Exxon Valdez Oil Spill
Restoration Project Final Report

Identifying Essential Habitat (Source vs. Sink Habitat) for Pacific Herring (*Clupea pallasi*) in Sitka Sound Using Otolith Microchemistry

Restoration Project 080834
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Study History: Project 080834**, "**Identifying Essential Habitat (Source vs. Sink Habitat) for Pacific Herring (*Clupea pallasi*) in Sitka Sound Using Otolith Microchemistry," originated from the need to better understand essential habitat for Pacific herring (*Clupea pallasi*) in Prince William Sound (PWS). Compared to the PWS herring stock, Sitka's herring stocks remain healthy and relatively intact, and can be used as a control group, providing baseline data for comparison to other depleted herring stocks around the region. The close relationship of PWS herring and Sitka Sound herring was investigated further with the use of otolith microchemistry. The project addresses herring restoration in PWS by using trace elements in herring otoliths as markers to identify successful spawning and juvenile habitats in Sitka Sound. Essential herring habitat in Sitka Sound can be compared to PWS essential herring habitat. This 2-year project was conducted in Sitka between October 2006 and June 2008. The project began as Project 070834, and additional funding was provided by the Council for completion of the project in FY 2009. The project complements Project 070782, "Herring Restoration in Prince William Sound: Identifying Natal and Nursery Habitats."

Abstract: The primary objective of this project was to obtain information leading to better identification of essential fish habitat in Prince William Sound. By using trace element signatures of edge portions of juvenile herring otoliths, we identified the otolith chemical signature of individual rearing bays within Sitka Sound. We used trace element signatures of edge portions of adult herring otoliths to identify the otolith chemical signature of spawning areas within Sitka Sound. We also used trace element signatures of edge portions to compare to core portions of juvenile and adult herring to identify source and sink habitat in Sitka Sound. The results of the technique used in this project indicate that herring use different and distinct habitats in Sitka Sound during their life. Once we know which population contributes more to the spawning groups, we can then identify those variables that enhance the life histories of the source population. This will allow managers to protect the most important populations and also identify which variables can be altered to improve habitat for other populations. These techniques used in Sitka Sound can be directly transferred to Prince William Sound, leading to better identification of essential fish habitat in Prince William Sound.

Key Words: Adult herring, *Clupea pallasi*, essential habitat, juvenile herring, microchemistry, otolith microchemistry, Pacific herring, restoration, Sitka Sound.

Project Data: Data was collected from adult herring collected during spawning and from juvenile herring in nursery bays. All biological data was processed in Sitka. The otoliths were sent to the University of Massachusetts for analysis of concentrations of trace metals using a laser ablation (LA; New Wave UP 213nm Nd: YAG) Perkin Elmer inductively coupled plasma – mass spectrometer (ICP –MS). All data was entered in Excel spreadsheets. Statistical analysis included analysis of variance (ANOVA $\alpha = 0.05$) to distinguish differences in the otolith chemical signature. Contact: Nate Bickford, University of Great Falls, Division of Biology, 1301 20th Street S., Great Falls, MT 59405.

Citation: Meuret-Woody, H. and N. Bickford. 2009. Identifying essential habitat (source vs. sink habitat) for Pacific Herring (*Clupea pallasi*) in Sitka Sound using otolith microchemistry, *Exxon Valdez* Oil Spill Restoration Project Final Report (Restoration Project 080834), Alaska Department of Fish and Game, Habitat and Restoration Division, Anchorage, Alaska.

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Executive Summary

The Trustee Council has classified Pacific herring in Prince William Sound as a non-recovering injured resource based on population trends that became evident four years after the *Exxon Valdez* oil spill. One of the Council's long-term goals is to restock Pacific herring in Prince William Sound. The factors that continue to impede herring recovery in Prince William Sound not well understood. This research explored the utility of otolith chemistry in the reconstruction of past habitat use, the identification of essential habitat, and the similarity of Sitka Sound herring population structure to that of herring in Prince William Sound. The identification of essential spawning habitat, and the ability to assess recruitment within major herring populations, will have profound consequences for these forage fish. The results will assist in the prioritization of restoration of essential habitats, as well as in the continued management and sustainability of herring fisheries.

The primary objective was to obtain information leading to better identification of essential fish habitat in Prince William Sound. By using trace element signatures of edge portions of juvenile herring otoliths, we identified the otolith chemical signature of individual rearing bays within Sitka Sound. We used trace element signatures of edge portions of adult herring otoliths to identify the otolith chemical signature of spawning areas within Sitka Sound. We also used trace element signatures of core portions of juvenile and adult herring to identify source and sink habitat in Sitka Sound. These results from Sitka Sound can be compared to the source and sink habitats of Prince William Sound.

Otolith samples were collected in 2007 from adult and juvenile herring. The otoliths were analyzed for concentrations of trace metals using a laser ablation (LA; New Wave UP 213nm Nd:YAG) Perkin Elmer inductively coupled plasma – mass spectrometer (ICP –MS). Elemental abundances were compared to relative to Calcium content among otolith samples. Statistical analysis included analysis of variance (ANOVA $\alpha = 0.05$) to distinguish differences in the otolith chemical signature (Mg/Ca, Mn/Ca, Sr/Ca, Sr^{86}/Sr^{87}, and Ba/Ca). The results from linear discriminant analysis geographically distinguished the distinct groups of herring and allowed us to classify the individuals into groups (i.e., natal group, nursery group).

Sitka Tribe of Alaska is a strong advocate for the conservation of herring and protecting the subsistence fishery. In recent years, Sitka Tribe has been unable to harvest their subsistence need of herring eggs, while the commercial sac roe fishery harvests record quotas year after year. Sitka Tribe became quite concerned for the overall health and sustainability of the Sitka Sound herring stock, and began researching the population in 2004. In 2005 and 2006, Sitka Tribe conducted a stock delineation project using herring otolith microchemistry and stable isotopes. Both edge and core chemistries of the examined otoliths revealed 2 distinct chemical signatures (i.e. Sitka Sound and Salisbury Sound). This analysis distinguished 2 distinct herring spawning locations and 2 distinct hatch locations. This previous study sparked the Tribe's interest in continuing with herring research and exploring the technology of otolith chemistry to identify the temporal and spatial migrations of larval, juvenile, and adult herring. Like most Alaska herring populations, little is known about the dynamics of the Sitka Sound herring stock, specifically larval drift, juvenile rearing areas, spawning habitat and ecosystem relationships, and the role of predators and disease. The *Exxon Valdez* Oil Spill Trustee Council funding provided the opportunity for the Sitka Tribe to research adult and juvenile populations and their habitats, and

yield results that can be used in the restoration of herring in Prince William Sound and the restoration of other herring populations in Alaska.

Introduction

Native peoples throughout coastal Alaska, including Sitka Sound and Prince William Sound (PWS) have relied heavily upon herring as a subsistence food source since time immemorial. Herring eggs are one of the most prioritized traditional food sources for many Alaska coastal tribes, including Sitka Tribe of Alaska. Alaska Department of Fish and Game (ADF&G) surveys have documented the use of herring eggs by households of the Sitka Tribe. ADF&G has estimated 97% of Sitka Tribal households utilize herring eggs, and that an average household uses 177 pounds of subsistence herring eggs (Schroeder & Kookesh, 1990). In 2009, the State Board of Fisheries increased the amount reasonably necessary for subsistence use of herring eggs from 139,000 to 225,000 lbs as specified in 5 AAC 01.716(b), just for Sitka alone. Sitka Tribe has been conducting subsistence herring harvest surveys in subsistence households since 2002, to document the importance of herring to native people's diet and culture. The estimated harvest of herring roe by subsistence users in Sitka in 2004 was 381,226 pounds harvested on hemlock branches, hair seaweed and *Macrocystis* kelp (Turek & Ciccone, in preparation).

Since the early 20th century, Pacific herring stocks have been heavily targeted by a massive commercial fishing industry and a bounty of herring reduction plants. Elsewhere, once healthy herring populations have been challenged by habitat loss or environmental degradation, as in the case of PWS herring. In March 1989, during a period of high biomass, the tanker vessel *Exxon Valdez* ran aground on Bligh Reef in northeastern PWS and spilled 42 million liters of crude oil. Immediately following the oil spill, herring spawned in PWS. In 1989, herring embryos and larvae had low survival, morphologic and genetic damage. Herring larvae had slow growth rates (Hose et al., 1996; Kocan & Hose, 1995; Kocan et al., 1996; Norcross et al., 1996). Estimates of spring spawning herring biomass from 1989 through 2000 ranged from 102,481 metric tons in 1992 to 14,378 metric tons in 1994 (Morstad et al., 1998). Herring catches were reduced in 1993 (Funk, 1995; Marty et al., 1998, 1999), and the fisheries were closed from 1994 to 1996. The harvest prior to the collapse was 48,317 metric tons in 1992; the highest catch since 1993 was 10,979 metric tons in 1997. However, the population of herring in PWS again collapsed in 1999 (Marty et al., 2003).

As a comparison to the PWS herring stock, Sitka's herring stocks remain healthy and relatively intact, and can in fact be used as a control group, providing baseline data for comparison to other herring stocks around the region. Estimates of Sitka's spring spawning herring biomass from 1989 through 2008 ranged from 58,500 tons in 1989 to 87,715 tons in 2008 (Pritchett & Hebert, 2008). The highest commercial sac roe harvest on record was 14,723 tons, taken in 2008 (Pritchett & Hebert, 2008). Sitka's herring population is stable and supports one of Alaska's largest subsistence herring harvests, as well as one of the largest commercial herring sac-roe fisheries in the world.

The Trustee Council has classified Pacific herring in PWS as a non-recovering injured resource based on population trends that became evident four years after the *Exxon Valdez* oil spill. One of the Council's long-term goals is to restock Pacific herring in PWS. The factors that continue to impede herring recovery in PWS are not well understood. To date, there has been no satisfactory explanation of the lack of recovery of herring in PWS. Why the herring populations in PWS remain in a non-recovered status twenty years after the *Exxon Valdez* oil spill is unknown. One of the Trustee Council's recovery objectives for Pacific herring in PWS is a highly successful year class that is recruited into the population when other indicators of population health are within normal bounds. Herring are an important part of the marine ecosystem, as forage fish they are the staple source of food for many marine mammals, birds and fish. In Sitka Sound, herring is the food for many congregating Steller sea lions (*Eumetopias jubatus*), humpback whales (*Megaptera novaeangliae*), and grey whales (*Eschrichtius robustus*). If the decline continues, species that rely on herring as a food source will more than likely decline as well.

It is important to investigate and understand the factors preventing herring populations from recovering in PWS. A major factor is herring habitat preference during all life stages. Essential fish habitat is difficult to identify, much less conserve or improve. Therefore, it is critical to protect those habitats that contribute a disproportionately large number of recruits to future generations. It is quite often difficult to identify these source habitats and distinguish them from those habitats that may contain significant biomass but produce few recruits (sink habitats). In the case of Pacific herring in PWS, recruitment success has been measured by comparing the abundance of spawning adults in different habitats thereby approximating the relative importance of different natal and nursery habitats (Norcross et al., 2001). The technology of otolith chemistry allows researchers to investigate survivorship, and as a result, identify essential spawning habitats. Trace element chemistry preserved by the otoliths provides powerful insight into the environmental life history of fish. For example, otolith chemistry has been used to determine population structure and dynamics at both large (between estuaries) and small (between sea grass habitats within an estuary) spatial scales (Thorrold et al., 2001; Dorval et al., 2002). Chemical analysis of trace element concentrations in otoliths can be used to identify the geographic signatures of natal habitats used by fish captured either as juveniles or adults (Bickford et al., 2003).

This investigation used otolith microchemistry to identify the essential habitat of Pacific herring in Sitka Sound (Figure 1). This technique can then be transferred to PWS for comparison of essential habitat of Pacific herring. The research explored the utility of otolith (fish ear bones) chemistry in the reconstruction of past habitat use, the identification of essential habitat, and the similarity of Sitka Sound herring population structure to that of herring in PWS. In Sitka Sound, the identification of essential habitat utilized by a control population will have profound consequences for the Pacific herring reclamation in PWS.

To date there has been no way to correlate larval, juvenile, and adult populations for Pacific herring. Otolith microchemistry offers researchers a way of identifying the temporal and spatial migrations of larval, juvenile, and adult herring. The use of otoliths to describe the potential transport of herring larvae from spawning sites to nursery areas, and the identification of the most important areas, will aid researchers in understanding the recovery status of herring and achieving the goals of the 1994 Restoration Plan (Bickford et al., 2003).

The life cycle of Pacific herring in Sitka Sound is conducive to otolith chemical analysis. In Sitka Sound, herring mature at 3-4 years old and annually migrate to coastal waters and consistently spawn on tidal and sub-tidal shores. Adult herring migrate in mid March to spawn on 40-104 nautical miles of coastline in Sitka Sound (Davidson et al., 2006). Spawning in Sitka Sound usually occurs in the third week of March and continues into mid-April, and sometimes can occur through May in some areas. Sitka Sound herring eggs incubate in these spawning areas for about 14 days before hatching as larvae in May and June. The planktonic herring larvae tend to drift to the northern end of Sitka Sound, which serves as a retention area (Haldorson & Collie, 1990). Metamorphosis of the larval herring begins in June of that same year (Stokesbury et al., 2002). The herring then become nektonic and swim to favorable habitats where they are no longer at the mercy of the currents. In August, the young herring begin to form schools and aggregate at the heads of bays far from coastal waters (Brown et al, 2002; Stokesbury et al., 2000). These populations stay isolated in their respective nursery bays until June of their second year (Stokesbury et al., 2000). At that time this cohort of herring leaves the bays and joins adult schools (Stokesbury et al., 2000).

Throughout the life of a herring, as it migrates among Sitka Sound fjords and bays, the trace element content of the water is recorded in the otolith. This creates a permanent record of habitat use by an individual fish. Otolith bands are accrued during the fish's time of residence in the spawning areas, thus recording the unique spatial chemical signatures. Otoliths are formed in the latter part of the egg stage. The initial deposition of material becomes the core of the otolith (Wright et al., 2002). As the juvenile herring grows the otolith accretes bands of new material, which surround its original core deposit. Daily bands, monthly bands, and yearly bands are accrued as layers. Growth is recorded as assorted bandwidths inside the otolith, much as a tree accumulates annual rings. The daily, monthly, and annual bands have long been used as detectors of age and growth rate in fish (Campana & Thorrold, 2001). In recent years, the chemical composition of individual bands have been used to identify past habitat use of the fish (Rooker et al., 2003; Campana & Thorrold, 2001; Thresher, 1999). The incorporation of and the concentration levels of trace metals in the otoliths are a function of abiotic (i.e., temperature, salinity) and biotic (i.e., diet, fish growth rate) conditions (Thresher, 1999).

The *Exxon Valdez* Oil Spill Restoration Plan of 1994 set recovery objectives, strategies and goals for Pacific herring in PWS. One of the Trustee Council's recovery objectives for Pacific herring in PWS is a highly successful year class that is recruited into the population when other indicators of population health are within normal bounds. This project meets that objective and provides the information needed to improve the management and recovery of this important commercial and subsistence species. The *Exxon Valdez* Oil Spill Trustee Council has identified Pacific herring as not recovered to a healthy and productive state. The Council stated herring do not exist at pre-spill abundance. This project focuses on the reproductive success and identification of essential fish habitat. This identified habitat will support abundant recruits using a healthy herring population, located in Sitka Sound, as a control group. This project contributes greatly to knowledge needed for herring recovery in PWS.

This project determined chemical trace metal signatures found in rearing and spawning areas. Through otolith chemical analysis, the spatial and temporal description of where herring spend their early life history was identified. This technique is necessary to identify those habitats where enhancement of the herring population is needed. The first step is protection of the population that is the source group, with the hopes that more fish will be added to the environment. The second step is identification of similar habitats without herring and seeding new herring into the environment. These steps require identification of source and sink habitats that control herring population numbers (Bickford et al., 2003). The data can also be used to consider the effect the *Exxon Valdez* oil spill continues to have on the recovery of herring populations in PWS. Using the data, we hope to identify where herring were spawned (natal), where they spent time after spawning (nursery), where they go to spawn, and whether or not they spawn at their natal beach. This data lends understanding to survival between the life stages, and which habitats contribute herring to the population.

There has been a consistent downward trend in the biomass of Pacific herring in PWS. These sub-tidal and tidal spring spawners have distinct spawning strategies, as well as unique habitat needs and life histories. Currently, the methods applied to identify spawning habitats and recruitment success include spawn deposition dive surveys, which allocate habitat based on the presence of spawning adults. This EVOS research explored the utility of otolith chemistry in the reconstruction of past habitat use, the identification of essential habitat, and the similarity of Sitka Sound herring population structure to that of herring in PWS. The identification of essential spawning habitat, and the ability to assess recruitment within major herring populations, will have profound consequences for these forage fish. The results will assist in the prioritization of restoration of essential habitats, as well as in the continued management and sustainability of herring fisheries.

Objectives

The primary objective was to obtain information leading to better identification of essential fish habitat in Prince William Sound. By using trace element signatures of the edge portions of juvenile herring otoliths, we identified the otolith chemical signature of individual rearing bays within Sitka Sound.

1.) Use trace element signatures of edge portions of adult herring otoliths to identify the otolith chemical signature of spawning areas within Sitka Sound.

2.) Use trace element signatures of core portions of juvenile and adult herring to identify source and sink habitat in Sitka Sound.

3.) The techniques used in this project can be transferred directly to Prince William Sound, specifically EVOS Project No. 070782.

Methods

Water temperature and salinity were sampled at 1-meter at each collection site using an YSI 85 hand-held meter. A Garmin eTrex Legend hand-held GPS unit was used to record coordinates of collection locations. The coordinates were entered into maps created in ArcMap GIS 9.2. A random sample of 25 winter herring was collected during the 2007 winter bait fishery. During the spawning event in March and April 2007, random samples of adult herring were collected during the spring from 9 different collection sites. A total of 374 adult herring were collected in 2007 (Figure 1). The herring were sampled for weight, length, sex, maturity, and otoliths were excised. The fish were lightly rinsed and wiped down. Each fish was weighed to the nearest 0.01 g using an Ohaus Scout Pro digital scale. Each fish was measured from snout to hypural plate to the nearest 0.01 mm using Tesa IP65 waterproof digital calipers. Sex was determined by a visual inspection and will be classified as mature, spent, or immature. Sagittal otoliths were extracted from the herring in a clean environment using standard techniques (Bickford et al., 2003; Campana, 1999; Campana, et al., 1995). The otoliths were then rinsed and cleaned with distilled water, and placed in micro centrifuge tubes. Each tube was labeled with the fish identification number, date and collection site information. All adult herring otolith pairs were sent to Dr. Nate Bickford and then processed at the University of Massachusetts for trace metal analysis.

Random samples of juvenile herring were collected during winter 2007 from five near shore nurseries. A total of 407 juvenile herring were collected in 2007 (Figure 1). All juvenile fish were lightly rinsed. Each individual juvenile fish was then wiped off using paper towels. The fish were identified as 1-50 according to date and sample site. Each juvenile fish was weighed to the nearest 0.01 g using an Ohaus Scout Pro digital scale. Each juvenile fish was measured from snout to hypural plate to the nearest 0.01 mm using Tesa IP65 waterproof digital calipers. Because these were immature fish, they were not sexed. Sagittal otoliths were extracted from the herring in a clean environment using standard techniques (Bickford et al., 2003; Campana, 1999; Campana et al., 1995). The otoliths were then rinsed and cleaned with distilled water, and placed in micro centrifuge tubes. Each tube was labeled with the fish identification number, date, and collection site information. All juvenile herring otolith pairs were sent to Dr. Nate Bickford and then processed at the University of Massachusetts for trace metal analysis.

Otolith Chemical Analysis
Sagittal otoliths were thin sectioned using a Beuhler isomet low speed saw. This exposed the otolith core and edge for chemical analysis and aging (Campana, 1999). The sagittal otoliths were analyzed for concentrations of trace metals using a laser ablation (LA; New Wave UP 213nm Nd:YAG) Perkin Elmer inductively coupled plasma – mass spectrometer (ICP –MS) located at the University of Massachusetts. These analyses were performed on thin sections of otoliths on a transect extending from the core across to the otolith margin. All analyses were calibrated using the external matrix-matched standard USGS MACS-1 (carbonate standard). Each sample measurement was preceded by a gas blank measurement with re-calibration (gas blank and MACS-1) every 10 samples. The concentration of all elements was calculated relative to MACS-1 after proper correction for the gas blank, matrix, and drift effects. Elemental abundances were compared to relative Calcium content among otolith samples (Campana, 1999; Campana & Neilson, 1985).

Statistical analysis included analysis of variance (ANOVA $\alpha = 0.05$) to distinguish differences in the otolith chemical signature (Mg/Ca, Mn/Ca, Sr/Ca, Sr^{86}/Sr^{87}, and Ba/Ca):

- Juvenile edge (nursery) vs. juvenile core (natal): if the signature is the same, then the fish has not left spawning grounds.
- Juvenile core (natal) vs. juvenile core (natal): if the signature is the same, then the fish were spawned in the same area.
- Juvenile edge (nursery) vs. adult area just outside the core (nursery): if the signature is the same, then the adult used the same nursery habitat as the juvenile.
- Adult edge (spawning area) vs. adult core (natal): if the signature is the same, then the adult returned to spawn in the same area in which it hatched.

- Adult core (natal) vs. adult core (natal): if the signature is the same, then the adults were hatched in the same area.

Linear discriminant analysis (LDA) explicitly attempts to model the difference between classes of data. The LDA results geographically distinguished the distinct groups of herring and allowed us to classify the individuals into groups (i.e., natal group, nursery group).

Results

We analyzed the juvenile and adult herring otolith edge (known location) chemistries independently using nonparametric discriminant analysis (SAS v. 9.1) in order to validate whether we can correctly classify herring to their capture site using elemental ratios. We then used the validated otolith edge chemistries to classify otolith core (unknown location) signatures for determination of spawning locations of herring.

We were able to use all juvenile otolith elemental ratios (Mg/Ca, Sr/Ca, Sr/Sr, and Ba/Ca) to validate correct classification of the captured locations. Cove Marina (Zone II), Old Sitka Rocks (Zone II), and Barge Dock (Zone II) all had strong correct classifications (86%, 86%, and 74%, respectively). However, Bear Cove (Zone II) only had 57% of the individuals correctly classified (Table 2). Though this classification was not as strong as at other locations, it composed a majority of the individuals and allowed us to confidently proceed with the classification of the juvenile core signature. The juvenile core signatures were then primarily classified to the Barge Dock, indicating that most of the individuals were spawned in this region. However, herring captured at the Barge Dock did not classify to this region. A majority of the individuals from the Barge Dock (83%) had an elemental signature that did not meet the probability threshold of any location and thus classified into the 'Other' category. Overall: 57% of all individuals classified into the Barge Dock region; 9% classified into the Old Sitka Rocks region; and the remaining 34% of individuals did not meet the probability threshold and thus classified into the 'Other' category (Table 3). No individuals were classified into either Bear Cove or Cove Marina.

We then used Mg/Ca, Sr/Ca, and Ba/Ca elemental ratios to validate the otolith edge signatures of adult herring. We were unable to use individual sampling locations, but we were able to use the three defined zones of sampling locations. We were not able to use individual sampling locations due to overlap of chemical signatures. This is due to a majority of the sampling locations being found in close proximity to one another in Zone II. We had strong correct classification in Zone III (96%), Zone II (67%) and Zone I (67%) (Table 4). Though the correct classification of individuals from the region north of Zone I (56%) was not as strong as the other two regions, the majority still correctly classified into this region, allowing us to use this data to classify individuals using the otolith core of adult herring (Table 4). When we classified the adult core elemental signature, based on the adult edge elemental signature, we found that a majority of the individuals classified into Zone II (90%). Ten percent of the individuals classified into Zone I. No individuals were classified into the region north of Zone I or Zone III (Table 5).

We also classified the juvenile core elemental signature based on the adult edge signature. We found the majority of the individuals classified into Zone II (85%). Fifteen percent of the individuals classified into Zone I. No individuals classified into the region North of Zone I. Twenty-one percent of individuals could not be classified into a zone based on the given elemental signature from the edge of adult herring (Table 6). These results are similar to all classifications based on otolith edge elemental ratios. Zone II appears to be an important region for the spawning of Pacific herring in the Sitka area.

Discussion

The adult pacific herring otolith chemistry indicates that many of the adult fish hatched in Zone II. Adult pacific herring that hatched in Zone II could not be defined, on a smaller scale, to sites within Zone II due to chemical overlap. This overlap is likely due to the fact that the adults move very quickly from area to area and many of the sites within Zone II are in close proximity to one another. The signature of the otolith is composed of about 7 days worth of a fish's life and consequently if that fish does not stay in one area then the chemical signature can be a mix of multiple sites. That is one of the reasons that juvenile fish are so important to a study like this. Juvenile fish typically do not move around as much as adults. Consequently the otolith chemical signature has the potential for a much better site discrimination. We find that in Sitka Sound, herring juveniles do have better site discrimination than other regions in Alaska. The adult otolith chemistries indicate that Zone II is a source habitat. The juvenile otolith chemistries indicate that the area south of Starrigavan Bay, in Zone II, appears to be the most productive source area in Sitka Sound. The bulk of herring spawn occurs in the area. Ninety percent hatch in Zone II and over 57% of juvenile herring use the Barge Dock area as a nursery bay. Based on the results of the otolith chemistries from the juvenile herring sampled, the Barge Dock appears to be the most productive rearing habitat for juvenile herring in Sitka. The Cove Marina site is less than 1 nautical mile south of the Barge Dock and less than 0.5 nautical miles northeast of the Old Sitka Rocks. The Barge Dock is located within the highly productive Starrigavan Bay estuary (Sitka Parks and Recreation Plan, 1991). Starrigavan Bay is located in Zone II and herring consistently spawn in this area and along the entire eastern shoreline south of Starrigavan Bay. Although these sites are in close proximity to each other, the Barge Dock area appears to be optimum herring habitat, as it supports spawning habitat and nursery grounds. As described by Sundberg (1981), the northward flowing ocean currents move along the Sitka shoreline, probably transporting herring larvae into the Old Sitka Rocks, Cove Marina, Barge Dock, and the Starrigavan Bay estuary where they would retain, undergo metamorphosis, and utilize the habitats as nursery bays (Figure 2). The planktonic larvae of the herring that spawn in areas distant from the Starrigavan Bay estuary face a wide variety of biotic and abiotic factors that can greatly influence their dispersal into this area. These factors can greatly influence larval survival and recruitment. Successful recruitment events can ultimately affect adult populations.

Although information describing oceanographic characteristics of Sitka Sound is quite limited, most of the surface ocean currents in Zone II move in a northerly direction (Sundberg, 1981). Herring that spawn in the eastern portion of Zone II may have a higher larvae survival rate than herring that spawn along the western portion of Zone II, i.e. Kruzof Island shoreline. The ocean currents may drive larvae from the eastern portion of Zone II into the protected estuaries, bays, inlets, and near shore habitats like the Barge Dock area, Starrigavan Bay estuary, and even Katlian Bay and Nakwasina, thus increasing their success. The ocean currents along the Kruzof Island shoreline may advect herring larvae out of Sitka Sound and into the Gulf of Alaska where the survival rate is predicted to be extremely low (Figure 2). The herring spawning beaches in Zone III have greater exposure to open ocean conditions than the herring spawning beaches within the greater Sitka Sound. Herring larvae from Zone III are more than likely driven northward into Zone II by the ocean currents that arrive in Sitka Sound from the south.

Herring hatch in Zone II and then disperse to other sites such as Salisbury Sound. Sitka Sound appears to be supplying Salisbury Sound, along with other nursery areas north of Zone I, with juveniles. Salisbury Sound may be a source population for Hoonah, but also a sink population for Sitka Sound. Fourteen percent of fish collected in Hoonah Sound hatched in Salisbury Sound and the remainder came from Zone II. Based on the results, we hypothesize that the ocean currents may drive herring larvae from Salisbury Sound north, through Peril Straits, to Hoonah Sound. The currents in the greater Sitka Sound area may drive herring larvae up through the narrows into Salisbury Sound and, subsequently, Hoonah Sound. The Alaska Department of Fish and Game manages Salisbury Sound and Sitka Sound as one stock, and Hoonah Sound as a separate stock. According to this data, all three populations should be managed as separate stocks, or combined as one metapopulation.

In 2005 and 2006 the otolith chemistry of spawning adult herring collected on the northern part of Salisbury Sound (Zone I), specifically east of Kane Island, was distinct from those herring that were collected in Sitka Sound (Zone II). In 2007 the herring sampled in Zone I spawned on a different beach, Sukoi Inlet, in southern Salisbury Sound. The chemistry of the herring collected in 2007 is different from the chemistry of the herring collected in 2005 and 2006. In 2006 the ADF&G commercial herring sac roe fishery harvested 4,204 tons, about half the guideline harvest limit, in Zone I (Davidson et al., 2009). This large commercial harvest in Zone I may have contributed to the inability to locate herring for sampling in 2007. None of the herring collected in 2007 in Zone I were hatched in Zone I, while 50% hatched in Zone II and 50% hatched in an unknown location.

Conclusions

The Barge Dock is along the Sitka road system and is an industrial area; there is a barge services facility and the Alaska State Marine Highway ferry terminal located at the sample site. The Cove Marina, also located on the Sitka road system, is a small boat harbor located less than 1 nautical mile south of the Barge Dock. Future development of this shoreline must be thoroughly considered, because it is the most important habitat for Sitka Sound herring that we sampled. From this research we conclude the following: Zone II is the most productive area for both adult and juvenile herring in Sitka Sound; the area along the northeast shoreline of Sitka Sound, specifically the Barge Dock shoreline and also Old Sitka Rocks and the Starrigavan Bay estuary, is the most essential habitat for juvenile herring production; and the Sitka Sound herring metapopulation contributes greatly to the Zone I population, the Zone II population, and the Zone III population; and finally, the Zone 1 population contributes to the Zone II population and the north of Zone I population.

Using otolith chemistry we were able to identify both source and sink habitats in Sitka Sound. Based on this study and other work done in Sitka Sound, the greatest weakness of the technique to identify essential habitat is obtaining a complete sample from all habitats. The greater number of sites sampled, the greater the range of collection site chemical signatures. This data complements the Bickford and Norcross EVOS Project No. 070782, “Herring Restoration in PWS: Identifying Natal and Nursery Habitats.” With the knowledge gained from this project, this technique will be able to transfer directly to Prince William Sound in order to identify other habitats that may be suitable for herring recolonization projects.

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Figure 1. Locations of collection sites and dates of adult and juvenile herring samples from 2007 in the Sitka Sound area, including Salisbury Sound and Hoonah Sound. Sitka is located at N 57° W 135°.

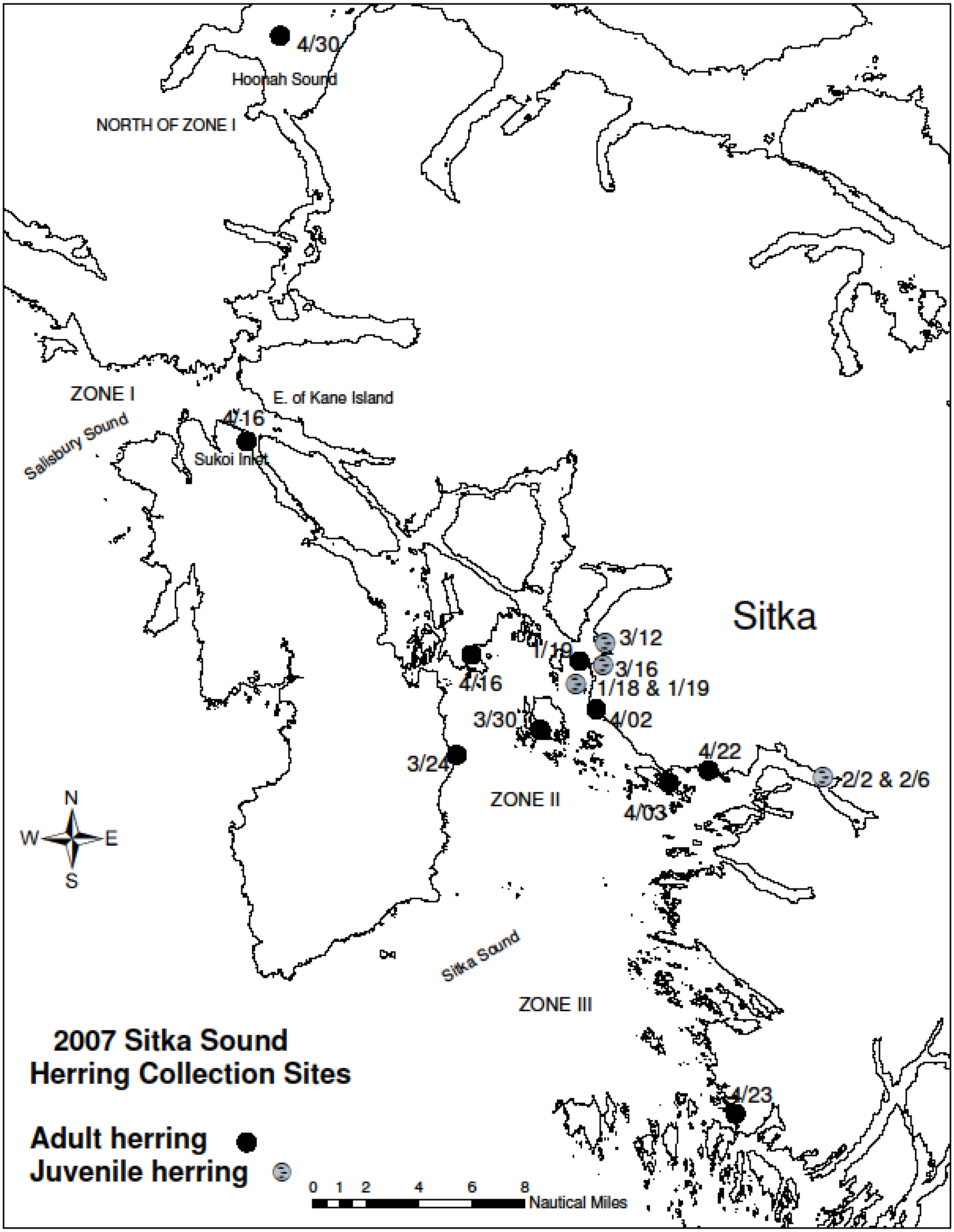

Figure 2. Sitka Sound circulation study from Sundberg, 1981. Net surface circulation flows northward along the Sitka shoreline to the Barge Dock and north to the Starrigavan Bay estuary.

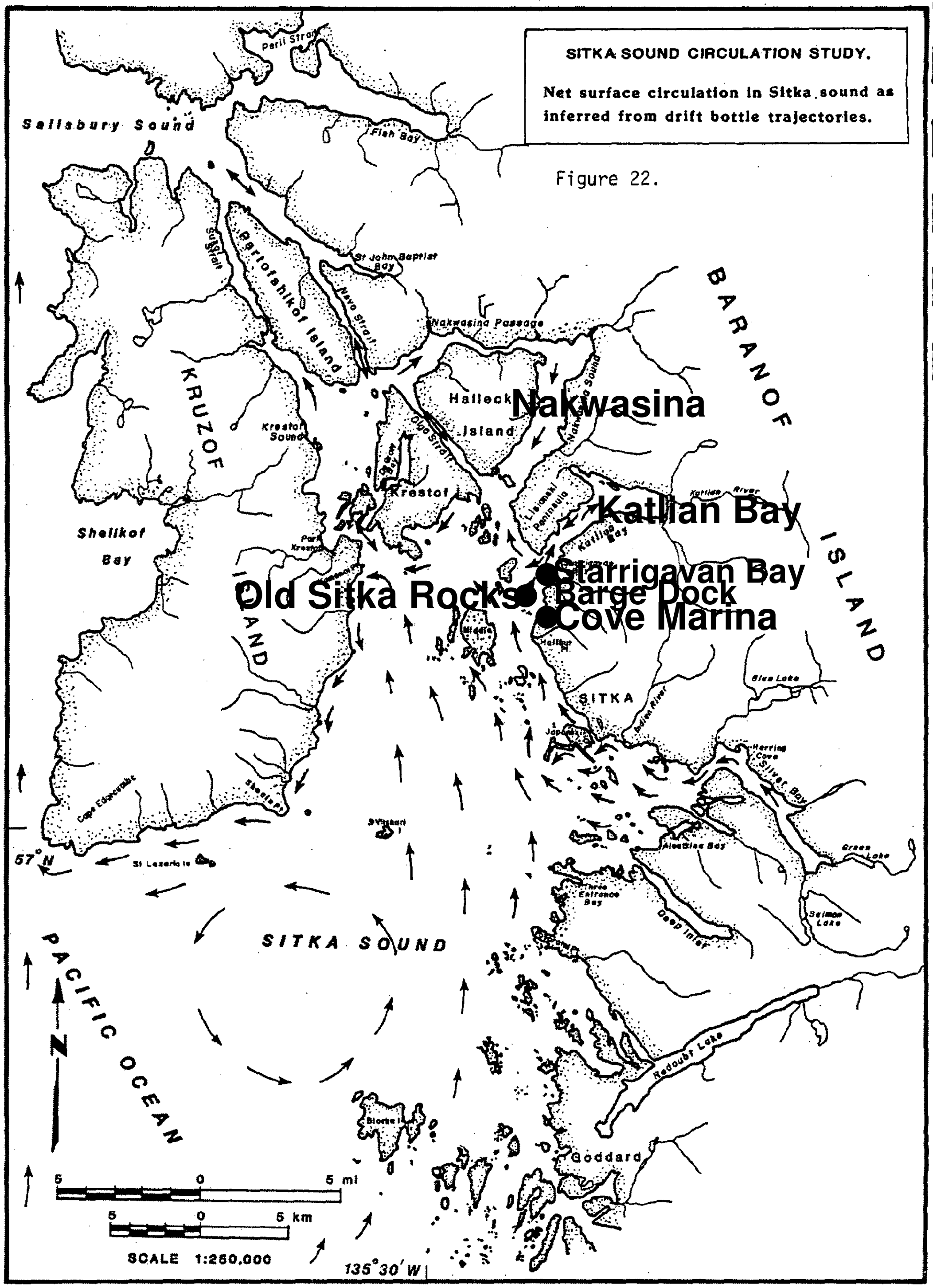

Table 1. Number of individual Pacific herring collected in each sampling location and zone, and where adults and juveniles were collected.

Location	Zone	n	Age Class
Bear Cove	II	37	Juvenile
Kliuchevoi	III	22	Adult
Cove Marina	II	21	Juvenile
Harbor Point	II	23	Adult
Hoonah Sound	N. of I	21	Adult
Magic Island	II	19	Adult
North Inner Point	II	19	Adult
Old Sitka Rocks	II	14	Adult
Old Sitka Rocks	II	14	Juvenile
Promisula Bay	II	25	Adult
Sage Rocks	II	20	Adult
Barge Dock	II	23	Juvenile
Sukoi Inlet	I	18	Adult
Thimbleberry Bay	II	20	Adult
Whiting Harbor	II	20	Adult

Table 2. Validation of correct classification of juvenile otolith edge elemental rations using nonparametric discriminant analysis with Mg/Ca, Sr/Ca, Sr/Sr, and Ba/Ca as the variables. The shaded column represents juvenile collection locations; rows represent the classification into each zone.

Juvenile collection location	Zone II Bear Cove	Zone II Cove Marina	Zone II Old Sitka Rocks	Zone II Barge Dock	Other	Total
Bear Cove	57% n=21	19% n=7	19% n=7	5% n=2	0%	100% 37=n
Cove Marina	10% n=2	86% n=18	5% n=1	0%	0%	100% 21=n
Old Sitka Rocks	7% n=1	7% n=1	86% n=12	0%	0%	100% 14=n
Barge Dock	9% n=2	4% n=1	9% n=2	74% n=17	4% n=1	100% 23=n
Total	27% n=26	24% n=27	23% n=22	20% n=19	1% n=1	100% 95=n

Table 3. Classification of juvenile otolith core elemental signature based on the otolith edge elemental signature. The shaded column represents juvenile collection locations; rows represent the classification into each zone.

Juvenile collection location	Zone II Bear Cove	Zone II Cove Marina	Zone II Old Sitka Rocks	Zone II Barge Dock	Other	Total
Bear Cove	0%	0%	5% n=2	73% n=27	22% n=8	100% 37=n
Cove Marina	0%	0%	14% n=3	81% n=17	5% n=1	100% 21=n
Old Sitka Rocks	0%	0%	29% n=4	43% n=6	29% n=4	100% 14=n
Barge Dock	0%	0%	0%	17% n=4	83% n=19	100% 23=n
Total	0%	0%	9% n=9	57% n=54	34% n=32	100% 95=n

Table 4. Validation of correct classification of adult otolith edge elemental rations using nonparametric discriminant analysis with Mg/Ca, Sr/Ca, and Ba/Ca as the variables. The shaded column represents adult collection locations; rows represent the classification into each zone.

Adult collection location	Zone I	Zone II	Zone III	Zone N of I	Total
Zone I	56% n=10	22% n=4	11% n=2	11% n=2	100% 18=n
Zone II	12% n=19	67% n=106	11% n=17	10% n=16	100% 158=n
Zone III	0%	0%	96% n=22	4% n=1	100% 23=n
Zone N of I	14% n=2	14% n=3	14% n=4	67% n=14	100% 21=n
Total	14 n=31	51% n=112	20% n=45	15% n=32	100% 220=n

Table 5. Classification of adult otolith core elemental signature based on the otolith edge elemental signature. The shaded column represents adult collection locations; rows represent the classification into each zone.

Adult collection location	Zone I	Zone II	Zone III	Zone N of I	Total
Zone I	11% n=2	89% n=16	0%	0%	100% 18=n
Zone II	11% n=18	89% n=140	0%	0%	100% 158=n
Zone III	0%	100% n=23	0%	0%	100% 23=n
Zone N of I	14% n=3	86% n=18	0%	0%	100% 21=n
Total	10% n=23	90% n=197	0%	0%	100% 220=n

Table 6. Classification of juvenile otolith core elemental signature based on the adult otolith edge elemental signature. The shaded column represents juvenile collection locations; rows represent the classification into each zone.

Juvenile collection location	Zone I	Zone II	Zone III	Zone N of I	Total
Bear Cove	14% n=5	86% n=13	0%	0%	100% 37=n
Cove Marina	24% n=5	76% n=16	0%	0%	100% 21=n
Old Sitka Rocks	0%	100% n=14	0%	0%	100% 14=n
Barge Dock	17% n=4	83% n=19	0%	0%	100% 23=n
Total	15% n=14	85% n=81	0%	0%	100% 95=n