk Assessment

The risks to Fraser River Sockeye Salmon abundance and diversity due to *T.maritimum* transferred from Atlantic Salmon farms operating in the Discovery Islands area (see Figure 1) were assessed under current farm practices, including fish health management.

Current fish health management practices include regulatory requirements (e.g., Salmonid Health Management Plan, accompanying proprietary Standard Operating Procedures (SOPs) and regulation of movement of live fish) and additional voluntary industry practices (e.g., surveillance and testing, use of nursery sites).

Conceptual Model

The risk assessment followed three main steps outlined in Figure 2, including likelihood assessment, consequence assessment and risk estimation.

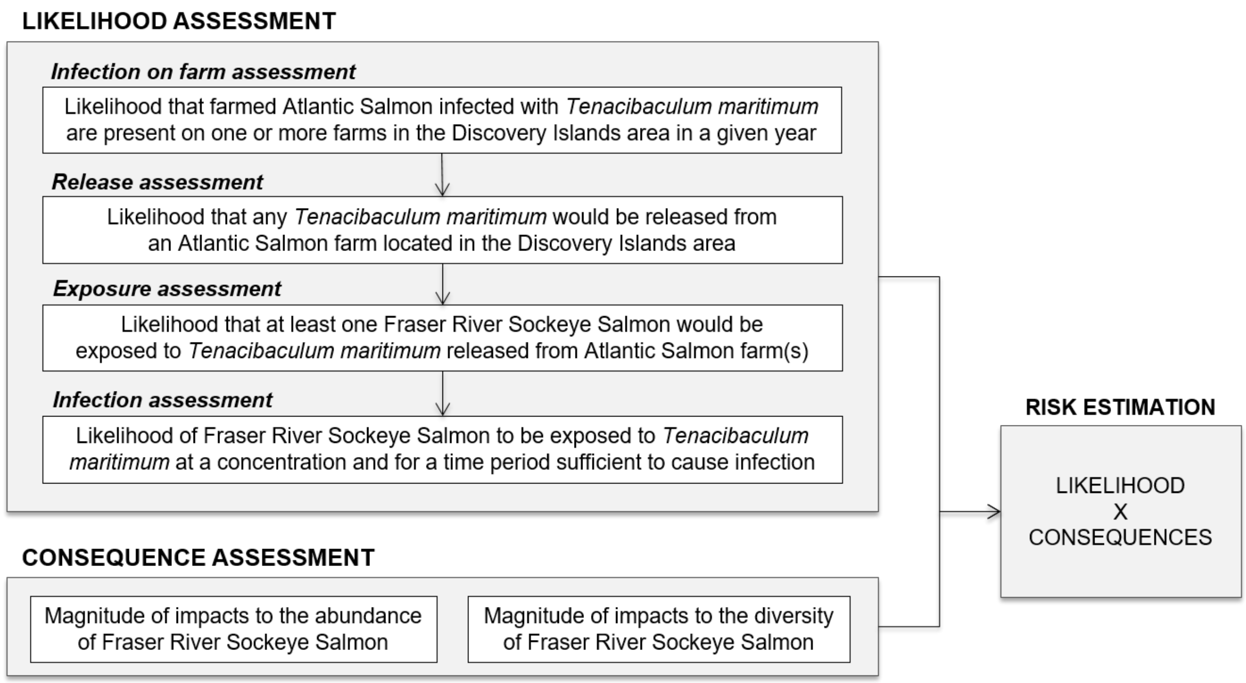

Figure 2. Conceptual model to assess the risks to Fraser River Sockeye Salmon resulting from Tenacibaculum maritimum *attributable to Atlantic Salmon farms located in the Discovery Islands area, BC. Adapted from Mimeault et al. (2017).*

Likelihood Assessment

The likelihood assessment was conducted through four sequential assessments: farm infection, release, exposure and infection assessments. Each step of the likelihood assessment assumes that current management practices on Atlantic Salmon farms are followed and maintained. The main considerations and conclusions of each step are reported here.

Farm infection assessment

The farm infection assessment determined the likelihood that farmed Atlantic Salmon infected with *T. maritimum* are present on one or more farms in the Discovery Islands area in a given year.

Between 2002 and 2018, mouthrot was diagnosed at the farm-level during fish health audits conducted on Atlantic Salmon farms in the Discovery Islands area in 7 out of 17 years. In the same period, Fish Health Events were attributed to mouthrot in 12 out of 17 years. The disease was not attributed to mortality events on Atlantic Salmon farms in the Discovery Islands area.

Overall, between 2002 and 2018, clinical signs of mouthrot have been reported on Atlantic Salmon farms in the Discovery Islands area through the Fish Health Audit Surveillance Program and/or as a Fish Health Event in 13 of 17 years. It was therefore concluded with reasonable certainty that, in any given year, the likelihood of farmed Atlantic Salmon infected with *T. maritimum* are present on one or more Atlantic Salmon farms in the Discovery Islands area is very likely under the current farm management practices.

Release assessment

The release assessment determined the likelihood that any *T.m maritimum* would be released from an Atlantic Salmon farm located in the Discovery Islands area into an environment accessible to Fraser River Sockeye Salmon assuming Atlantic Salmon infected with the bacterium are present on at least one farm. Two pathways were considered: release through infected farmed Atlantic Salmon and mechanical vectors (e.g., personnel, visitors and wildlife) and fomites (e.g., farm equipment and vessels).

Given the evidence of shedding and horizontal transmission (i.e., spread from fish to fish) of *T. maritimum* under experimental conditions, it was concluded with high certainty that the bacterium would be extremely likely to be released from an infected Atlantic Salmon farm into the marine environment.

T. maritimum can form biofilms and adhere to structures, such as those found at an aquaculture site, which can act as a transient reservoir for the bacterium. As part of licence requirements, biosecurity and biocontainment practices are specified in Salmonid Health Management Plans and associated SOPs. Low levels of operational deficiencies related to fish health on Atlantic Salmon farms in the Discovery Islands area have been documented in DFO's Fish Health Audit and Surveillance Program as summarized by Wade (2017). It was therefore concluded with reasonable uncertainty that the likelihood of release through vectors or fomites is likely under the current fish health management practices.

The overall likelihood of release was obtained by adopting the highest likelihood of the release pathways. It is therefore extremely likely that *T. maritimum* would be released from an infected Atlantic Salmon farm.

Exposure assessment

The exposure assessment determined the likelihood that at least one Fraser River Sockeye Salmon would be exposed to *T. maritimum* in a given year assuming that the bacterium has been released from at least one Atlantic Salmon farm in the Discovery Islands area. Two exposure groups were considered: juvenile and adult Fraser River Sockeye Salmon.

The exposure assessment examined whether mouthrot on Atlantic Salmon farms occurred during the time period that Fraser River Sockeye Salmon migrate through the Discovery Islands area.

Juvenile lake-type Fraser River Sockeye Salmon migrate through the Discovery Islands area from approximately mid-May to mid-July, while returning adults migrate through the area from approximately late-June to early-October (reviewed in Grant et al. (2018)). To account for annual variations in migration timing, it was assumed that juveniles could be present in the

Discovery Islands area from the beginning of May through the end of July. Similarly, for returning adults, it was assumed that adult Sockeye Salmon could be present in the Discovery Islands area from the beginning of June through to the end of October.

Mouthrot has been reported on Atlantic Salmon farms in the Discovery Islands area in every month of the year; and consequently there is temporal overlap between migrating Fraser River Sockeye Salmon and mouthrot occurrences on Atlantic Salmon farms located in the Discovery Islands area. It was therefore concluded with reasonable certainty that it is very likely that at least one juvenile or adult Fraser River Sockeye Salmon will be exposed to *T. maritimum* attributable to an Atlantic Salmon farm located in the Discovery Islands.

Infection assessment

The infection assessment determined the likelihood that Fraser River Sockeye Salmon exposed to *T. maritimum* released from Atlantic Salmon farm(s) in the Discovery Islands area are exposed to a concentration of bacteria and for a period of time sufficient to cause infection.

As of late 2019, mouthrot has not been reported in wild salmonids (including Sockeye Salmon) in BC or Washington State (reviewed in Wade and Weber (2020)) and the susceptibility of Sockeye Salmon to *T. maritimum* infection and disease is unknown. Nonetheless, given the molecular detection of *T. maritimum* in juvenile Fraser River Sockeye Salmon (Nekouei et al., 2018) and given that mouthrot has been reported in farmed Chinook Salmon in BC (reviewed in Wade and Weber (2020)), Sockeye Salmon were assumed to be susceptible to infection with *T. maritimum* in this risk assessment.

Mouthrot mainly affects Atlantic Salmon smolts recently transferred into saltwater (Frelier et al., 1994; Frisch et al., 2018a) and has not been reported in the second year of the production cycle of farmed salmon in BC, which suggests a decrease in susceptibility to the disease with age.

The amount of *T. maritimum* shed from an Atlantic Salmon farm infected with the bacterium could not be determined given that the shedding rate from *Tenacibaculum maritimum*-infected Atlantic Salmon, or other salmonids, is unknown (Wade and Weber, 2020). Additionally, there are also no data on the decay rate of *T. maritimum* in the marine environment (Wade and Weber, 2020). Consequently, it was not possible to estimate the infection pressure or to model the dispersal of *T. maritimum* from infected Atlantic Salmon farms in the Discovery Islands area for this risk assessment.

To date, the minimum concentration of Western Canadian *T. maritimum* isolates and exposure time required to cause infection (minimum infectious dose) in Sockeye Salmon is unknown. Frisch and colleagues, however, reported on the duration of exposure and the concentration of different Western Canadian isolates of *T. maritimum* that induced mortality in Norwegian Atlantic Salmon under experimental conditions (Frisch et al., 2018b). Their work demonstrated differences in pathogenicity among isolates with, for example, challenges with one strain causing 100% mortality at a concentration of 6.36 $\times 10^5$ cells/mL whereas challenges with another strain for the same duration at a concentration of 1.28 $\times 10^7$ cells/mL did not cause mortality and fish showed no signs of disease (Frisch et al., 2018b).

The duration of exposure of Fraser River Sockeye Salmon to Atlantic Salmon farms is not precisely known. Based on Sockeye Salmon swimming speed summarized by Grant et al. (2018), it was estimated that juveniles could encounter Atlantic Salmon farms over three to eight days during their migration through the Discovery Islands area while adults could encounter farms over two days (Mimeault et al., 2017). Additionally, telemetry studies (Rechisky et al.,

2018) suggest that juvenile Sockeye Salmon are generally in proximity of an individual farm for less than 20 minutes. There are no data for the returning adults.

Given the limited direct interaction of Fraser River Sockeye Salmon with farm sites, the lack of published reports of clinical signs associated to *T. maritimum* infection in Sockeye Salmon, the five positive detections of *T. maritimum* out of 2006 juvenile Sockeye Salmon sampled around and north of the Discovery Islands area, and that Fraser River Sockeye Salmon are already adapted to saltwater when reaching the Discovery Islands area, it was concluded with high uncertainty that it is unlikely that juvenile Fraser River Sockeye Salmon will become infected with *T. maritimum* attributable to Atlantic Salmon farms in the Discovery Islands area under the current farm practices.

Given very limited direct interactions of returning adults with the farms, their quick migration to freshwater, and the fact that mouthrot is primarily a disease concern for farmed Atlantic Salmon smolts, it was concluded with reasonable uncertainty that it is very unlikely that adult Fraser River Sockeye Salmon will become infected with *T. maritimum* attributable to Atlantic Salmon farms in the Discovery Islands area under the current farm practices.

Overall likelihood assessment

Table 1 summarizes the likelihood assessment. Overall, it was concluded that the likelihood that Fraser River Sockeye Salmon would become infected with *T. maritimum* released from Atlantic Salmon farms in the Discovery Islands area is unlikely for juveniles and very unlikely for adults. This conclusion was driven by the likelihood of infection which is associated with important uncertainties. These uncertainties are: the lack of data about (i) *T.maritimum* shedding rates from Atlantic Salmon infected with the bacterium; (ii) *T.maritimum* decay rates in the marine environment; (iii) the susceptibility of Sockeye Salmon to *T. maritimum;* and (iv) the minimum dose of *T. maritimum* required to infect Sockeye Salmon.

Uncertainties for each step in the likelihood assessment are not combined but are rather reported separately for clarity and transparency.

Table 1. Summary of the likelihood and uncertainty rankings for the likelihood assessment part of the assessment of the risk to Fraser River Sockeye Salmon due to Tenacibaculum maritimum *transfer from Atlantic Salmon farms in the Discovery Island area. Uncertainties are not combined.*

Step		**Ranking**	
Farm infection assessment	**Likelihood *(uncertainty)***	Very likely *(reasonable certainty)*	
Release assessment	**Release pathways**	**Farmed Atlantic Salmon**	**Mechanical vectors and fomites**
	Likelihood *(uncertainty)*	Extremely likely *(high certainty)*	Likely *(reasonable uncertainty)*
	Combined likelihood	Extremely likely	
Exposure assessment	**Exposure groups**	**Juveniles**	**Adults**
	Likelihood *(uncertainty)*	Very likely *(reasonable certainty)*	Very likely *(reasonable certainty)*
Infection assessment	**Likelihood *(uncertainty)***	Unlikely *(high uncertainty)*	Very unlikely *(reasonable uncertainty)*
Overall likelihood for each exposure group (combination of all four steps)		Unlikely	Very unlikely

Consequence Assessment

The consequence assessment aims to determine the potential magnitude of impacts of *T. maritimum* attributable to Atlantic Salmon farms in the Discovery Islands area on the abundance and diversity of the Fraser River Sockeye Salmon assuming that Fraser River Sockeye Salmon became infected with the bacterium from Atlantic Salmon farms in the Discovery Islands area.

The consequence assessment focuses only on potential impacts resulting from juvenile Fraser River Sockeye Salmon infection given that the disease primarily affects juveniles.

A quantitative consequence assessment was conducted using mortality as the endpoint to determine the potential magnitude of consequences in both abundance and diversity of Fraser River Sockeye Salmon resulting from infection with *T. maritimum* attributable to Atlantic Salmon farms in the Discovery Islands area.

Potential impacts on abundance

Few studies have looked at *T. maritimum* and/or mouthrot in wild salmon. Fisheries and Oceans Canada sampled a total of 2419 Sockeye Salmon in the Strait of Georgia between 2010 and 2012. Results from this study have yet to be published but no gross signs of mouthrot (yellow plaques) were reported (S. Johnson, Fisheries and Oceans Canada, pers. comm. 2020). The published data on the molecular detection of *T. maritimum* in juvenile Fraser River Sockeye Salmon (Nekouei et al., 2018) were used as an estimate of the prevalence of infection at the population level.

The mouthrot mortality rates in farmed salmonids reported by Frelier et al. (1994) were used as it is the only relevant surrogate data available to estimate population-level mortality in infected juvenile Fraser River Sockeye Salmon. The mortality rates of farmed Atlantic Salmon smolt during an outbreak (ranged between 0 and 30% with a mode of 10%) are considered to be higher than what would be anticipated in wild populations due to the prolonged exposure time and higher densities within the cage. Overall, this was considered to be a worst-case scenario.

Two scenarios were developed using the estimated prevalence based on the positive molecular detections reported in Nekouei et al. (2018). Both scenarios assumed that the molecular detection of *T. maritimum* in juvenile Fraser River Sockeye Salmon were from truly infected fish and that the infection was attributable to the Atlantic Salmon farms in the Discovery Islands area (Mimeault et al., 2020).

- The first scenario, considered to be a conservative scenario, used the weighted average of the prevalence of *T. maritimum* in Sockeye Salmon sampled in 2012 and 2013. Under this scenario, there was 99% certainty that the mortality attributable to *T. maritimum* infections from Atlantic Salmon farms would be less than 0.29% in juvenile Fraser River Sockeye Salmon.
- The second scenario, considered to be a worst case scenario, only used the prevalence of *T. maritimum* in Sockeye Salmon sampled in 2012, as all samples were negative in 2013. Additionally, in 2012 there were no Atlantic Salmon farms in the Discovery Islands area that had reported incidences of mouthrot. Under this scenario, there was 99% certainty that the mortality attributable to *T. maritimum* infections from Atlantic Salmon farms would be less than 1% in juvenile Fraser River Sockeye Salmon.

Based on the above two scenarios, *T. maritimum* infections attributable to Atlantic Salmon farms in the Discovery Islands area would result in negligible consequences (i.e., 0 to 1% reduction in the number of retuning adults) to the abundance of Fraser River Sockeye Salmon. This conclusion was made with reasonable uncertainty given reliance on a single study for prevalence of infection (based on molecular detection) and the use of surrogate data for mortality.

Potential impacts on diversity

The potential impacts on abundance resulting from infection with *T. maritimum* on Fraser River Sockeye Salmon over two generations (eight years for Fraser River Sockeye Salmon) were used to explore potential impacts on diversity.

Between 2002 and 2018, *T. maritimum* infection on Atlantic Salmon farms happened during the out-migration window of juvenile Fraser River Sockeye Salmon in 11 of 17 years (about 65%) (Mimeault et al., 2020). Consequently, in 6 of 17 years (about 35%), juvenile Fraser River Sockeye Salmon were not exposed to *T. maritimum* attributable to Atlantic Salmon farms in the Discovery Islands area.

In years without evidence of infection during the juvenile migration window, there would not be impacts to Fraser River Sockeye Salmon abundance attributable to *T. maritimum* on Atlantic Salmon farms. In the years with evidence of infection on farms, impacts on abundance was determined to be negligible (i.e., there would be 99% certainty that mortality in the out-migrating population would not exceed the threshold of 1%).

Given that no impact would be expected in years without infection and the very low probability of population mortality (<1%) in years with the evidence of infection, it was concluded that the potential magnitude of consequences to the diversity of juvenile Fraser River Sockeye Salmon is negligible over two generations (eight years). This conclusion was made with reasonable uncertainty given reliance on a single study for prevalence of infection and the reliance on surrogate data for mortality.

Risk Estimation

The estimated risks to the abundance and diversity of Fraser River Sockeye Salmon are based on the results of the likelihood and consequence assessments. Risk matrices were developed, as described in Mimeault et al. (2017), and are aligned with relevant scales of consequences for DFO fisheries management and policy purposes, existing policy and current management risk tolerances relevant to the risk assessment.

Under the current farm practices, the risk to the abundance of Fraser River Sockeye Salmon as a result of a *T. maritimum* infection attributable to Atlantic Salmon farms in the Discovery Islands area is minimal (Figure 3).

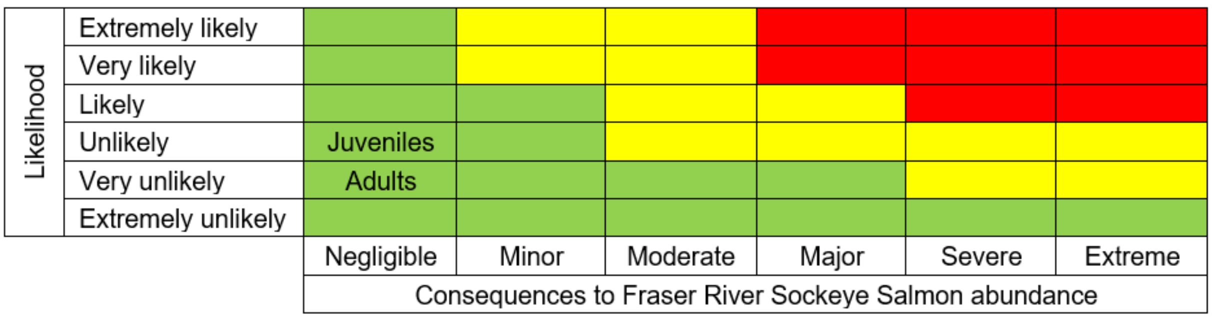

Figure 3. Risk matrix for combining the results of the assessment of the likelihood and consequences to Fraser River Sockeye Salmon abundance. Green, yellow and red, respectively, represent minimal, moderate and high risk.

Under the current farm practices, the risk to the diversity of Fraser River Sockeye Salmon as a result of a *T. maritimum* infection attributable to Atlantic Salmon farms in the Discovery Islands area is minimal (Figure 4).

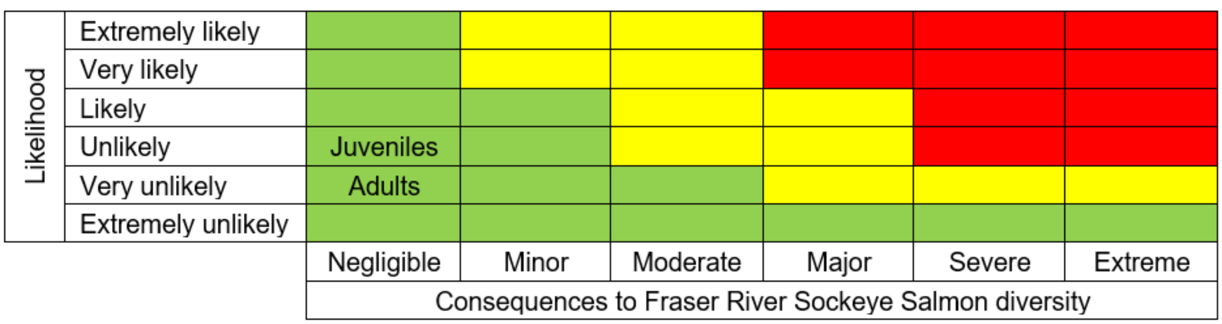

Figure 4. Risk matrix for combining the results of the assessment of the likelihood and consequences to Fraser River Sockeye Salmon diversity. Green, yellow and red, respectively, represent minimal, moderate and high risk.

Sources of Uncertainty

Overall, uncertainty includes both variability, which is a function of the system that is not reducible with additional measurements, and lack of knowledge that may be reduced with additional data or expert opinion (Vose, 2008).

The main uncertainty in this risk assessment relates to the susceptibility of Sockeye Salmon to infection with *T. maritimum.* To date, evidence of the pathogen in Sockeye Salmon is limited to its molecular detection. There is no evidence of *T. maritimum* isolation or clinical signs attributed to the pathogen in Sockeye Salmon. Mouthrot has been identified in farmed Atlantic Salmon, Rainbow Trout and Chinook Salmon.

Taking a conservative approach in this risk assessment, Sockeye Salmon were assumed to be susceptible to infection with *T. maritimum*. Additionally, in the consequence assessment, the clinical signs in Sockeye Salmon resulting from infection with *T.maritimum* were assumed to be similar to the ones observed in Atlantic Salmon to explore worst case scenarios albeit acknowledging that mouthrot is not common in farmed Pacific Salmon.

Uncertainties in the likelihood assessment

Other important uncertainties are related to the infection assessment and are due to a lack of knowledge related to: (i) *T. maritimum* infection pressure attributable to Atlantic Salmon farms, since the on-farm prevalence and shedding rates from *T. maritimum*-infected Atlantic Salmon are unknown; and (ii) the minimum infectious dose in Sockeye Salmon.

Given the limited and short direct interaction of Fraser River Sockeye Salmon with farm sites, it was concluded that infection with *T. maritimum* would “occasionally” occur. However, given the lack of knowledge and reliance on surrogate data, this ranking was made with high uncertainty.

Uncertainties in the consequence assessment

The main uncertainties in the consequence assessment are related to the lack of knowledge about (i) the true prevalence of *T. maritimum* in migrating Fraser River Sockeye Salmon attributable to Atlantic Salmon farms in the Discovery Islands area; and (ii) the mortality rate attributable to infection with *T. maritimum* in Sockeye Salmon. To address those, the molecular detection prevalence of the bacterium in Fraser River Sockeye Salmon sampled along their out-migration route and the mortality among infected cages of farmed salmonids were used.

CONCLUSIONS

Characterization of *Tenacibaculum maritimum* and mouthrot

Tenacibaculum maritimum is a marine bacteria with global distribution. The strain of *T. maritimum* that is found in BC causes mouthrot in juvenile farmed salmonids, and is characterized by yellow plaques in the mouth. The literature specific to mouthrot is not abundant, and much of the basic epidemiology of the disease is unknown. There remains work to understand strain-specific virulence/pathogenicity, geographic distribution, reservoirs, transmission pathways of the causative agent, Pacific salmon susceptibility and stock-specific susceptibility, as well as characterizing contributing factors to the development of disease and outbreaks.

There is, however, abundant literature on some of these aspects of *T. maritimum* causing tenacibaculosis globally, which was used as surrogate information to assess the risk of transfer from farmed Atlantic Salmon to Fraser River Sockeye Salmon. However, there are important differences between strains of *T. maritimum* causing mouthrot and those that cause tenacibaculosis, including: different clinical signs; lower culture temperatures for mouthrot strains of *T. maritimum*; differences in the genetics; antibody response; and pathology. There are also significant differences in antigenic characteristics and virulence among the BC isolates causing mouthrot.

It is likely that environmental factors such as temperature and salinity affect the incidence of mouthrot but specific ranges are unknown.

T. maritimum causing mouthrot has been demonstrated to transfer horizontally between fish in a cohabitation experiment.

Between 2002 and 2018, mouthrot was diagnosed at the farm-level in 106 fish health audits conducted on Atlantic Salmon farms in BC. In the same time period (excluding 2013 to 2015), 537 Fish Health Events were attributed to mouthrot on Atlantic Salmon in BC. Between 2011 and 2018, a total of four mortality events were attributed to mouthrot on Atlantic Salmon farms in BC.

Tenacibaculum maritimum Transfer Risk Assessment

The assessment concluded that *T. maritimum* attributable to Atlantic Salmon farms in the Discovery Islands area poses minimal risk to Fraser River Sockeye Salmon abundance and diversity under the current farm practices.

Two main factors influenced the conclusion of the minimal risk. First, it is unlikely that juvenile and very unlikely that adult Fraser River Sockeye Salmon would become infected with *T. maritimum* attributable to Atlantic Salmon farms in the Discovery Islands area given that mouthrot mainly affects farmed Atlantic Salmon smolts recently transferred to seawater; that the disease has rarely been reported in farmed Pacific salmon suggesting a relatively low susceptibility; and that Fraser River Sockeye Salmon have limited and short interaction with Atlantic Salmon farms in the Discovery Islands. Second, based on the detection prevalence of *T. maritimum* in juvenile Fraser River Sockeye Salmon, infection with the bacterium attributable to Atlantic Salmon farms in the Discovery Islands area is expected to result in negligible impacts to Fraser River Sockeye Salmon abundance and diversity.

Uncertainty remains around the susceptibility of Sockeye Salmon to infection with *T. maritimum* and long-term impacts of the infection in specific and vulnerable stocks of Fraser River Sockeye Salmon.

RECOMMENDATIONS

- Actions could be undertaken to reduce the key areas of uncertainties and knowledge gaps regarding the epidemiology of infection with *T. maritimum* outlined in the sources of uncertainties.
- Conclusions of this risk assessment should be reviewed as new research findings fill the knowledge gaps.

OTHER CONSIDERATIONS

The points below should be considered in all fish pathogen transfer risk assessments in the Discovery Islands area.

- The long-term impacts of changing climatic conditions on the bacteria, farmed and wild salmon will need to be more understood and investigated.
- The Discovery Islands area is not the only area along the migration route of Fraser River Sockeye Salmon where Atlantic Salmon farms are located.
- An analysis of the risks associated with infection with more than one pathogen was not undertaken, but is an area that warrants more research/studies.

- This risk assessment is based on current industry size and practices, if there is a change in the size or practices of the Atlantic Salmon aquaculture industry in the Discovery Islands area, these changes would warrant further analyses and/or considerations in the risk estimate.

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SOURCES OF INFORMATION

This Science Advisory Report is from the December 3-5, 2019 National Peer Review Meeting on the Assessment of the risk to Fraser River Sockeye Salmon due to bacteria causing erosive lesions transferred from Atlantic Salmon farms located in the Discovery Islands area, British

Columbia. Additional publications from this meeting will be posted on the Fisheries and Oceans Canada (DFO) Science Advisory Schedule as they become available.

Avendaño-Herrera, R., Toranzo, A. E. and Magariños, B. 2006. Tenacibaculosis infection in marine fish caused by *Tenacibaculum maritimum*: a review. Dis. Aquat. Org. 71: 255-266.

Cohen, B. I. 2012. Recommendations, summary, process. *In* The uncertain future of Fraser River Sockeye. Minister of Public Works and Government Services Canada. Publishing and Depository Services, Ottawa, ON. Vol 3: 211 p.

Declercq, A. M., Haesebrouck, F., Van den Broeck, W., Bossier, P. and Decostere, A. 2013. Columnaris disease in fish: a review with emphasis on bacterium-host interactions. Vet. Res. 44(1): 27-27.

DFO. 2010. Pathways of effects for finfish and shellfish aquaculture. DFO Can. Sci. Advis. Sec. Sci. Advis. Rep. 2009/071. 22 p.

DFO. 2019a. Fish health events at British Columbia marine finfish aquaculture sites. Fisheries and Oceans Canada.

DFO. 2019b. Results of DFO fish health audits of British Columbian marine finfish aquaculture sites, by facility. Fisheries and Oceans Canada.

Frelier, P. F., Elston, R. A., Loy, J. K. and Mincher, C. 1994. Macroscopic and microscopic features of ulcerative stomatitis in farmed Atlantic salmon *Salmo salar*. Dis. Aquat. Org. 18: 227-231.

Frisch, K., Smage, S. B., Brevik, O. J., Duesund, H. and Nylund, A. 2017. Genotyping of *Tenacibaculum maritimum* isolates from farmed Atlantic salmon in Western Canada. J. Fish Dis. 41(1): 131-137.

Frisch, K., Smage, S. B., Johansen, R., Duesund, H., Brevik, O. J. and Nylund, A. 2018a. Pathology of experimentally induced mouthrot caused by *Tenacibaculum maritimum* in Atlantic salmon smolts. PLoS One 13(11): e0206951.

Frisch, K., Smage, S. B., Vallestad, C., Duesund, H., Brevik, O. J., Klevan, A., Olsen, R. H., Sjaatil, S. T., Gauthier, D., Brudeseth, B. and Nylund, A. 2018b. Experimental induction of mouthrot in Atlantic salmon smolts using *Tenacibaculum maritimum* from Western Canada. J. Fish Dis. 41: 1247-1258.

GESAMP. 2008. Assessment and communication of environmental risks in coastal aquaculture. *In* Reports and Studies GESAMP. Rome, Italy. FAO 76: 198 p.

Grant, S. C. H., Holt, C., Wade, J., Mimeault, C., Burgetz, I. J., Johnson, S. and Trudel, M. 2018. Summary of Fraser River Sockeye Salmon (*Oncorhynchus nerka*) ecology to inform pathogen transfer risk assessments in the Discovery Islands, British Columbia. DFO Can. Sci. Advis. Sec. Res. Doc. 2017/074. v + 30 p.

Hicks, B. 1989. British Columbia salmonid disease handbook. British Columbia salmon farming manual Vol. 1. B.C. Ministry of Agriculture and Fisheries Vancouver, BC. 1-44 p.

ISO. 2009. Risk management - Risk assessment techniques. *In* International Standard. IEC/FDIS 31010. 90 p.

Kent, M. L. 1992. Diseases of seawater netpen-reared salmonid fishes in the Pacific Northwest. Can. Spec. Publ. Fish. Aquat. Sci. Vol. 116. DFO. PBS, Nanaimo, BC. 1-76 p.

Kent, M. L. and Poppe, T. T. 1998. Diseases of seawater netpen-reared salmonid fishes. DFO. PBS, Nanaimo, B.C. 66 p.

Levipan, H. A., Tapia-Cammas, D., Molina, V., Irgang, R., Toranzo, A. E., Magarinos, B. and Avendano-Herrera, R. 2019. Biofilm development and cell viability: An undervalued mechanism in the persistence of the fish pathogen *Tenacibaculum maritimum*. Aquaculture 511: 1-8.

Mandrak, N. E., Cudmore, B. and Chapman, P. M. 2012. National detailed-level risk assessment guidelines: assessing the biological risk of aquatic invasive species in Canada. DFO Can. Sci. Advis. Sec. Res. Doc. 2011/092. vi + 17 p.

Mimeault, C., Nekouei, O., Garver, K. A., Jones, S. R. M., Johnson, S., Holt, K., Aubry, P., Weber, L., Burgetz, I. J. and Parsons, G. J. 2020. Assessment of the risk to Fraser River Sockeye Salmon due to *Tenacibaculum maritimum* transfer from Atlantic Salmon farms in the Discovery Islands area, British Columbia. DFO Can. Sci. Advis. Sec. Res. Doc. 2020/059. In press.

Mimeault, C., Wade, J., Foreman, M. G. G., Chandler, P. C., Aubry, P., Garver, K. A., Grant, S. C. H., Holt, C., Jones, S., Johnson, S., Trudel, M., Burgetz, I. J. and Parsons, G. J. 2017. Assessment of the risk to Fraser River Sockeye Salmon due to infectious hematopoietic necrosis virus (IHNV) transfer from Atlantic Salmon farms in the Discovery Islands, British Columbia. DFO Can. Sci. Advis. Sec. Res. Doc. 2017/075. vii + 75 p.

Morrison, D. B. and Saksida, S. 2013. Trends in antimicrobial use in Marine Harvest Canada farmed salmon production in British Columbia (2003-2011). Can. Vet. J. 54(12): 1160-1163.

Nekouei, O., Vanderstichel, R., Kaukinen, K. H., Thakur, K., Ming, T., Patterson, D. A., Trudel, M., Neville, C. and Miller, K. M. 2019. Comparison of infectious agents detected from hatchery and wild juvenile Coho salmon in British Columbia, 2008-2018. 14(9):

Nekouei, O., Vanderstichel, R., Ming, T., Kaukinen, K. H., Thakur, K., Tabata, A., Laurin, E., Tucker, S., Beacham, T. D. and Miller, K. M. 2018. Detection and assessment of the distribution of infectious agents in juvenile Fraser River Sockeye Salmon, Canada, in 2012 and 2013. Front. Microbiol. 9: 1-16.

Ostland, V. E., Morrison, D. and Ferguson, H. W. 1999. *Flexibacter maritimus* associated with a bacterial stomatitis in Atlantic salmon smolts reared in net-pens in British Columbia. J. Aquat. Anim. Health. 11(1): 35-44.

Suzuki, M., Nakagawa, Y., Harayama, S. and Yamamoto, S. 2001. Phylogenetic analysis and taxonomic study of marine *Cytophaga*-like bacteria: proposal for *Tenacibaculum* gen. nov. with *Tenacibaculum maritimum* comb. nov. and *Tenacibaculum ovolyticum* comb. nov., and description of *Tenacibaculum mesophilum* sp. nov. and *Tenacibaculum amylolyticum* sp. nov. Int. J. Syst. Evol. Microbiol. 51: 1639-1652.

Vose, D. 2008. Risk analysis: a quantitative guide. 3rd ed. Wiley, Chichester, England. 735 p.

Wade, J. 2017. British Columbia farmed Atlantic Salmon health management practices. DFO Can. Sci. Advis. Sec. Res. Doc. 2017/072. vi + 55 p.

Wade, J. and Weber, L. 2020. Characterization of *Tenacibaculum maritimum* and mouthrot to inform pathogen transfer risk assessments in British Columbia. DFO Can. Sci. Advis. Sec. Res. Doc. 2020/061. In press..

Wakabayashi, H., Hikida, M. and Masumura, K. 1986. *Flexibacter maritimus* sp. nov., a pathogen of marine fishes. Int. J. Syst. Bacteriol. 36(3): 396-398.

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