Algal Neurotoxins in Pink Salmon (*Oncorhynchus gorbuscha)* from Icy Strait and Icy Point, Alaska

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Abstract

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Blooms of algae in the genera *Pseudo-nitzschia* and *Alexandrium* produce neurotoxins that have the potential to harm humans and other mammals. While the effects of these toxins are best known for causing closures of shellfish fisheries, some finfish also consume toxic algal cells and can contain the algal toxins at levels that can be dangerous for mammals that frequently consume whole fish, such as sea lions. However, commercial finfish fisheries are rarely closed due to toxic blooms because most of the toxin remains in the gastrointestinal tracts of fish and is excreted fairly quickly, posing less risk to humans. In 2016, pink salmon returns in Alaska were disastrously low. The 2015 bloom of *Pseudo-nitzschia* was the largest on record and coincided with the coastal juvenile phase of the fish that would have been caught in the 2016 commercial fishery, suggesting that a mortality event may have occurred simultaneously with the *Pseudo-nitzschia* bloom, though direct mortality due to toxin exposure is an unlikely explanation for finfish mortality. I sought to determine whether mortality of juvenile pink salmon was associated with the *Pseudo-nitzschia* bloom, and whether exposure of juvenile pink salmon to algal neurotoxin levels in 2015 differed from previous years. I analyzed gut contents from juvenile salmon that had been collected from Icy Strait and Icy Point, Alaska, over the past twenty years for the presence of two algal neurotoxins. Both toxins were present at non-lethal levels in all years sampled, and domoic acid in gut contents from Icy Strait was significantly higher in 2015

than in any other year. Concentrations of both toxins were correlated with environmental conditions. Other salmonids have been demonstrated in laboratory settings to be highly resistant to environmental exposure to domoic acid, suggesting that the consumption of domoic acid did not directly harm the juvenile pink salmon. The anomalous environmental conditions in 2015 suggest a food web shift that may have affected juvenile salmon survival.

Introduction

Algal blooms that produce neurotoxins are of significant concern to commercial fisheries and appear to be increasing in frequency and intensity worldwide (Anderson, 1994; VanDolah, 2000). In the California Current System, the season in which toxic blooms can occur may be expanding due to ocean warming, thus enhancing the frequency and duration of bloom events of toxic species (Moore et al., 2008). The neurotoxins of greatest concern on the west coast of North America are domoic acid (DA) and paralytic shellfish toxins (PSTs).

Toxin Definitions and Abundance

Domoic acid is an excitatory neurotoxin produced by some diatoms in the genus *Pseudo-nitzschia*. In humans, intoxication with DA causes Amnesic Shellfish Poisoning (ASP). The first documented outbreak of ASP occurred in 1987 on the Canadian east coast as a result of the consumption of DA-contaminated blue mussels from the Prince Edward Islands. After 153 illnesses and three deaths, the outbreak was attributed to a newly-discovered toxin produced by the pennate diatom *Pseudo-nitzschia multiseries* (Wright et al., 1989). This event caused the closure of the entire Canadian east coast shellfish fishery. Four years later, a sudden increase in pelican deaths in Southern California was attributed to the same toxin produced by another species, *Pseudo-nitzschia australis* (Scholin et al., 1997), and the bloom event triggered closures of human harvest in the commercial Dungeness crab fishery for several weeks (Buck et al., 1992). Species in the genus *Pseudo-nitzschia* are a natural and often innocuous component of the phytoplankton community in the northern Pacific (Anderson et al., 2015), but since 1991 blooms of the toxic species *P. australis, P. multiseries, P. pungens,* and *P. fraudulenta* have occurred repeatedly in the California Current System (Trainer & Suddleson, 2005). The regulatory limit for DA in seafood for the food to be considered safe for human consumption is 20 micrograms of DA per gram of shellfish tissue. This limit was established by determining the lowest symptom-producing dose in the Prince Edward Islands intoxication event as well as laboratory studies in non-human primates, and dividing it by a factor of ten for safety (Wekell, Jurst, & Lefebvre, 2010).

Distinct from DA, PSTs are comprised of sixteen chemically similar toxin variants. These are measured in “saxitoxin equivalents,” saxitoxin (STX) being the most toxic of the suite (Wekell et al., 2010). STX equivalents are produced by three genera of dinoflagellates:

Alexandrium, Gymnodium, and *Pyrodinium* (Lewitus et al., 2012). *Alexandrium* is responsible for outbreaks in the United States, whereas *Gymnodium* and *Pyrodinium* cause outbreaks in Mexico (Ochoa, et al., 1997). The first incidence of poisoning by PSTs was recorded in 1793, when five people in Captain George Vancouver's Royal Navy ate shellfish and became ill in what is now known as "Poison Cove" in British Columbia, Canada (Quayle, 1969). Prior to a more comprehensive understanding of PSTs, they were monitored by necessity through a mouse bioassay and measured in "Mouse Units." One Mouse Unit is defined as the amount of toxin that will kill a 20 g mouse in 10-20 minutes. The safe consumption limit of 80 μg/100 g shellfish was determined more than 60 years ago and the reasoning has been lost to time (Wekell et al., 2010). Currently, while the mouse bioassay is still the official method of the surveillance of STX equivalents, there are other assays available and legally viable including High Performance Liquid Chromatography, a rat bioassay, the Jellett Rapid Test, and enzyme-linked immunosorbent assays (ELISAs), all of which have their own benefits and drawbacks (Costa et al., 2009).

Both toxins have been reported in Alaskan waters and the state has a long history of intoxication from shellfish consumption along the Gulf of Alaska coast, from the border with British Columbia to the Aleutian Islands (Lewitus et al., 2012). The Alaska Department of Health and Human services reported 182 STX equivalent-related illnesses from 1963 through 2008. In Alaska, murrelets and sand lance (Shearn-Bochsler et al., 2014) have been recorded to have ingested STX equivalents. Moreover, thirteen marine mammal species from Alaska have been found to contain DA and twelve marine mammal species have been found to contain STX equivalents (Lefebvre et al., 2016). While fisheries can be closed when toxins are present, the presence of toxins in finfish rarely is an impetus for fishery closures. Finfish do not appear to absorb or accumulate DA in tissues so the toxin remains in their gastrointestinal tract and is excreted very rapidly, and they are therefore generally only considered to be toxic during a bloom event itself (Lefebvre et al., 2005, 2007). However, in 2015 a warm sea surface temperature anomaly in the Northern Pacific, coupled with a series of anomalous late spring storms, created environmental conditions that prompted an unprecedented *Pseudo-nitzschia* bloom along the west coast, reaching as far north as British Columbia. This bloom resulted in the relatively unusual event of a finfish fishery closure—of Southern California anchovies—that raised concern about toxin levels in other commercial finfish species (McCabe et al., 2016).

Oceanographic Associations

Pseudo-nitzschia blooms have been observed under diverse oceanographic conditions, and the varied environmental factors associated with blooms in different regions make it difficult to clearly identify factors that would encourage a toxic bloom. However, bloom events have been known to occur *after* large nutrient inputs to a coastal system, such as the relaxation following an upwelling event, wherein large quantities of macronutrients are introduced and then assimilated, with a bloom of *Pseudo-nitzschia* developing as the declining quantity of nutrients is less able to support a multi-species phytoplankton bloom (Kudela et al., 2004). Some bloom events have been correlated with strong positive phases of the El Niño-Southern Oscillation (ENSO), due to the associated warm temperature anomalies and low nutrient abundance (Trainer et al., 2000).

Alexandrium blooms appear to be more related to large-scale ocean forcing, such as the Pacific Decadal Oscillation (PDO), though in general blooms tend to occur when temperatures are warmer (D. M. Anderson et al., 2008). In Alaska, the weakening of the Aleutian low in the summer allows deep, nutrient-rich water into coastal areas, spurring the development of seasonal algal blooms (Trenberth & Hurrell, 1994; Horner et al., 1997; Macias et al., 2012). Water column stratification has been found to be a condition that can favor dinoflagellates (Margalef, 1978). In laboratory settings, *Alexandrium* sourced from the Gulf of Maine and the Bay of Fundy showed higher growth rates as temperatures increased, though the rates slowed at the highest temperatures, and higher toxicity at temperatures less than 10˚C (Etheridge & Roesler, 2005). Diatoms, which include *Pseudo-nitzschia,* and dinogflagellates, which include *Alexandrium*, generally have similar nutrient requirements, with the notable exception that diatoms require silica and dinoflagellates do not (Smayda, 2002). Under similar nutrient conditions, dinoflagellates tend to grow more slowly than diatoms, causing them to be inferior competitors when nutrients are plentiful, though they may dominate if they begin from larger initial populations (Kremp, Tamminen, & Spilling, 2008).

Pink Salmon Exposure

Pink salmon (*Oncorhynchus gorbuscha*) are the most abundant salmon in the Pacific Ocean. They are terminal spawners, and unlike other salmon species, pink salmon only live to two years of age, spending a single summer feeding in the open ocean. In October, pink salmon emerge in streams, often very close to the mouth, and have a brief residence in the nearby nearshore environments in the summer of their first year. During this time, they feed on plankton at the surface (Bonar, Paulery, & Thomas, 1989).

In 2016, despite the Alaska Department of Fish and Game's forecast expecting the return of 90 million pink salmon, the harvest in Alaska was a nearly unprecedented 39 million fish, the lowest harvest since 1977 (Summers, 2016). Most salmonid species do not have fixed rates of maturation; mature adults may return to spawn at a wide range of ages. Pink salmon, however, invariably mature at two years of age. Because their maturation time is fixed, the pink salmon that would have been caught in the 2016 commercial salmon harvest would have been coastal juveniles during July 2015.

Given the record-setting *Pseudo-nitzschia* bloom that same year (McCabe et al., 2016), there was concern that a juvenile mortality event had occurred in association with the bloom, resulting in the low returns observed in 2016. Domoic acid and STX equivalents can be transferred to finfish such as pink salmon via consumption: as the phytoplankton produce the toxins, they are consumed by zooplankton and planktivorous fish, which ingest the toxins along with the plankton. Because juvenile pink salmon are planktivorous during their estuarine residence (Bonar et al., 1989), they are likely to consume toxic plankton when it is present. Finfish have not shown any toxin avoidance behavior and may actively track toxic blooms in order to feed on the high cell densities associated with blooms (Lefebvre, Silver, Coale, & Tjeerdema, 2002). In the Icy Strait region, juvenile pink salmon have been found to reside in the coastal waters from June to August before venturing out to open ocean waters. The diets of these salmon do not vary between warm and cold years; there are no detectable changes in diet that reflect climate effects (Sturdevant, Orsi, & Fergusson, 2012), suggesting that changes in toxin consumption are likely reflective of toxin presence, not changing diets.

Objectives

Given the increasing likelihood of toxic blooms associated with changing ocean conditions (Moore et al., 2008) and growing concerns over finfish toxicity, I asked whether algal neurotoxins had been present in the Icy Strait region throughout the past two decades, and if so, if any meaningful patterns in their abundance could be detected. The three objectives of the study were to:

1) Assess the historic presence of DA and STX equivalents in juvenile pink salmon from Icy Strait and Icy Point, AK, from 1997 to 2017
2) Investigate relationships between the toxin levels in salmon stomach contents and ocean conditions in order to examine the effect of oceanographic conditions on finfish toxicity
3) Determine whether toxin levels were significantly different in 2015 than in previous years.

Methods

Juvenile pink salmon were sampled opportunistically from 1997-2017 as part of the Southeast Alaska Coastal Monitoring (SECM) project conducted by NOAA's Alaska Fisheries Science Center. Two to thirteen fish were collected in July of each year, depending on the incidence of pink salmon in the survey.

Samples were frozen solid upon collection at sea and kept frozen in a dark freezer until analysis, protecting the toxins from UV damage and possible dissolution into other fluids. The samples were partially thawed and the guts removed while partially frozen to avoid loss immediately prior to use in enzyme-linked immunosorbent assays (ELISAs) (Litaker et al., 2008). This study used kits manufactured by Abraxis Inc.

For the STX equivalent and DA ELISAs, samples were prepared separately. For both, viscera of the fish were manually removed from the body. For DA ELISAs, three times the weight of the viscera of 50% MeOH in miliQ was added and the contents were homogenized. For STX equivalent ELISAS, the same procedure was followed using 80% EtOH instead of 50% MeOH. All samples were then centrifuged at 4˚C at 5000 rpm for 20 minutes, and the supernatant reserved for use in the assays.

To determine DA presence and concentration, the ELISA process involved first creating a standard curve from a DA standard ranging from 1-10,000 pg DA/mL in double-distilled water, then placing duplicate or triplicate 50 µL aliquots of each standard and sample into a 96-well plate pre-coated with DA. Next, 50 µL of anti-DA antibody were added to each well, and the plate was incubated in the dark at room temperature on an orbital shaker for one hour. The plate was then washed four times with washing buffer, at which point 100 µL of a second antibody (goat anti-rabbit horseradish protein conjugate) was added to each well and the mix was incubated in the dark on an orbital shaker for 30 minutes. After washing an additional four times with washing buffer, 100 µL of K-Blue TMB substrate (5.5' tetramethylbenzidine, Neogen Corporation) was added, and the plate incubated on an orbital shaker for fifteen minutes. Finally, 100 µL of stop solution was added to each well, and after two minutes the plate was read at 450 nm using a Versamax plate reader. This assay has a linear range from 0.1 to 3 ppb (Litaker et al., 2008).

To determine presence and concentration of STX equivalent, 10 µL aliquots of each standard and sample as well as 490 µL of buffer in duplicate were placed into a 96-well microtiter plate pre-coated with sheep anti-rabbit antibody. Next, 50 µL of anti-STX antibody were added to each well, and the plate was incubated in the dark at room temperature on an orbital shaker for half an hour. The plate was then washed four times with washing buffer, at which point 100 µL of a second antibody was added to each well and the mix was incubated in the dark on an orbital shaker for 30 minutes. After washing an additional four times with washing buffer, 100 µL of blue TMB substrate was added. Finally, 100 µL of stop solution was added to each well, and after two minutes the plate was read at 450 nm using a Versamax plate reader.

Temperature data were collected on the same SECM cruises at intervals of a few meters by a conductivity temperature depth (CTD) probe. I binned temperature data in the upper 1-5 m of the water column, because most juvenile salmon feed in that range (Tang et al., 2011). I obtained values for the North Pacific Index (NP Index) and PDO from the National Center for Atmospheric Research (Hurell et al., 2018). I used linear regression to explore the relationship between toxin concentration and local ocean temperature. Specifically, I tested for relationships between toxin levels and:

(1) Average monthly temperature in May, June, and July
(2) Average temperature over the period May through July
(3) Yearly PDO Index
(4) Yearly NP Index

To determine whether toxin levels in 2015 were significantly different from levels in other years, I used one-way ANOVA and Tukey HSD tests on toxin levels across years at each location.

Results

Toxin Presence and Abundance

Both DA and STX equivalents were found in juvenile pink salmon in Icy Strait at detectable levels each year from 1997 to 2017 (Fig. 1). The peak levels of DA in Icy Strait in an individual fish were observed in 2015 and 2012, respectively, as were the peak average levels of DA. None of the DA levels detected in Icy Strait approached regulatory limits. However, levels of DA in 2015 were significantly different ($p<0.05$) from levels detected in all other years. The peak individual levels and the peak average levels of STX equivalents in Icy Strait were detected in 2006 and 2011, respectively (Fig. 2). None of the STX equivalent levels in Icy Strait approached the regulatory limit.

Unlike within Icy Strait, DA was not detected in every year in juvenile pink salmon caught off Icy Point (Fig. 3). No salmon were sampled from 2005-2009, or in 2014, and in those years that were sampled, no DA was detected in 1997, 2001, or 2012. Peak individual levels of DA off Icy Point were detected in 2010 and 2003, respectively, while the highest average levels of DA were detected in 2013 and 2010, respectively. None of the DA levels measured off Icy Point approached the regulatory limit. STX equivalents, on the other hand, were detected in every year of sampling off Icy Point (Fig. 4), with the peak individual levels detected in 2010 and 2016 and the peak average levels detected in 1998 and 2010. None of the detected STX equivalent levels off Icy Point approached the regulatory limit.

Oceanographic Correlations in Icy Strait

The concentrations of DA detected in juvenile pink salmon in Icy Strait appear to be unrelated to average summer sea surface temperatures or the Pacific Decadal Oscillation. However, the concentration of DA does show a positive correlation with the average of temperatures recorded by the SECM trawl CTD from 1-5 m in June specifically (Fig. 5), a month before the salmon were collected ($R^2=0.30$, $p=0.01$). The concentration of STX equivalents detected in Icy Strait shows no correlation with temperatures or the Pacific Decadal Oscillation throughout the sampling period. However, the quantity of STX equivalents detected does display a significant positive correlation (Fig. 6) with the yearly NP index, which depicts changes in the intensity of the Aleutian Low Pressure system ($R^2=0.25$, $p=0.02$).

I found no statistical association between oceanographic conditions and levels of DA or STX equivalents at Icy Point. This result is likely due to sparse sampling density.

Pink Salmon Exposure

Both DA and STX equivalents were present in the stomachs of juvenile salmon in all years (Figs. 1-4), indicating regular exposure to toxins during their nearshore residence (Fig. 7). None of the samples analyzed had levels of DA or STX equivalents that would be dangerous to humans and these juvenile fish would likely have excreted all of the toxins during their ocean phase before being caught in the commercial or subsistence fisheries.

Discussion

Toxin Presence and Abundance

Both toxins were present in all years sampled (Figs. 1-4). While previous studies have reported the presence of toxins in Alaskan waters (Lefebvre et al., 2016), the extent of DA in particular is not widely documented in the area; however, high levels of STX equivalents in shellfish are common (AKDEC, 2018). Individual and average maxima for both toxins and locations varied between 1997 and 2017. Moreover, maximum values were not synchronous between Icy Point and Icy Strait, reflective of the variation in conditions between the two locations and indicative of the importance of local conditions to bloom formation. In Icy Strait, maximum levels of DA and STX equivalents were not simultaneous, suggesting that different oceanographic conditions are required to induce bloom formation by the different taxa and/or that the area is unable to support blooms of both species simultaneously. Conversely, at Icy Point, peak levels of both DA and STX equivalents occurred in 2010 (Figs. 3 and 4). Icy Point is more exposed to the open ocean, suggesting that the underlying physical forcing may differ from that in Icy Strait or that some other attribute of the location (e.g., reduced interspecific competition, increased nutrient input from upwelling) allows the two taxa to proliferate at the same time.

The presence of these toxins is consistent with other studies that have found STX equivalents in Alaskan marine mammals, finfish, and seabirds, and DA in Alaskan marine mammals (Lefebvre et al., 2016, 2002; Shearn-Bochsler et al., 2014), although the presence of *both* toxins in every single year sampled has not been previously documented. The lack of simultaneous peak levels of toxin in Icy Strait could be indicative of limited resources available to support blooms of multiple species of phytoplankton. Because diatoms and dinoflagellates have similar nutrient requirements (though diatoms require silica and dinoflagellates do not; Smayda, 2002), the two types of blooms would have to compete for nutrients if they were to proliferate simultaneously.

Correlation with Oceanographic Conditions

The positive correlation between June temperatures at 1-5 m in Icy Strait and the quantity of DA is significant (Fig. 5), and is consistent with previous experiments and field studies indicating that higher temperatures can lead to *Pseudo-nitzschia* blooms (Trainer et al., 2000; Moore et al., 2008; Trainer et al., 2012). It is notable that the abundance of DA is correlated with June temperatures, and not with summer or July temperatures, given that the samples were collected in July. Instead, the significant correlation with June temperatures could indicate that the blooms were initiated in June, and either that they persisted through the sampling period in July or that the toxins remained in salmon stomachs for a substantial period of time. The former explanation is more likely, given previous laboratory studies indicating that salmonids rapidly excrete DA (Lefebvre et al., 2007). The lack of correlation between STX equivalents and ocean temperatures at any point in the summer is surprising given the established relationship between increased temperature and the development of *Alexandrium* blooms, which have a wider window of opportunity to bloom in higher-temperature regimes (Moore et al., 2008).

Instead, the levels of STX equivalents measured in Icy Strait were positively and significantly correlated with the NP Index (Fig. 6). A higher NP Index indicates a weak Aleutian low, which is associated with coastal upwelling and a subsequent increase in phytoplankton abundance and productivity (Horner et al., 1997; Macias et al., 2012; Trenberth & Hurrell, 1994). It is possible that in these conditions, *Alexandrium* were able to outcompete *Pseudo-nitzschia*, the latter of which is more likely to bloom as nutrients subside (Kudela, Cruz, & Cochlan, 2002). The contrasting oceanographic conditions associated with toxin levels at these locations suggest that proliferation of the two different phytoplankton groups are tied to differing oceanic conditions and therefore that although both are present, the taxa may be unlikely to bloom simultaneously in Icy Strait.

Given that both toxins nonetheless occur simultaneously off of Icy Point, it is most likely that favorable oceanographic conditions are a necessary but insufficient prerequisite to blooming—the phytoplankton likely also require either the capacity to outcompete other phytoplankton clades, or access to sufficient resources to render interspecific competition irrelevant.

Pink Salmon Exposure

Juvenile pink salmon are most likely to be exposed to both DA and STX equivalents during their coastal residence phase in the first year of their life (Fig. 7), and this appeared to hold true for samples analyzed in this study. As such, these juvenile fish would likely have excreted the toxins during their ocean phase before being caught in commercial or subsistence fisheries, thus posing no danger to human consumers. Additionally, the toxin levels detected in these pink salmon were substantially below the seafood safety regulatory limits for each set of toxins. Larval Pacific herring exhibit transient inhibition of sensorimotor function when exposed to STX dissolved in surrounding water, indicating that STX is bioavailable to marine finfish larvae (Lefebvre et al., 2005), and it is therefore possible that exposure to STX equivalents could also cause temporary paralysis in larval pink salmon. While such paralysis in herring does not appear to affect growth or induce morphological defects, such temporary paralysis can have a significant impact on predator avoidance. Because pink salmon feed on plankton during their estuarine residence (Bonar et al., 1989), the primary route of exposure to toxins would not be absorption through the skin, but instead via filter-feeding or possibly via absorption through the gills. However, there is no clear correlation between STX equivalent concentration and year-lagged pink salmon landings, indicating that if temporary paralysis did occur in STX-exposed juvenile cohorts, it did not last long enough to substantially increase predation rates.

Juvenile Coho salmon under experimental conditions show limited uptake of DA from the gut and do not show signs of neurobehavioral toxicity even with high oral doses of DA (Lefebvre et al., 2007). Without evidence to the contrary, one might expect closely-related pink salmon to respond similarly, suggesting that typical environmental exposure does not pose a threat to the fish. Domoic acid levels were significantly higher in fish found in Icy Strait in 2015 than in any other year, consistent with the anomalous *Pseudo-nitzschia* bloom documented that year (McCabe et al., 2016). Given that lack of overt neurotoxicity to DA observed in Coho salmon, it is unlikely that ingestion of DA led directly to the increased juvenile mortality in the pink salmon analyzed here, in which the whole-body dose of toxins was at least 300 times lower (Lefebvre et al., 2002).

It is possible that juvenile pink salmon are more vulnerable to DA exposure than are juvenile Coho salmon, as they are much younger when they reach nearshore waters–Coho salmon rear for 1 – 2 years in freshwater before leaving their river system, whereas pink salmon are less than one year old when exposed. However, the results of this study are insufficient to make such a claim conclusively. Instead, the higher levels of toxin found in GI tracts could indicate a shift in species composition in the phytoplankton community or a shift in the toxic status of the cells themselves. It is therefore possible that the proliferation of *Pseudo-nitzschia* and their production of DA either led to or was a result of a shift in the composition of the plankton community that could have led to a higher mortality rate in juvenile pink salmon. Because the diets of these salmon do not vary between warm and cold years (Sturdevant et al., 2012), the presence of the toxin in their stomachs is likely reflective of changing toxin availability, not of changing diets. The shift in 2015, then, was not a previously observed shift between cold and warm sea surface temperature anomalies that have been routinely observed in large-scale ocean forcing such as throughout PDO or ENSO cycles. To cause such a dramatic loss of pink salmon and an unprecedented toxicity event, there were likely environmental conditions outside the realm of previously observed cycles; typical physical forcings such as the PDO or ENSO are insufficient to explain the occurrence. Indeed, these events were coincident with the fullest extent of a warm anomaly that appeared off the coast of Alaska in 2013 and spread across the West Coast by 2015 (McCabe et al., 2016). The large warm anomaly has been credited for a shift in copepod species along the coast of Oregon to more typically southern species (Peterson et al., 2015a), and many other species were observed well north of their usual habitats at the time of the warm anomaly (Bond et al., 2015; Peterson et al., 2015a; Peterson et al., 2015b), further suggesting a large shift in available prey during 2015 that may have influenced pink salmon survival. I found no correlation between DA presence and year-lagged commercial pink salmon landings in other years, suggesting that in no previous year has DA had an impact on juvenile salmon survival.

The precise functions and effects of algal neurotoxins in marine food webs requires further study. Key questions include the rate of toxin uptake by finfish given algal cell abundance, possible compound effects of simultaneous exposure to multiple toxins, the rate of toxin accumulation at higher trophic levels, and potential long-term impacts of prolonged toxin exposure in both individual finfish and in finfish populations. As toxic blooms increase in frequency and intensity, answers to these questions may be critical not only to the shellfish industry–the historical focus of algal toxin impacts on seafood–but also to finfish fisheries. It is possible that pink salmon and chum salmon are more vulnerable to longer-term neurotoxin exposure, because they reach saltwater much earlier in their development than do other salmon species. Conversely, it is possible that Chinook salmon are more vulnerable because they spend more time in the nearshore environment. The possible links between oceanic and climatic conditions and the impacts of algal toxins on finfish fisheries must be further explored in order to understand the changing impacts of harmful algal blooms on food webs and the commercial, subsistence, and recreational salmon fisheries.

Figures

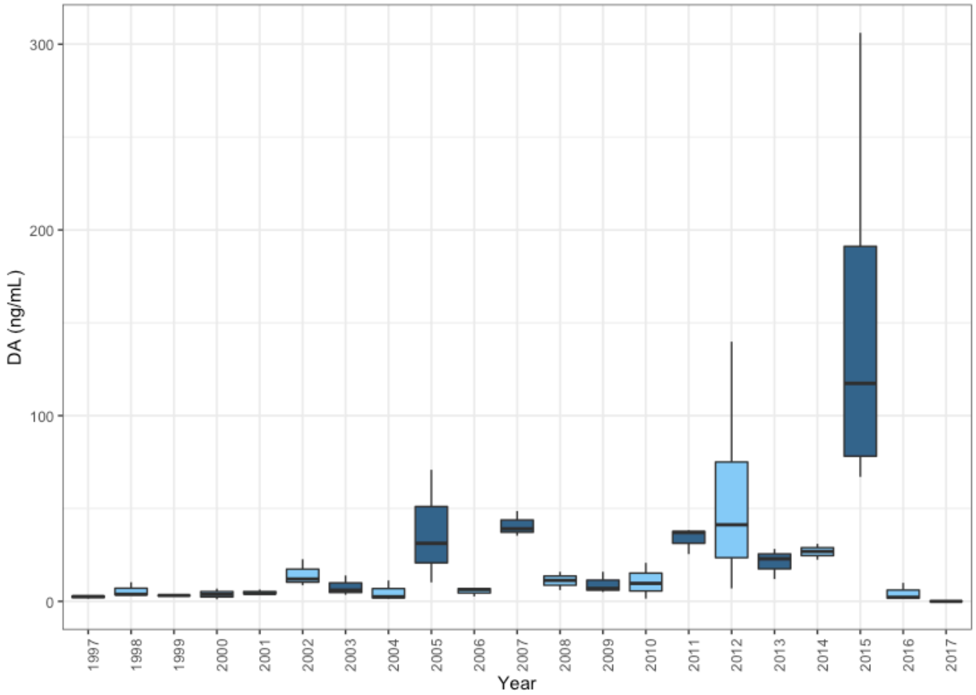

Figure 1. Domoic Acid (ng/mL) in juvenile pink salmon in Icy Strait, AK, from 1997-2017

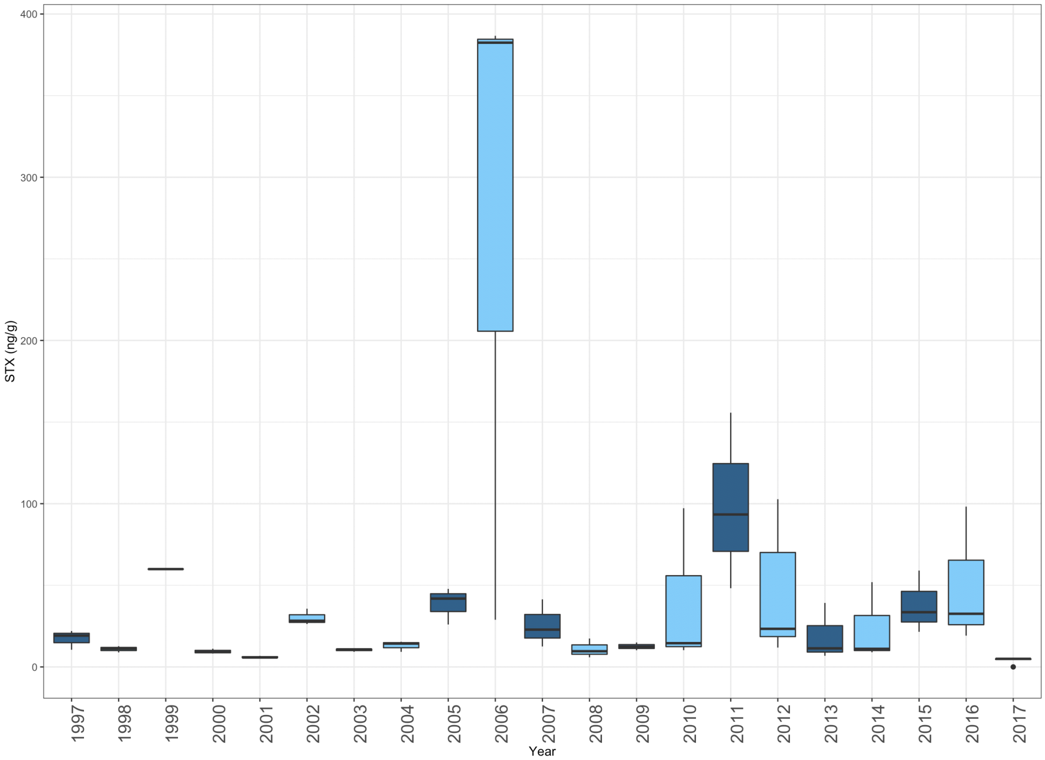

Figure 2. Saxitoxin Equivalents (ng/g) in juvenile pink salmon in Icy Strait, AK, from 1997-2017

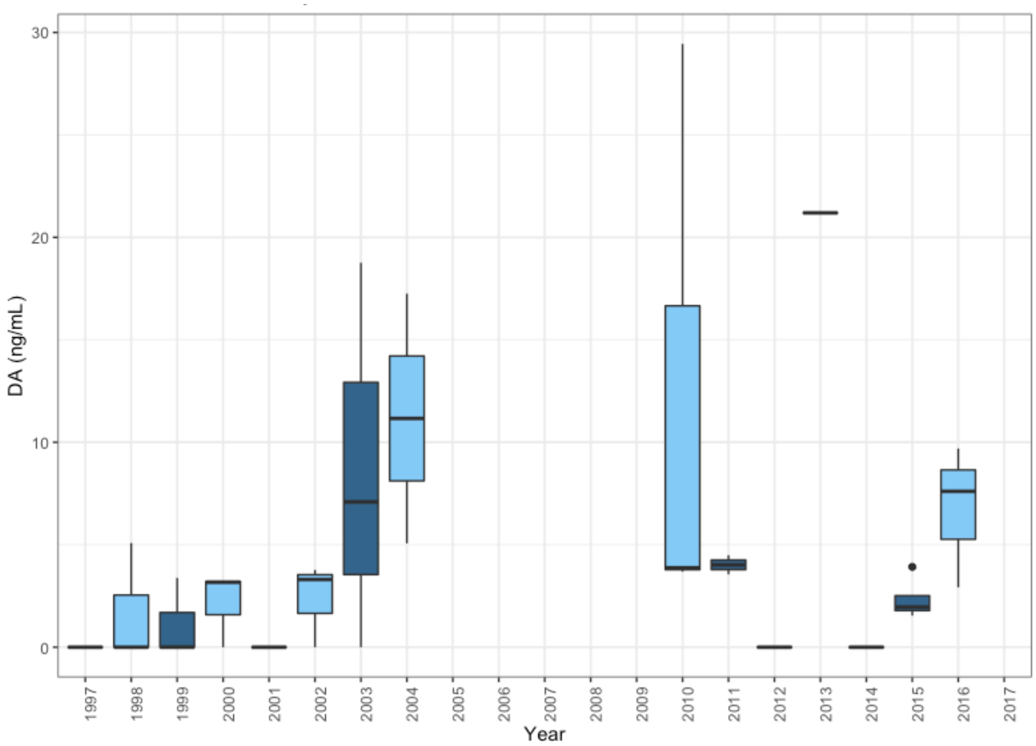

Figure 3. Domoic Acid (ng/mL) in juvenile pink salmon off Icy Point, AK, from 1997-2005 and 2010-2016.

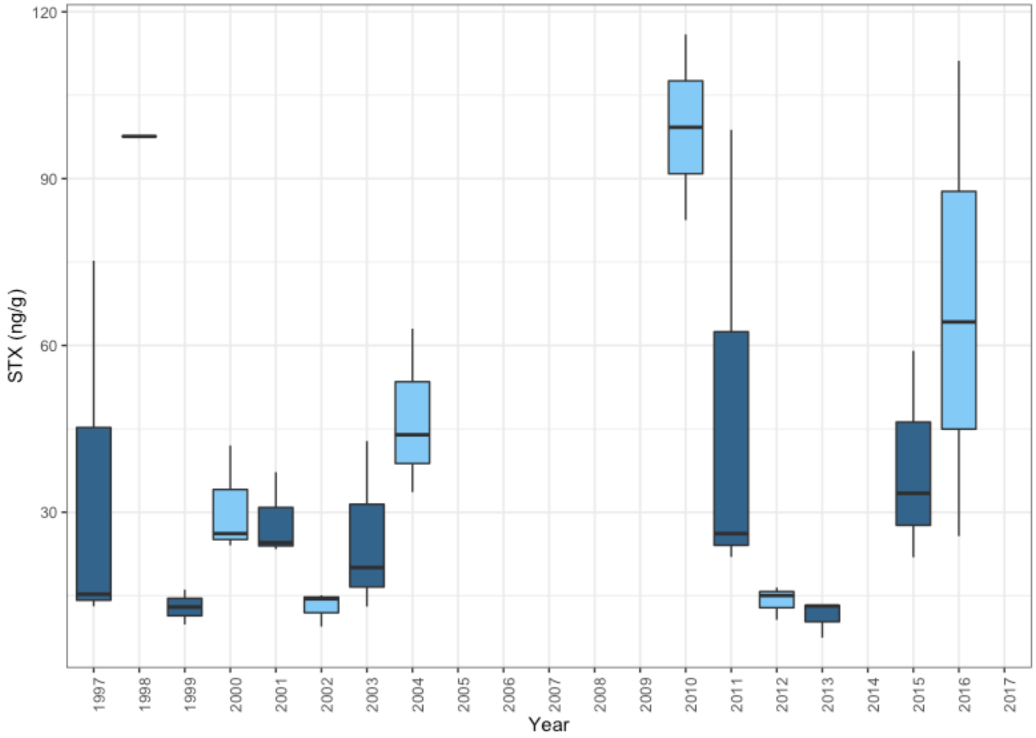

Figure 4. Saxitoxin Equivalents (ng/g) in juvenile pink salmon off Icy Point, AK, from 1997-2005 and 2010-2016.

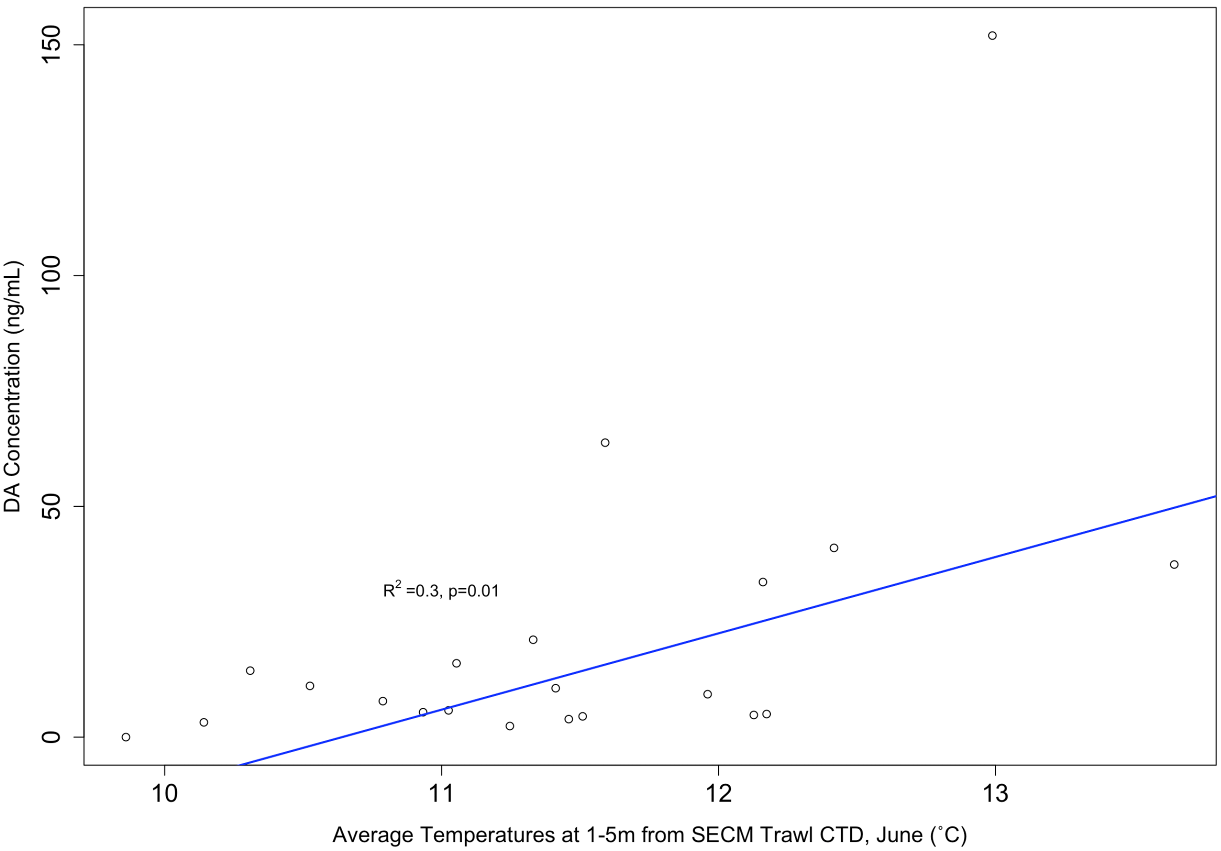

Figure 5. Average Domoic Acid concentration (ng/mL) in juvenile pink salmon in Icy Strait, AK in July each year plotted against average temperatures from trawls 1-5m in June of the same year.

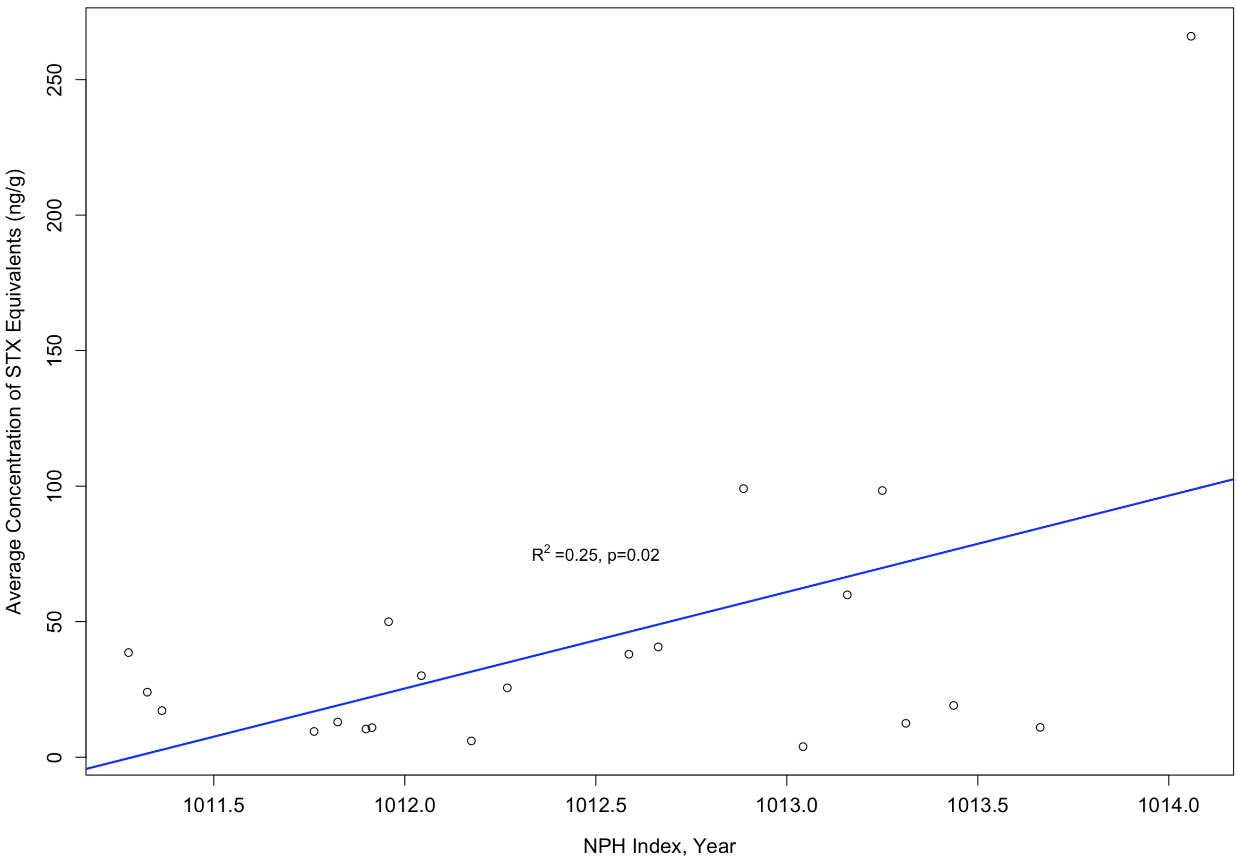

Figure 6. Average Paralytic Shellfish Toxin concentrations (ng STX equivalents/g) in juvenile pink salmon in Icy Strait, AK in July each year, plotted against the yearly North Pacific Index.

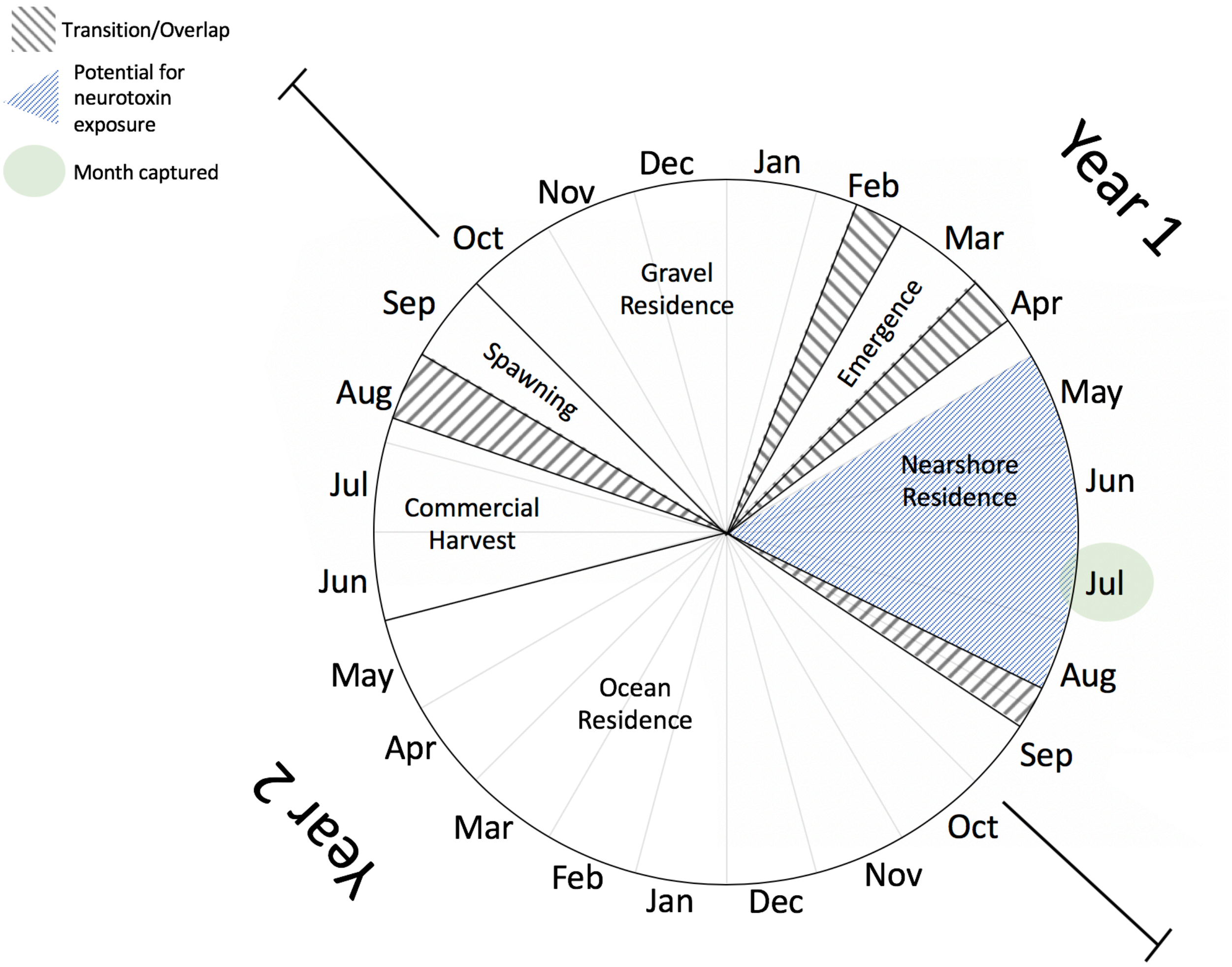

Figure 7. Generalized lifecycle of pink salmon in the Icy Strait area. Times of potential neurotoxin exposure and time of capture are shaded. Adapted from Bonar et al., (1989) with input from Beamer (2018) and Dr. Tom Quinn, personal communication.

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