Study Plan and Summary of Results for the Skagit River Estuary Intensively Monitored Watershed Project

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Contents

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Introduction

Chinook salmon are well known for utilizing natal river tidal deltas, non-natal "pocket estuaries" (nearshore lagoons and marshes), and other estuarine habitats for rearing during outmigration (Reimers 1973, Healey 1980, Beamer et al 2003). Several studies have linked population responses to availability of estuary habitat, either by examining return rates of groups of fish given access to different habitat zones (Levings et al. 1989) or by comparing survival rates of fish from populations with varying levels of estuary habitat degradation (Magnuson and Hilborn 2003). These studies support the hypothesis that estuarine habitat is vital for juvenile Chinook salmon. However, these necessarily coarse-scale studies did not address the potential for large-scale estuarine habitat restoration to benefit salmon population productivity and life history diversity. These issues may be critical to understand how to best restore Chinook salmon populations, as many estuaries within Puget Sound and elsewhere have been converted to agriculture and urbanization land uses.

The goal of the Skagit River Intensively Monitored Watershed (IMW) project is to understand changes in population characteristics (primarily abundance, productivity, and life history diversity) of wild Chinook salmon in response to reconnection and restoration of estuarine habitat. To accomplish this goal, we are studying the Skagit River Chinook salmon population at four stages of their migration: the mainstem Skagit River near estuary entry, the tidal delta, nearshore, and offshore. These monitoring programs allow us to examine changes in body size, abundance, and life history variation as fish migrate out of the estuary. The long time series of monitoring data allow us to examine the effects of large restoration projects in the tidal delta, which commenced in 2000 and will continue in future years. Additional status and trends monitoring of adults returning to the Skagit River provide a further reference to evaluate whether the cumulative amount of restoration can improve production.
This study plan and summary of results highlights the hypotheses, restoration projects, and methodologies, and results of the Skagit system-wide monitoring. In doing so, we address how our methodologies are answering two general questions relevant to monitoring the population response of Chinook salmon to estuary restoration: 1) do salmon exhibit limitations during estuarine life stages related to capacity and connectivity, and 2) has estuary restoration resulted in population- or system-level responses? An additional question – do restoration projects increase utilization of estuary habitat by juvenile salmon – is encompassed in project effectiveness monitoring at smaller spatial scales. Effectiveness monitoring is not funded through the Skagit IMW and depends upon the existence of funding in restoration project budgets. All constructed Skagit estuary restoration projects have at least two years of effectiveness monitoring. We briefly summarize effectiveness monitoring results in this report.

Study area

The Skagit River estuary is part of the larger Puget Sound fjord estuary, and consists of a mosaic of habitats with a tidal delta and its adjacent more marine bay, Skagit Bay (Fig. 1). Estuarine study sites consisted of blind tidal channels within the Skagit River tidal delta, and shoreline and nearshore (subtidal neritic) areas of Skagit Bay.

The Skagit River tidal delta is a prograding fan with numerous distributary channels and estuarine wetland islands. Estuarine habitats within the tidal delta include two zones. The riverine tidal zone is the area of river channels and wetlands where freshwater is tidally pushed but not mixed with marine water. The tidal estuarine zone includes the channeled emergent and scrub-shrub marshes where freshwater mixes with salt water. Within these areas a diversity of estuarine habitats are formed and maintained by tidal and riverine processes, creating a mosaic of wetlands and channels. These include blind tidal channels, which serve as our fish sampling units within the tidal delta.

The shoreline of Skagit Bay is 127.4 kilometers in length and its intertidal area is 8,838 hectares. Skagit Bay shorelines include a variety of beaches types based on differences in adjacent upland geologic materials (bedrock, glacial sediments, and recent coastal or river sediments), geomorphic processes within longshore drift cells, and the gradient of the shoreline. The beaches that dominate much of Skagit Bay are the sampling units for this study. In addition, subtidal surface (neritic) waters offshore of intertidal areas comprise the sampling locations for the final phase of population monitoring before fish migrate out of Skagit Bay.

Landscape analyses indicate that the Skagit River has lost much estuarine habitat to agricultural and residential development, despite a large amount of extant tidal delta and shoreline habitat. Under present day conditions, the contiguous habitat area of the Skagit tidal delta consists mostly of area in the vicinity of Fir Island, but it also includes a fringe of estuarine habitat extending from southern Padilla Bay to the north end of Camano Island. In 1991 the tidal delta footprint for this area was 3,118 hectares (Beamer et al 2005). Prior to diking, dredging, and filling in the delta (circa 1860s) 11,483 hectares of tidal delta footprint existed in the same area (Collins et al. 2003), indicating that 73% of tidal delta has been disconnected from floodplain and tidal processes. These estimates of tidal delta habitat area account for gains in delta habitat caused by progradation occurring between the 1860s and 1991 (Beamer et al. 2005) and indirect losses of habitat occurring as a result of changed tidal processes and sediment deposition (Hood 2004). In Skagit Bay, 24% of the shoreline has been armored to protect land uses adjacent to accretion shoreforms or eroding sediment source bluffs (Mcbride et al., 2006).

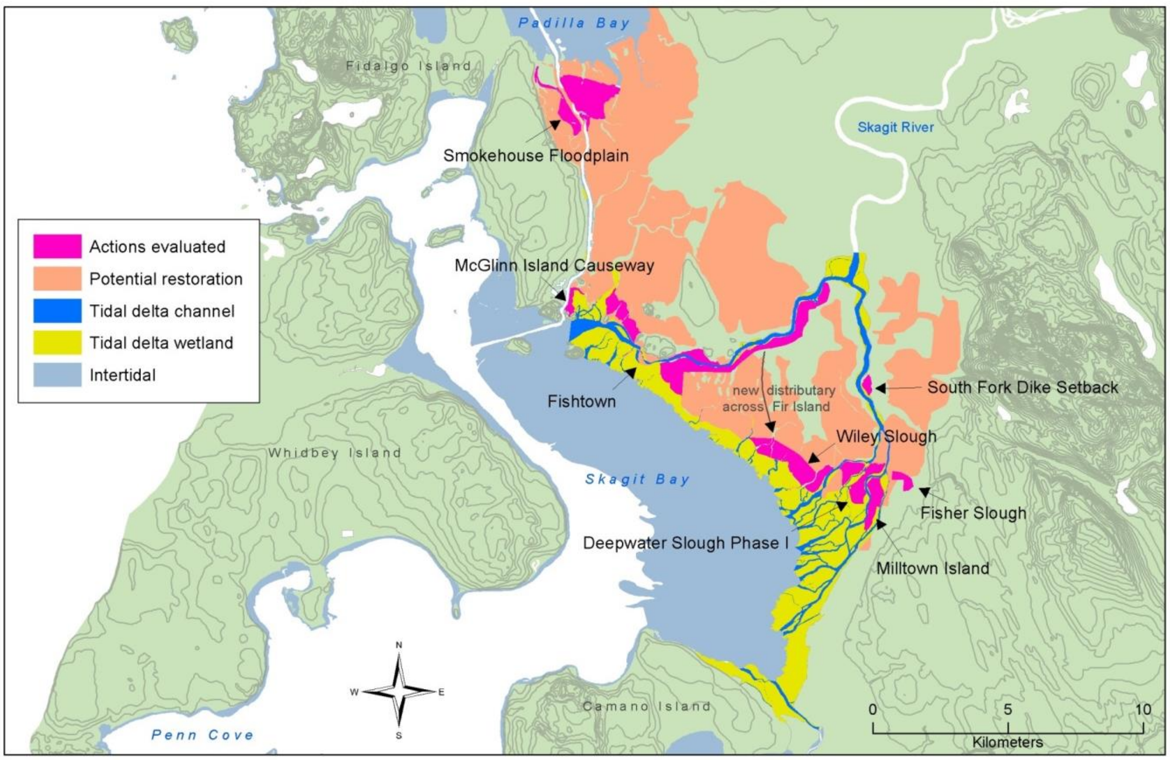

Figure 1. The Skagit River estuary, showing potential restoration areas and actions (i.e., restoration projects) that were evaluated in the Skagit Chinook Recovery Plan (SRSC and WDFW 2005). Many of these actions have occurred during the course of the Skagit IMW. The potential restoration area is the historic estuary footprint from Collins et al. 2003.

Rationale for the Skagit IMW

This section of the Skagit IMW Study Plan describes:

- why Chinook Salmon should be sensitive to restoration of estuarine habitat and why the Skagit is an appropriate location to test hypotheses related to Chinook salmon response to estuary restoration,
- summarizes the existing research that lead to the formation of the Skagit IMW hypotheses, and
- describes the Skagit IMW hypotheses.

The Skagit was chosen in part to provide a study system within the IMW Program of Washington State that targeted restoration of estuarine rearing habitat for the benefit of Chinook salmon. The Skagit IMW builts on over a decade of research (summarized in Beamer et al 2005) that was used as the scientific basis for the restoration actions proposed in the Skagit Chinook Recovery Plan (SRSC and WDFW 2005). This existing Skagit research forms the IMW's hypotheses (described below) which are tested through monitoring efforts funded by the IMW Program and its partners (i.e., SRSC, WDFW, and NOAA). Successful testing of the Skagit IMW hypotheses depends on estuary restoration being completed. The Skagit Chinook salmon restoration goal for estuary habitat is to increase juvenile Chinook salmon rearing carrying capacity by 60%. Approximately 20% of the work has been completed, not including the first major restoration project (Deepwater Slough) which occurred prior to the Recovery Plan.

Skagit Chinook salmon juvenile life history types

Chinook salmon are described as the most estuarine-dependent of all the Pacific salmon and well-known for their life history variation (Reimers 1973, Healey 1980, Greene and Beechie 2004). These life history types can be distinguished based on differences in body size and the seasonal timing that fish transition from habitat zone to another.

Existing research and long-term monitoring in the Skagit River suggests that four life history types comprise most of the juvenile life history variation of Chinook salmon (Table 1, Figure 2).The distinct juvenile life history types of Skagit Chinook salmon occur based on branching by juvenile Chinook patterns (i.e., does the fish remain or migrate) within three main ecological zones (freshwater, natal estuary, and marine nearshore). Branching occurs in each zone, resulting in five distinct juvenile life history types (Figure 2). The ecological zones correspond to distinct geographic areas: 1) freshwater = Skagit River and its tributaries; 2) natal estuary = Skagit tidal delta; and 3) marine nearshore = Whidbey Basin. Simply explained (and diagramed in Figure 2), each year cohorts of Chinook salmon fry emerge from their gravel egg pockets in the Skagit River and its tributaries during the winter and early spring months. Some fry migrate downstream without doing any appreciable rearing in the freshwater environment. Fry remaining in freshwater branch into two main life history types after an extended freshwater residence period. Some fish remain in freshwater for a few months and migrate downstream as parr, while others remain in the freshwater environment for over a year and migrate the following spring as yearlings. Of the fry that migrate downstream, some establish residence in the Skagit's natal estuary for a period of time while others migrate into the more marine waters of Skagit Bay, part of the Whidbey Basin. Of the fry that end up in the Whidbey Basin, some establish residence in nearshore refuge habitats while others do not.

In recent years (brood years 1993 – 2008), one million to over seven million wild juvenile Chinook salmon have migrated from the Skagit River each year (Zimmerman et al. in press). Out of each migration, we observe all juvenile life history types present. Below we describe the relationship of each life history types to the Skagit Tidal Delta.

Fry Migrants: Fry migrants move through the tidal delta without rearing there, but exhibit extensive rearing in non-natal estuaries (Beamer et al. 2003) and creek mouths (Beamer et al. 2013) in Skagit Bay and elsewhere in the Whidbey Basin. Baseline monitoring in the Skagit River and elsewhere (Reimers 1973) suggests that large fry migrant pulses are the outcome of density-dependent interactions in the tidal delta and river, and could be alleviated by restoration in the tidal delta (Beamer et al. 2005).While fry migrants are present in the Skagit's outmigration population each year, their abundance appears to be a phenotypic response to density dependence occurring first in freshwater (Zimmerman et al. in press) and then later in estuarine habitat of the Skagit River system (Beamer et al. reviewed). Depending on the total outmigration population size, all fry migrants (those that use and do not use nearshore refuge habitats) make up approximately 5% to over 40% of the juvenile Chinook salmon in Skagit Bay each year (Beamer et al. reviewed).

Delta Fry: Delta fry are by definition associated with the tidal delta, and rear there for a period of 0.5 –2 months. The average tidal delta residence period for tidal delta rearing Chinook salmon in 1995 and 1996 (combined) was 34.2 days (Beamer et al. 2000). Following the tidal delta rearing period, these fish migrate to Skagit Bay, usually starting in late May or June. We observe a tidal delta rearing region on their otolith. Beamer and Larsen (2004) further defined several life history sub-strategies for tidal delta rearing Chinook salmon based on movement patterns and overall residence period within the tidal delta. The number of tidal delta rearing migrants each year is a function of the river's outmigration population size of fry and density dependence occurring in estuary habitat (Beamer et al. reviewed). As tidal delta habitat fills up with migrating fry from upstream, the excess fry respond by moving downstream into the Skagit Bay. Beamer et al. (2005) estimated tidal delta rearing capacity at 2.25 million juvenile Chinook per year.

Parr Migrants: Parr migrants do not extensively reside in tidal delta habitats. We observe an extended freshwater rearing region and no tidal delta rearing region on their otolith (Beamer et al. 2000). Depending on the total outmigration population size, parr migrants make up approximately 15% to over 60% of the subyearling outmigration each year (Zimmerman et al. in press). Parr migrant abundance has averaged approximately 1.2 million per year and is a result of density dependence occurring in the freshwater rearing environment (Zimmerman et al. in press).

Yearlings: Yearlings do not reside in tidal delta habitats for an extended period of time like tidal delta rearing migrants do. Yearlings seem to pass through tidal delta habitats (possibly lingering briefly) and on to nearshore areas. Yearlings are rarely found in shallow intertidal environments, but are most commonly detected in deeper subtidal or offshore habitats. Yearling outmigration abundance has ranged from 6,000 to 97,000 in recent years (Zimmerman et al. in press).

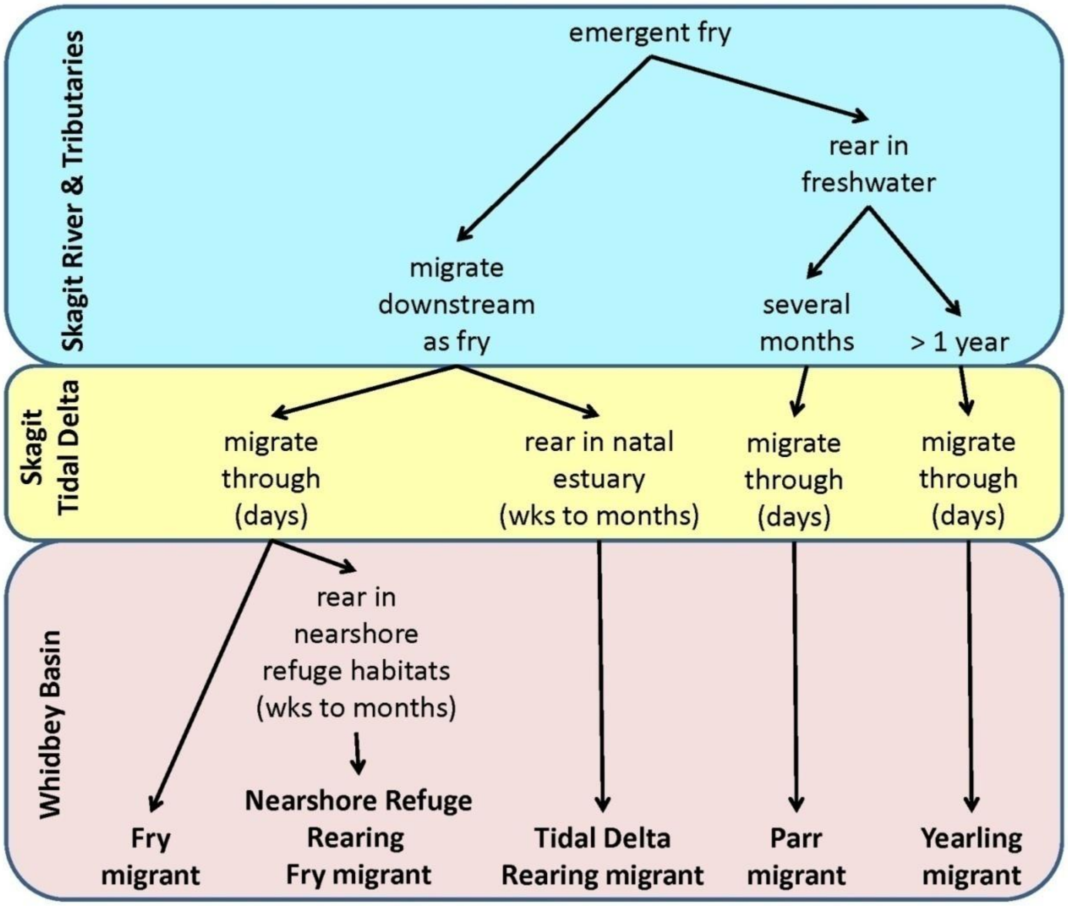

Figure 2. Phenotypic branching of juvenile Skagit Chinook salmon by major ecological zones, resulting in five distinct juvenile life history types.

Table 1. Size of juvenile Chinook salmon migrants by life history type at the transition from freshwater to estuary and estuary to nearshore.

	Subyearlings			**Yearlings**
	Delta fry	**Fry migrants**	**Parr migrants**	
Size at outmigration from freshwater to (or through) estuary (range in mm)	< 45	< 45	45 - 90	80 - 150
Size at outmigration from estuary to nearshore(average and range in mm)	74 (46-124)	39 (30-46)	75 (57-92)	120 (92-154)

Hypotheses about system-wide effects of estuary restoration

Baseline monitoring strongly suggests that restricted availability and connectivity of habitat in the tidal delta is limiting rearing opportunities for subyearling fry migrating downstream. We found four general patterns prior to restoration: an asymptoting level of population density in the tidal delta at high fry outmigration population sizes (Fig. 3A), negative relationships between tidal delta population and both body size (Fig. 3B), and the timing at which 50% of the tidal delta abundance is observed (Fig. 3C), and increases in abundance of fry migrants in the nearshore as a function of the number of fry migrants (Fig. 3D). If these patterns are the consequences of habitat limitations in the tidal delta, we predict that restoration should

- reduce the rearing density at a given level of outmigration abundance (i.e., fish can spread out to a greater degree in estuarine habitats)
- increase size of outmigrants as they leave the tidal delta due to greater per capita resource availability,
- increase duration of individual residency in the tidal delta, thereby leading to a protracted pattern of cohort-level timing in the delta (e.g., the date that 50% of the cohort is observed).
- reduce the abundance of fry migrants in the nearshore due increased rearing capacity in the delta.
- increase marine survival and hence the rate of adult return as a consequence of better individual condition as predicted by previous hypotheses.

These predictions are expected to play out in spatially-predictable ways. We developed spatially-based hypotheses by thinking how current delta habitat is being utilized by juvenile Chinook salmon (Fig. 4A) and then hypothesizing how juvenile Chinook salmon would respond to planned delta restoration (Fig. 4B). In these figures, the arrow directions depict how juvenile Chinook salmon move through delta habitat and into Skagit Bay. The pathways within the delta are based on where delta distributary channels are located or planned to be restored. The pathways for fish moving from delta habitat to Skagit Bay were derived from drift buoy data. Arrow thickness represents the number of juvenile Chinook salmon using each pathway based on the current or restored habitat amount and configuration. Figure 4B shows planned restoration areas in pink. Because of limitations in the migratory pathways that fish can take within delta habitat, we expect subsets of delta habitat to respond to delta restoration in similar ways. We do not expect the entire delta will respond to specific restoration projects in a homogeneous fashion. The sub-delta areas that we do expect to respond similarly are numbered and circled in Figure 4B. Monitoring hypotheses are stated for each area in Table 2. All monitoring hypotheses are interpreted as functions to account for varying outmigration population sizes, habitat conditions (e.g. channels with deep areas with low tide impoundments v. channels without these features), and environment (e.g., floods, temperature, salinity).

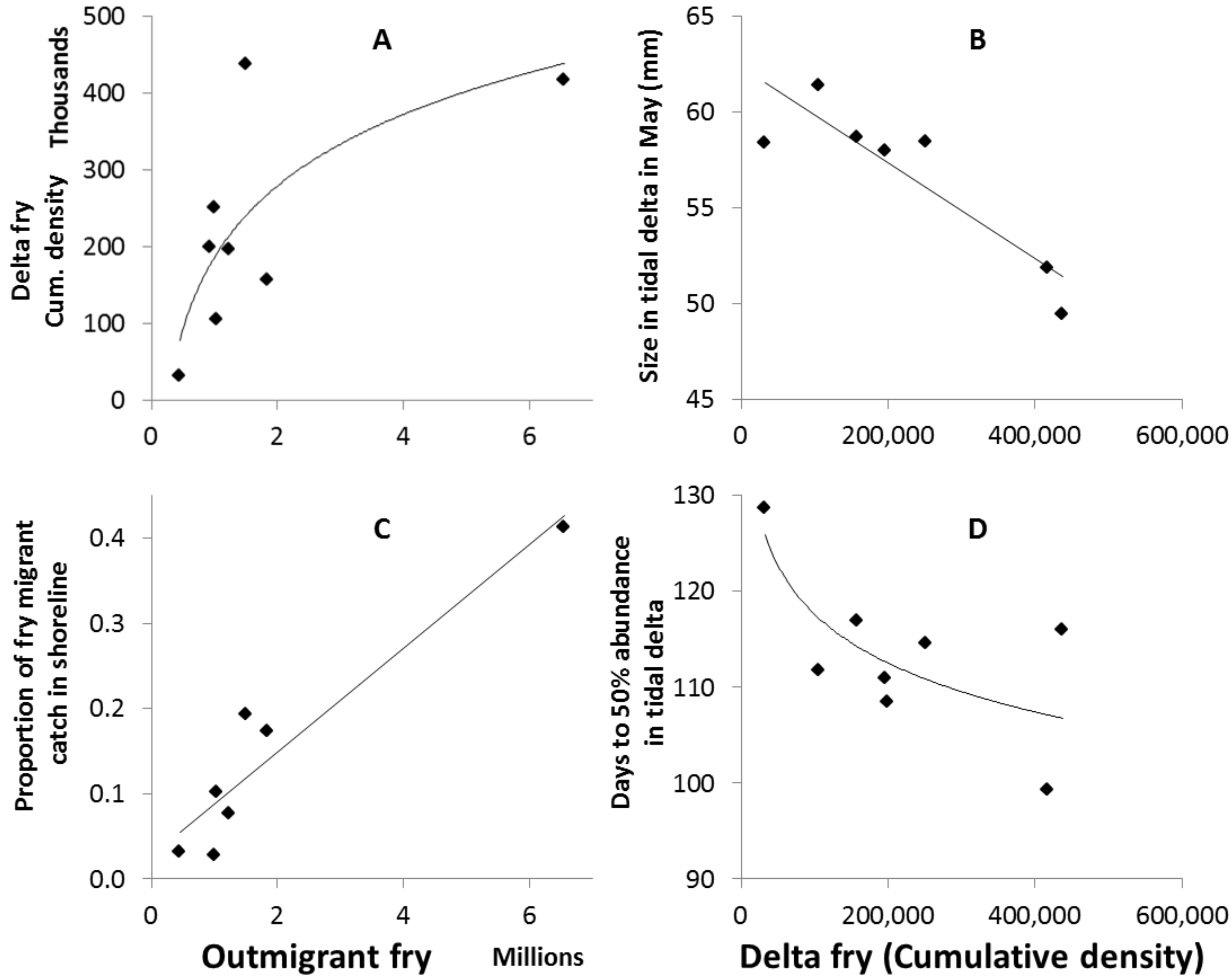

Figure 3. Biological relationships pointing to rearing habitat limitations in the Skagit tidal delta prior to restoration. A. The cumulative density (summed density over multiple sampling weeks) of fry rearing in the tidal delta flattens as a function of fry migrating downstream, B. the size of fish rearing in the tidal delta in May declines as a function of cumulative density in the tidal delta, the proportion of fry migrants captured along the shoreline of Skagit Bay increases as a function of outmigrant fry, and D. the timing of residency in the tidal delta declines as a function of fish rearing in the tidal delta. From Beamer et al. Reviewed.

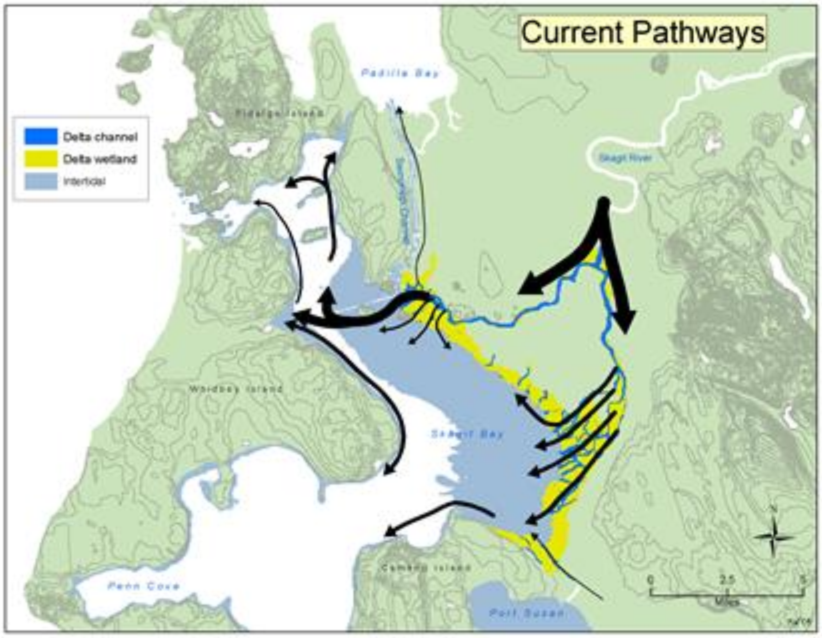

Figure 4A. Current juvenile Chinook salmon pathways in the Skagit River estuary before restoration. The arrow directions depict how fish move through the tidal delta and into Skagit Bay. Arrow thickness represents the number of Chinook salmon following these pathways, based on current habitat configuration and area.

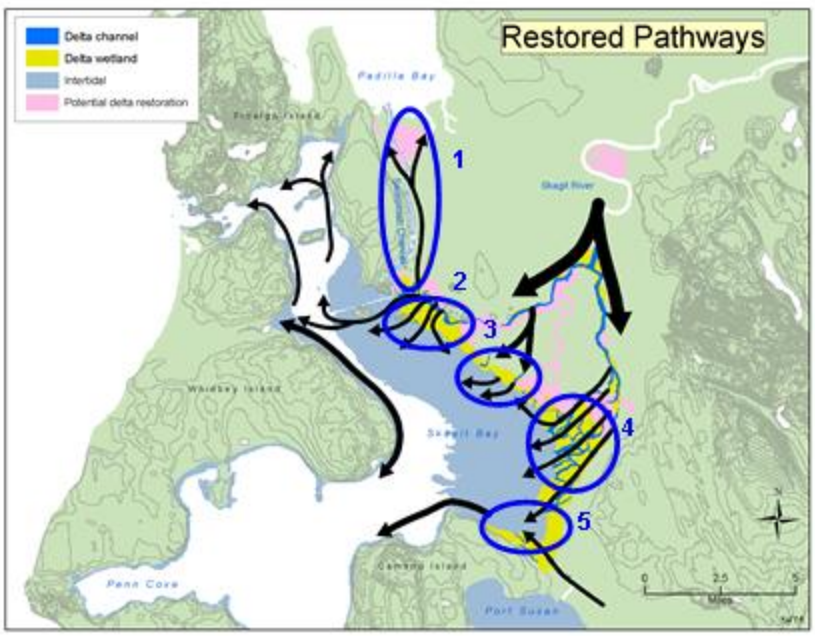

Figure 4B. Future juvenile Chinook salmon pathways in the Skagit River estuary after restoration. The arrow directions depict how fish move through the tidal delta and into Skagit Bay. Arrow thickness represents the number of Chinook salmon following these pathways, based on restored habitat area and connectivity. Conceptual habitat restoration areas are shown in pink. Subsets of delta habitat that are expected to respond in similar ways are circled and numbered. Monitoring hypotheses for each area are in Table 2.

Table 2. Draft monitoring hypotheses for juvenile Chinook salmon abundance in sub-delta polygons shown in Figure 3.

Sub-delta polygon #, name	Restoration potential (acres)	Juvenile Chinook response Pre-restoration	Juvenile Chinook response Post-restoration
#1 Swinomish Channel Corridor	770	Density lowest of all sub-delta polygons	Density increases and becomes more homogeneous due to increased connectivity with the North Fork Population increases due to increase capacity along the Swinomish Channel Corridor
#2 North Fork Delta	980	Density highest of all sub-delta polygons	Density decreases and becomes more homogeneous due to increased connectivity to other areas within the delta Population increases due to increase capacity within the North Fork Delta
#3 Central Fir Island Delta	470	Density 2^{nd} lowest of all sub-delta polygons	Density increases and becomes more homogeneous due to increased connectivity via a cross island corridor restoration project Population increases due to restored capacity within Central Fir Island
#4 South Fork Delta	630	Density is intermediate of all sub-delta polygons	Density remain the same but become more homogeneous due to increased connectivity within the South Fork Delta Population increases due to increase capacity with the South Fork Delta
#5 Stanwood/English Boom Delta Fringe	None Currently Identified	Density lowest of all sub-delta polygons	Density and population increases due to increased source population increase originating from Stillaguamish and Skagit Rivers.

Table 3. Restoration projects completed or planned in the Skagit River estuary, dates, benefit to salmon, and their acreage (area exposed to tidal inundation after restoration). Monitoring designs are: PT = post treatment design; BACI = before/after control impact design

Site	Year of completion	Benefit to salmon (connectivity, capacity, both)	Area of estuary	Acres	Effectiveness Monitoring Design and years monitored
Deepwater Slough	2000	Both	South Fork	221	PT, 2001-2003
Smokehouse Floodplain	2005-8	Capacity	Swinomish Channel	43	BACI, 2004-2011
Milltown Island	2006-7	Capacity	South Fork	212	PT, 2012-2013
South Fork dike setback	2007	Capacity	South Fork	40	PT, 2012, 2014
Swinomish Ch. fill removal	2008	Capacity	Swinomish Channel	12	PT, 2009-2013
Wiley Slough	2009	Capacity	South Fork	161	Partial BACI, 2003, 2012-2013
Fisher Slough	2010-11	Capacity	South Fork	68	BACI, 2009-2013 & 2015
Cottonwood Island	<5 years	Capacity	South Fork	169	Planned BACI, 2012
McGlinn Island Causeway	<5 years	Connectivity	North Fork	10	Planned BACI, 2005-present
Fir Island Farms	<5 years	Capacity	North Fork	130	Planned BACI, 2015-2019
Deepwater Phase II	<5 years	Capacity	South Fork	268	Not designed
TOTAL				**1334**	

Amount of Estuary Restoration

Given the reliance of juvenile subyearling Chinook salmon on estuary habitat and the amount of historical habitat loss, we would expect estuary restoration to benefit Skagit River Chinook populations. Starting in 2000, there has been a systematic effort to restore estuary habitat (Table 3), resulting in seven completed projects and over 750 acres of habitat restored. Within the next five years, four additional restoration projects are anticipated to be completed totaling 577 acres. Restoration includes improvements to capacity (amount of rearing habitat), connectivity (connection among rearing areas), or both. These efforts (i.e., constructed and anticipated projects) fulfill about 20% of estuary restoration goal of increased juvenile Chinook carrying capacity described in the Skagit River Chinook Recovery Plan (Beamer et al. 2005). Restoration in the estuary has been performed within the context of an overall portfolio of Chinook salmon recovery actions that also include habitat protection and restoration in tributary, floodplain, and nearshore habitats.

The Skagit IMW does not monitor the response of Chinook salmon to restoration occurring within freshwater habitats located upstream of the estuary, but it does account for their influence and natural environmental variation (e.g., floods) that influences juvenile Chinook migrants. This is done by maintaining the downstream migrant trap which measures migrant population abundance, timing, and body size by life history type.

Methods

Survey methods and effort

We are currently monitoring Skagit River Chinook salmon via a long-term interagency programs involving sampling of outmigrants at Mt Vernon (Washington Department of Fish and Wildlife, WDFW), fyke trapping of fish rearing in the tidal delta (Skagit River System Cooperative, SRSC), beach seining of nearshore habitats in Skagit Bay (SRSC), and townetting of offshore areas in Skagit Bay (Northwest Fisheries Science Center, NWFSC). This program provides us the capability for a system-wide analysis of patterns of abundance and life history diversity across the migration season.

Table 4. Current monitoring programs for assessing effects of restoration in the Skagit River estuary.

Method	Lead entity	Habitat	Sampling regime	# of sites	# of years
Outmigrant trapping	WDFW	Mainstem	Daily, Feb-Jul	1	23
Fyke trapping	SRSC	Tidal delta & Swinomish Channel	Biweekly, Feb-July Monthly in August	11	23
Beach seining	SRSC	Skagit Bay shore & Swinomish Channel	Biweekly, Feb-Aug Monthly, Sept-Oct	32	20
Kodiak trawling	NWFSC	Skagit Bay neritic	Monthly, Apr-Oct	12	14

We use differing levels of survey effort for the three main types of sampling in the Skagit River estuary. Table 4 summarizes the number of sites, frequency, and duration of sampling. One major change that has occurred since the beginning of funding through IMW has been a shift from an index sampling design to random sampling.

Intensive monitoring efforts in the Skagit River allows us to examine several metrics of abundance: abundance of juvenile Chinook salmon departing the Skagit River watershed for the estuary and beyond, density of juveniles rearing in the tidal delta, density of juveniles rearing in Skagit Bay, and density of fish residing in the neritic waters of Skagit Bay. Freshwater outmigrant data are essential for putting downstream abundance measures in the context of total outmigration size.

Freshwater rearing. WDFW operates a juvenile fish trap on the Skagit River at river km 39.1 in the city of Mount Vernon. Operation of this trap began in 1990 for the purpose of estimating coho smolt production. The focus of this trapping operation has expanded over time and now provides an estimate of the number of juvenile wild Chinook salmon emigrating from the entire Skagit Basin (Zimmerman et al. in press). The juvenile trap is operated each year beginning in mid-January and continues through July. This time frame was selected based on results from three extended trapping seasons conducted in the mid-1990s. The freshwater juvenile monitoring provides both abundance and life history data and includes juvenile migrant abundance by migrant type (fry, parr, yearling), juvenile body size, migration timing, and genetic sampling (details in Kinsel et al. 2008). The trap is actually two traps, an inclined-plane and a screw trap. The rectangular inclined plane trap (1.8 x 4.9 m) is fished by lowering the trap approximately 1 m into the water at an oblique angle, and the trap catches fish swimming in a 2 m^2 cross-sectional area near the surface of the water by forcing them onto the inclined plane and washing them into a collection box. The screw trap (2.5 m circular diameter) is fished by lowering it partially into the water. Fish swim downstream into the 2.35 m^2 cross-sectional entryway of the trap, and the rotation of plates within the trap forces fish into a collection box. The juvenile trap catches only a portion of the total juvenile Chinook emigrating from the Skagit River. Therefore, total abundance is estimated using a mark-recapture study design in order to expand the catch by a calibration factor (Zimmerman et al. in press). Missed catch is estimated during trap outages and is included in the final estimate. During the emigration period, a known number of marked fish (dye or fin-clip) are released upstream of the trap and a portion of these are recaptured in the trap. Releases of marked fish are conducted throughout the outmigration period in order to account for differences in trap efficiencies due to river conditions. The resulting trap efficiency data is applied to catch data in order to estimate total migrant abundance (details in Zimmerman et al. in press).

Skagit tidal delta. To measure abundance of juvenile Chinook salmon rearing in the tidal delta, we sample habitat use of unmarked subyearling Chinook salmon in blind channels using fyke traps. Fyke trap methodology followed Levy and Northcote (1982) and uses nets constructed of 0.3 cm mesh knotless nylon with a 0.6 m by 2.7 m diameter cone sewn into the net to collect fish draining out of the blind channel site. Nets feature a lead line that sink the bottom of the net to the benthos and a float line that maintains the top of the net at the water surface. Overall net dimensions (length and depth) vary depending on the blind channel's cross-sectional dimensions, but all nets were sized to completely block fish access at high tide.

We capture fish by setting a fyke trap across the mouth of the blind channel site at high tide and "fish" through the ebbing tide. Fish are captured as they move out of the dewatering channel. We sample twice a month over the period (February through August) during spring tide series at index sites. The effort started with four index sites in 1992 and expanded to six in 1995. Index sites were selected to represent the three estuarine wetland zones (estuarine emergent, estuarine scrub-shrub, and riverine tidal) present within the Skagit delta and the two major delta rearing areas for subyearling Chinook associated with the Skagit River's two dominant distributaries, the North and South forks.

Juvenile Chinook salmon catch are adjusted by trap recovery efficiency (RE) estimates derived from multiple mark-recapture experiments using a known number of marked fish released upstream of the trap at high tide. RE estimates are unique to each site and are related to hydraulic characteristics of the site during trapping (e.g., change in water surface elevation during trapping or water surface elevation at the end of trapping). We conduct five to eight different mark and recapture tests at each site to either calculate an average RE at the site or develop a regression model to convert the "raw" juvenile Chinook catch to an estimated population within the habitat upstream of the fyke trap on any sampling day. Average RE for the six fyke trap sites ranges from 29-57%. The RE adjusted Chinook catch is divided by the topwidth channel area of the blind channel network upstream of trap to calculate a juvenile Chinook density for each fyke trap set. Topwidth channel area is measured in the field.

Skagit Bay shoreline. To measure density of unmarked Chinook salmon rearing along shoreline habitats, we use beach seining techniques. Our beach seine is a 37 m by 3.7 m by 0.3 cm mesh knotless nylon net. The net is deployed by fixing one end of the net on the beach and the other on a boat which sets the net across the current and returns the net to the beach at a distance of approximately 60% of the net's length. After the set is held open against the tidal current for a period of a few minutes, the boat end is brought to the shoreline edge and both ends are retrieved, yielding a catch in the net's bunt section. We make three sets per site on each sampling day. Beach seine set area varies by site and sample day because tow times, set widths, and tidal current velocities moving past the site all varied dynamically. Tow time, set width and water surface velocity are measured for each beach seine set in order to calculate a set area for each beach seine set. The juvenile Chinook catch for each set is adjusted by set area to calculate a Chinook density for each beach seine set. Average set area for the six large net beach seine sites in Skagit Bay is 486 square meters.

We also have conducted 34 mark-recapture tests to estimate RE for beach seine methods. Marked fish were introduced to the seined area in 2 groups: 1) just before setting the net, and 2) just prior to closing the net and retrieving it to shore. Overall RE for the six beach seine sites was consistently high, averaging 84.5% (±10.1% C.I.).

Skagit Bay subtidal neritic areas. We sample subtidal neritic (surface and subsurface) areas of Skagit Bay using a 3.1 m high x 6.1 m wide Kodiak surface trawl, or "townet," deployed between two boats, each with a 15.2 m towline connected to a bridle on the net (see Rice et al. 2011). Mesh sizes in the net were 7.6 cm stretch in the forward section, 3.8 cm and 1.9 cm in the middle sections, and 0.6 cm in the codend. The primary vessel (13.7 m long, 174 hp inboard diesel) tows the left side of the net while trawling, and the second vessel (5.5 m long, 225 hp gasoline outboard) tows the right side. The net is towed at the surface for 10 minutes per tow, at 900-1000 rotations per minute (RPM) on the engine of the primary vessel and a typical towing speed of 2-3 knots through the water. Distance through the water is recorded with a mechanical flow meter deployed by the larger vessel. Area swept is calculated as the distance traveled through the water multiplied by the width of the net opening.

Adult returns. The long duration of status monitoring in the Skagit watershed will provide opportunities to relate various outmigrant metrics to adult returns of Chinook salmon (Greene et al. 2005), measured at index sites on spawning grounds by tribes and WDFW. Age data, derived from scales collected from carcasses on the spawning grounds and test fisheries, allow the reconstruction of annual abundance estimates into productivity ratios (recruits per spawner) organized by spawning cohort (i.e., brood year). These rates of return include estimates of terminal harvest. We currently have 18 complete cohorts with which to examine whether the benefits of estuary restoration can be detected at adult stages, but only 10 of these spawned after the initiation of restoration in 2000.

Indicators Measured

Fish abundance and density. Measures of abundance vary for each life stage. WDFW estimates the total number of juvenile outmigrants. In the Skagit tidal delta, Skagit Bay shoreline, and Skagit Bay neritic habitats, we use two indices of abundance: density and cumulative density. Both measures encompass the entire utilization curves of juvenile Chinook salmon in each habitat. Density was measured as the average density of juvenile Chinook salmon across index sites and rearing months.

Cumulative density is a measure of the abundance of juvenile Chinook salmon that occupy a per unit area of either tidal delta or shoreline habitat over the entire rearing period. Cumulative Chinook salmon density is estimated for the period February through August for tidal delta blind channel habitat (a period of over 200 days), and February through October for shoreline habitat (a period of over 270 days). Cumulative density (fish*days*ha^{-1}) is calculated as

$$C = \sum_{m=F}^{L} D_m n_m \qquad \text{Eq. 1}$$

where D_m is the average monthly density, n_m is the number of days in the month, and F and L is the first and last month (m) sampled, respectively.

Both density and cumulative density have interesting properties when viewed in the context of restoration. On one hand, restoration could improve local abundance or survival, resulting in increases in the density metric, the direction we normally expect for restoration. However, the expectation is different at larger spatial and temporal scales because restoration can increase capacity, thereby reducing density. Hence, the system-wide prediction of monitoring data within the tidal delta is a reduction in either density metric. Outside the tidal delta, we should expect restoration to increase recruitment, thereby resulting in an increase in density metrics.

Fish length. Outmigrants are measured at all stages for body size (fork length in mm), which are used in combination with capture date and region to describe and enumerate life history types. Change in size is also a potential outcome of restoration, and we used cohort-level estimates of size calculated by averages of log-transformed data and weighted by the abundance of fish captured in sampling events.

Migrant timing. We produce an annual measure of migrant timing at each stage of sampling by calculating the Julian day at which 50% of the cumulative abundance is reached.

Linkage to Puget Sound Chinook Monitoring and Adaptive Management Framework

The Skagit IMW indicators contribute to tracking implementation of the Skagit Chinook Recovery Plan for local watershed (Skagit Watershed Council) and regional (Puget Sound Partnership) efforts as necessary for Puget Sound Chinook monitoring and adaptive management. The Skagit IMW indicators are consistent with regional guidance described in Bartz et al (2013) and contribute to data for two ecosystem components (*Chinook Salmon*; *Natal Chinook Estuaries*). Our Chinook Salmon indicators relate to three Key Ecological Attributes (KEAs): *abundance, productivity, and diversity*. Our Natal Chinook Estuary indictors relate to KEAs for *habitat connectivity* and *multiple ecosystem processes*, including indictors for estuarine habitats (extent & condition) and water quality.

Restoration study designs

Project Level. Fish effectiveness monitoring design for Skagit estuary restoration projects include before/after control impact and post-treatment designs. Both designs use stratified random site selection. Fish sampling is done by beach seine or fyke trap methods (described above), depending on the site characteristics and occurs over the full juvenile Chinook outmigration period (February through August). Monitoring questions typically addressed are:
What fish species are present within the restored area?
How do juvenile Chinook salmon densities vary by year, season, and habitat type within the restored area?
What is the seasonal and spatial variation in local environment (e.g., temperature, salinity, dissolved oxygen, etc.) within the restored area?
Doe local environment influence juvenile Chinook salmon use within the restored area?
How does seasonal juvenile Chinook salmon density in the restored area compare to reference sites?
What is the carrying capacity of the restored area for juvenile Chinook salmon rearing?

System Level. Our current dataset, when examined in light of the restoration that has already occurred, provide several pathways for analyzing the benefits of estuary restoration. The most comprehensive of these is a multiple BACI design, in which various metrics can be examined in the context of increasing cumulative acreage of restoration in the South Fork over time, and using data from the North Fork as a no-restoration reference area. All data collected within the tidal delta can be readily examined using this study design. Data collected in Skagit Bay and at adulthood are also important because they best represent the consequences of restoration within the tidal delta. However, because juveniles that have reared in the North Fork reference commingle with those that have reared in the South Fork “treatments”, it is impossible to assign a reference system for analysis of Skagit Bay townetting and adult data. Therefore, these datasets will need to be analyzed in the context of before-after designs and regression designs of cumulative restoration. It is well-known that this type of design is much weaker than BACI designs (Roni and Quimby 2005) because multiple uncontrolled factors can be coincident with restoration implementation. Therefore, we expect to perform these analyses in the context of ecosystem indicators that provide insight into temporal covariation.

Results through 2014

Local effects of restoration

All seven built restoration projects have been monitored for juvenile Chinook use within the restored area at least two seasons (Table 3). These effectiveness monitoring results offer some important insights into what restoration strategies offer the greatest potential for improving utilization of juvenile Chinook salmon in restored estuarine habitat. Below we summarize the findings.

If you build it they will come. All monitored projects in all years after restoration found juvenile Chinook using the restored habitat consistent with the timing curve of juvenile Chinook salmon in reference sites.

Some restoration designs work better than others for fish. Projects using dike setback, dike breach, or fill removal had juvenile Chinook densities within the restored area consistent with the levels in nearby reference sites (Figure 5). Projects using self-regulating tidegates (SRT) had much lower juvenile Chinook densities than nearby reference sites. SRT's were better for juvenile Chinook salmon than the tradition flapgate they often replace (approx. double), but SRT's averaged an order of magnitude lower in juvenile Chinook density compared to nearby reference sites (Figure 5). One project combination project (dike setback with floodgate replacement) also performed well (Figure 6). We detected an order of magnitude (10-fold) increase in habitat use by juvenile Chinook salmon in Fisher Slough upstream of the floodgate, consistent with habitat use observed at other reference sites throughout the Skagit tidal delta. This increase is predominantly associated with the dike setback and current operation of the floodgate to allow fish passage during slack and flood stages of the tide cycle.

Individual projects are contributing to estuary restoration goal. Where juvenile Chinook abundance has been quantified and compared to habitat-based juvenile Chinook carrying capacity estimates for restored areas (Fisher Slough, Wiley Slough), the built restoration projects have performed better than the conceptual projects described in the Skagit Chinook Recovery Plan. At Fisher Slough, the combination of dike setback and current floodgate operation translated to an increase in the smolt carrying capacity of Fisher Slough by nearly 22,000 estuary rearing Chinook salmon smolts per year based on two years of monitoring after dike setback (Beamer et al 2014). The Skagit Chinook Recovery Plan estimate for the Fisher Slough Restoration Project was slightly over 16,400 smolts per year. At Wiley Slough, dike setback restoration translated to an increase in the smolt carrying capacity of over 70,000 estuary rearing Chinook salmon smolts per year based on two years of monitoring after dike setback (Beamer et al 2015). The Skagit Chinook Recovery Plan estimate for the Wiley Slough Restoration Project was under 39,000 smolts per year.

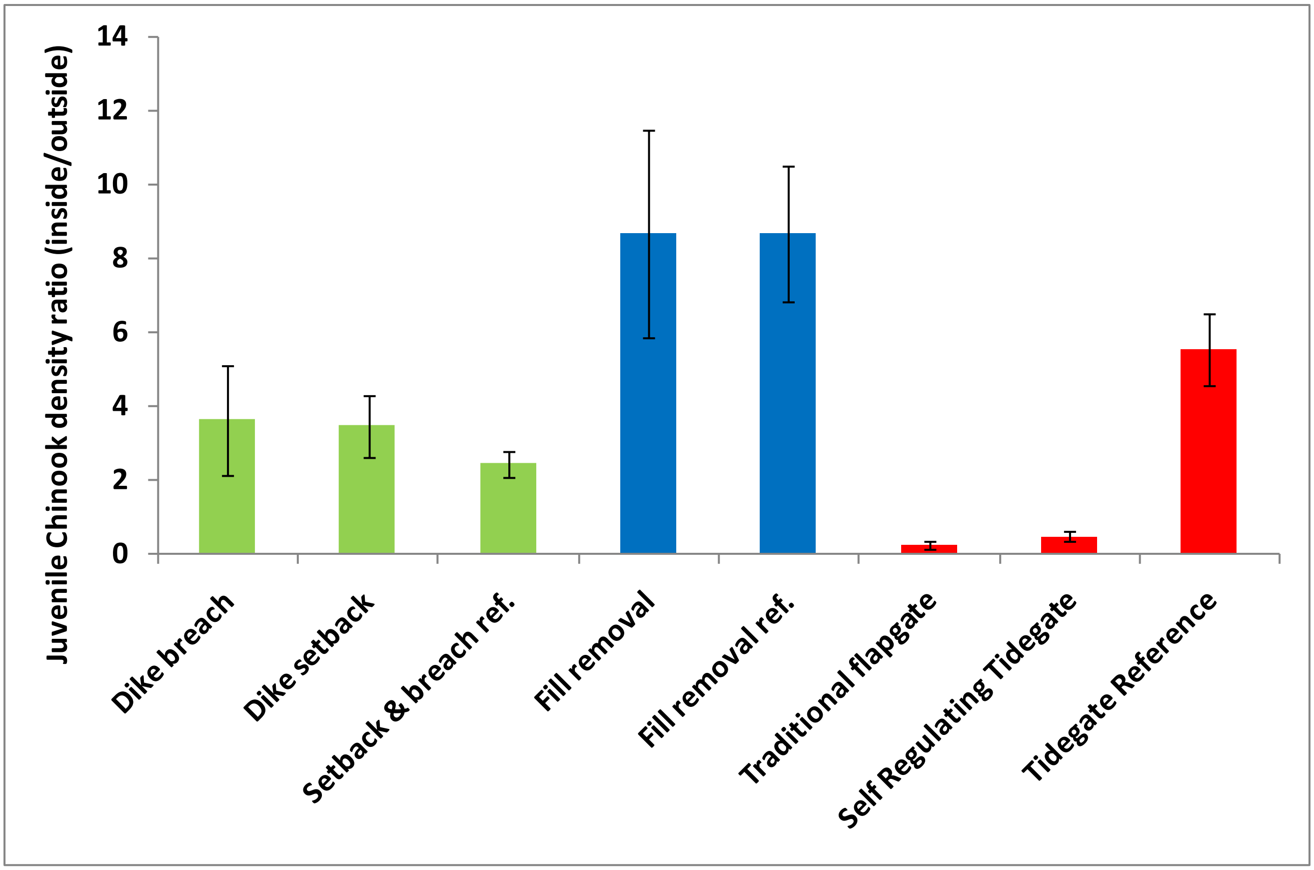

Figure 5. Estuary restoration effectiveness by restoration design type compared to reference sites. Estuary restoration project monitoring effectiveness: tidegate/SRT = 3 sites, 8 different years (from Greene et al 2012); fill removal restoration = 2 sites, 7 different years (SRSC data); dike setback or breach = 4 sites, 5 different years (Beamer et al 2006; Beamer et al 2015; and SRSC data). Juvenile Chinook density ratio is an indicator used in Greene et al 2012 to compare results across sites. It is calculated as a separate cumulative Chinook density (equation 1 above) for upstream and downstream locations, and then the "upstream" result is divided by the "downstream" result to obtain a juvenile Chinook density ratio. "Upstream" is restored channel or reference blind channel habitat. "Downstream" is distributary channel adjacent to restored channel or reference blind channel habitat. Error bars are standard error.

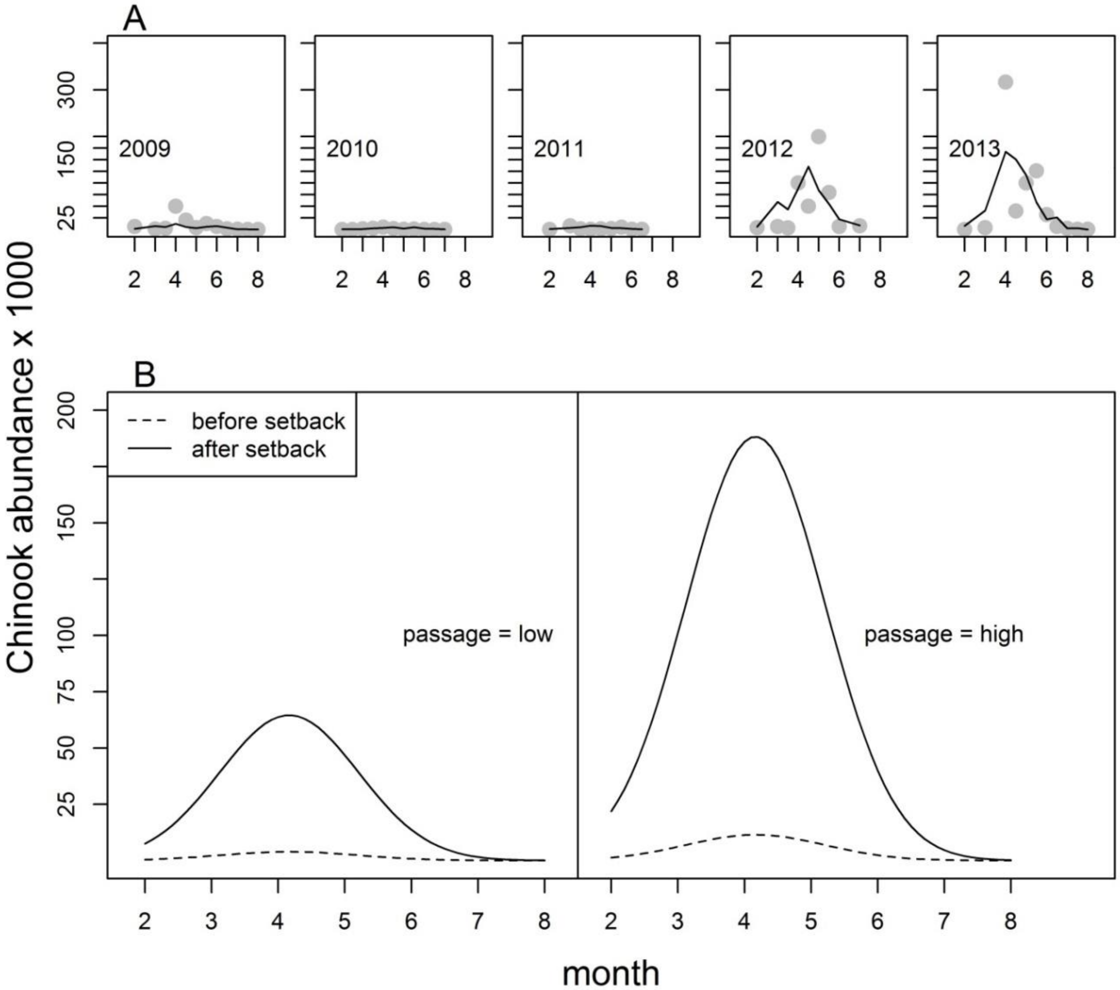

Figure 6. A) Fitted model predictions (black lines) of juvenile Chinook encounters to observed values (grey dots) using the top candidate model including Month, floodgate operation during the non-ebb period, and pre- versus post-dike setback. B) Monthly projections of juvenile Chinook encounters in the area of Fisher Slough upstream of the floodgate under low fish passage (20 % of the total time in a week) and pre- versus post-dike setback restoration, and high fish passage (60 % of the total time in a week) and pre- versus post-dike setback restoration scenarios. From Beamer et al 2014. Floodgate replacement occurred in before the 2010 monitoring season. Dike setback occurred in before the 2012 season.

System effects of restoration

Between 2000 and 2012, nearly 290 ha were restored to tidal inundation in the South Fork but no restoration occurred in the North Fork, providing the basis to rigorously test for restoration effects using a paired BACI study design. We have examined three juvenile Chinook salmon metrics measured within the tidal delta: average density, timing of residence within the tidal delta (relative to timing at WDFW's trap), and average body length (Fig. 7). To visualize effects of restoration, we graphed annual measurements as detected in the North Fork and South Fork, and focused first on the relationship of these characteristics before restoration. As restoration has accumulated over time, we would expect measurements to depart farther from the pre-restoration relationship. Hence, the effects of restoration can be represented as the difference between the post-restoration data and the pre-restoration regression line.

Following our prediction that added habitat from restoration should allow fish to redistribute at lower densities, average density in the South Fork of the tidal delta dropped relative to density in the North Fork after restoration was initiated (Fig. 7A). Successive restoration efforts had a cumulative effect on reducing density ($R^2 = 0.26$, $p < 0.05$), which is understated in Figure 7B due to the log-transformation. The added capacity translated into approximately 690 daily residents per ha restored at high outmigrations.

We also predicted that added capacity should result in longer individual residency, which would increase the timing of abundance. We calculated a cohort-based index of residency within the tidal delta by subtracting the Julian day at which 50% of the cumulative catch was observed within the tidal delta from that day observed at WDFW's trap at Mt Vernon. Prior to restoration, this value was not highly correlated in the North and South Forks, and successive restoration efforts increased residency in the South Fork relative to that measured in the North Fork (Fig. 7C). Residency significantly increased as a function of restoration ($R^2 = 0.25$, $p < 0.05$, Fig. 7D), such that a 200 ha restoration effort would result in an average increase in cohort residency of 15 days within the tidal delta.

We found little support that habitat restoration resulted in increases in the average length of tidal delta residents measured over the course of the rearing season. Average length was highly correlated between North and South Forks, and it appeared to decline in post-restoration years (Fig. 7E) by 2-5 mm. However, overall declines did not strongly depend upon the amount of restoration (Fig. 7F), suggesting other possible causes for declines in size (e.g. environmental covariates not incorporated into analysis of size, reduced growth at earlier life stages).

We tested three additional predictions of restoration benefits occurring subsequent to residence in the tidal delta. Because mobile fish captured outside of the tidal delta could not be tracked to a North or South Fork pathway, these comparisons could not benefit from the paired study design. We examined effects of cumulative restoration in a regression context, but note that any patterns we observed could be explained by other temporally varying factors in addition to cumulative restoration.

The first prediction, that tidal delta restoration results in protracted residency in estuary and nearshore habitats because fish have more opportunities to rear in the tidal delta, was strongly supported. To calculate effects of restoration, we first regressed pre-restoration estuary/nearshore residency (Julian day at which 50% of cumulative catch was observed in the nearshore relative to that measured at the Mt Vernon trap) as a function of fry captured in the river because residency is strongly density-dependent (Fig. 8A). Post-restoration residuals correlated with cumulative amount of restoration even more strongly than tidal delta residency data ($R^2 = 0.37$, $p < 0.05$, Fig. 8B), and resulted in about the same magnitude of effect, i.e., an increase in cohort residency of about 15 days would track 200 ha of habitat restoration.

Despite exhibiting strong evidence for density dependence tied to juvenile stages, both the frequency of fry migrants in Skagit Bay (Fig. 8C) and smolt-adult-return rate (SAR, Fig. 8E) showed little evidence of being influenced by the cumulative amount of restoration (Figs. 8D and F). However,

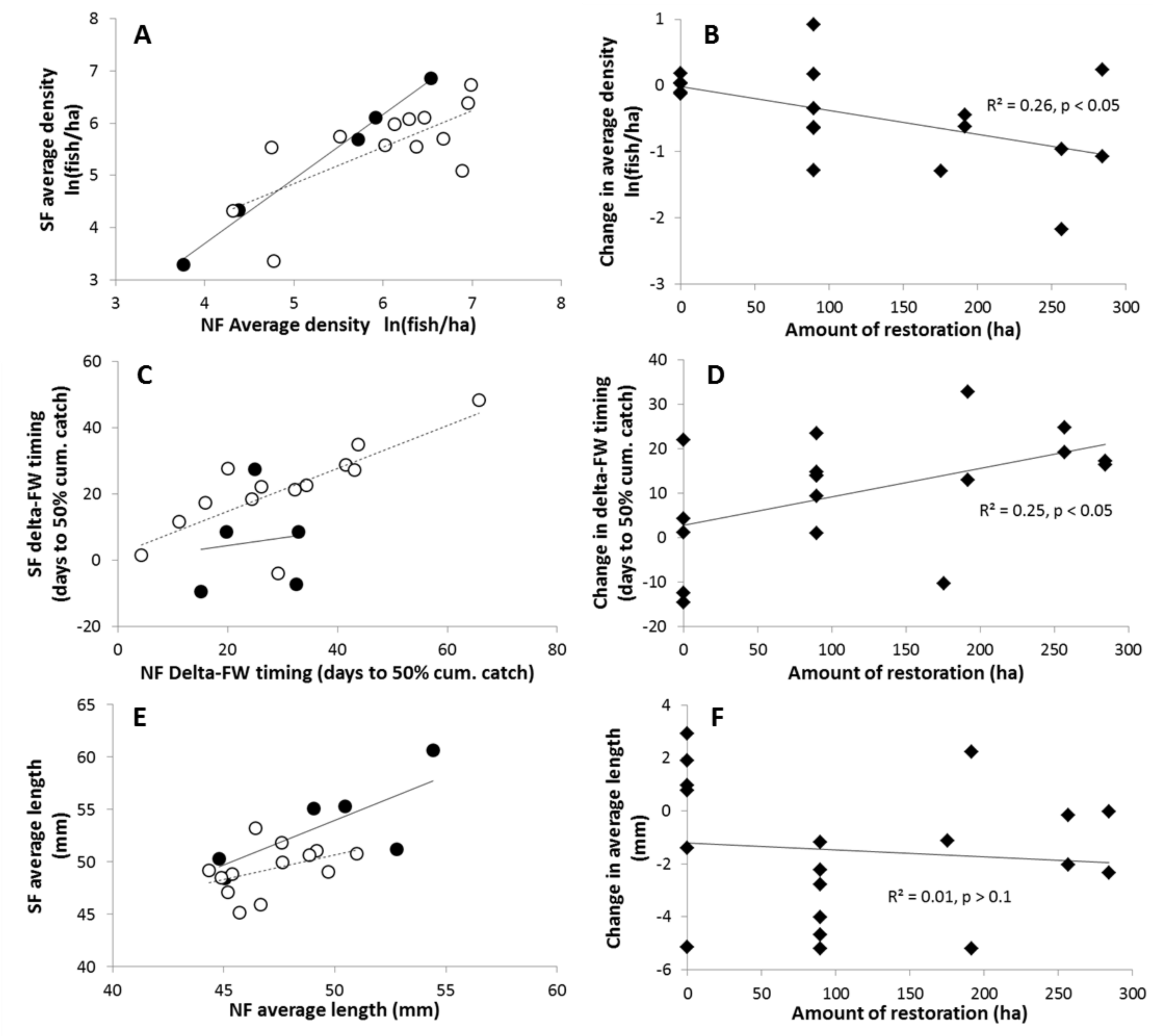

Figure 7. Correspondence of biological metrics (measured annually) expected to be sensitive to restoration measured in the two forks of the Skagit tidal delta, and the change from pre-restoration levels as a function of cumulative restoration. Average population density (Panel A), cohort residency in the tidal delta (B), and average body length (C) were measured in the North Fork (NF, reference) and South Fork (SF, restoration treatments) before (filled circles, solid regression lines) and after restoration (open circles, dashed lines). Residuals from the pre-restoration regression were then plotted as a function of amount of restoration (Panels B, D, and F) to examine population response to cumulative restoration.

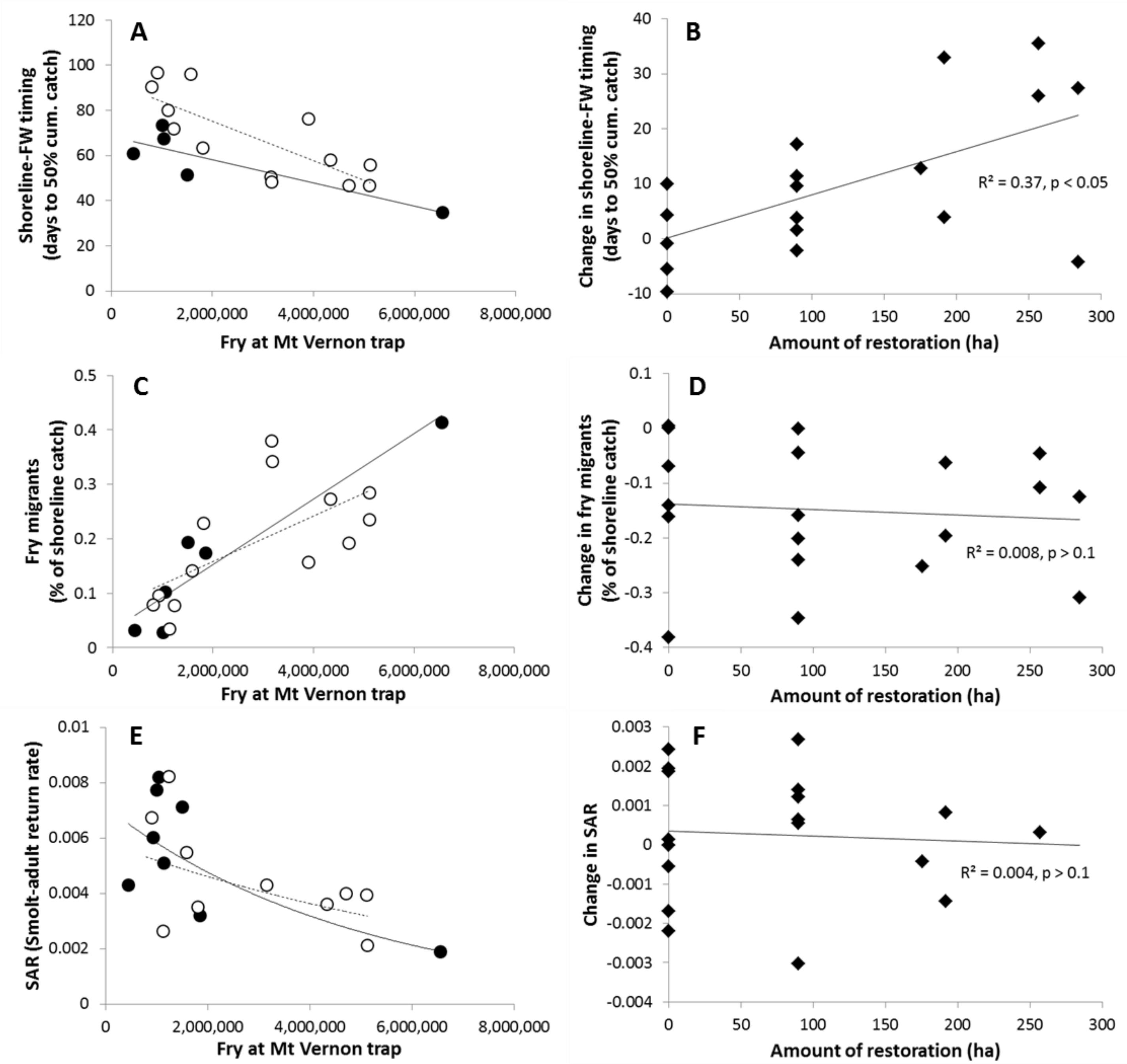

Figure 8. Density-dependent biological metrics measured in Skagit Bay in years before (filled circles, solid regression lines) and after restoration (open circles, dashed lines) as functions of the abundance of in-river fry captured by WDFW at Mt Vernon. Panel A shows annual cohort-level timing in the nearshore, adjusted by timing of outmigrants at the trap. Panel B shows the proportion of catch in shoreline monitoring composed of fry migrants in each year. Panel C graphs the annual smolt-adult return rate (age-corrected pre-harvest adults from a given cohort, adjusted by the number of migrants estimated at the Mt. Vernon trap). Residuals from the pre-restoration regression were then plotted as a function of amount of restoration (Panels B, D, and F) to examine population response to cumulative restoration.

regressions of pre- and post- restoration data suggest that their density-dependent relationships with in-river fry are trending in the expected direction: post-restoration frequency of fry migrants is increasing less, and SAR is declining less strongly, as a function of in-river fry. Based on the relatively small change pre- and post-restoration, detecting future changes to these metrics might be expected to require years of high abundance when the benefits of restoration are most fully realized. Alternately, scenario testing using various life cycle modeling techniques may be able to test the consequences of cumulative restoration when large outmigrations occurred. These efforts are currently under development.

Future efforts

The above results provide a solid basis for concluding that restoration in the tidal delta is having beneficial effects beyond a project-by-project level. Where possible, effectiveness monitoring has shed light on what project designs are most beneficial to juvenile Chinook salmon. Yet several questions remain that we plan to address in future years. While the long-term monitoring has provided good evidence for system-level effects during juvenile rearing stages, we have as yet not documented whether restoration is in fact resulting in population benefits (i.e., higher returns of adults). The hypotheses of density dependent interactions by fry entering the Skagit tidal delta is strongly supported, as is the reduced SARs resulting from large fry migrations. Why does the now significant amount of restoration not produce higher SARs? Possible reasons include: 1) SAR exhibits high inherent variability from multiple causes at several spatial scales, 2) incomplete adult cohorts that experienced the highest levels of cumulative restoration need to return over the next two years before the benefits can be fully realized, 3) the greatest benefits of restoration are observable during large outmigrations, which have been lacking in the most recent years, and 4) migrating fry do not behave uniformly to typical habitat targets of estuary restoration. The first three possibilities can be addressed by additional years of monitoring and/or via additional large restoration projects, and additional analyses that better take into account variability in marine mortality and/or life cycle dynamics under scenarios of high cohort abundance.

The fourth possibility deserves additional attention and additional approaches. If migrant fry are not solely the losers of density-dependent interactions, but seek habitat types fringing tidal deltas that have greater bioenergetic opportunities than river dominated habitats, up-river restoration actions may have a muted benefit for this life history type. This hypothesis could explain why both the frequency of fry migrants in the nearshore and SAR do not exhibit much response to restoration. To address this possibility, continued monitoring will need to be paired with other types of restoration. Significantly, the upcoming McGlinn Island Causeway restoration should provide an opportunity to test this hypothesis, as this reconnection of the North Fork with Swinomish Channel to the north will provide more marine-influenced estuarine rearing opportunities along Swinomish Channel and in Padilla Bay. Testing this hypothesis will require additional monitoring in Swinomish and Padilla Bay habitats before and after the restoration event.

Monitoring lessons learned

The Skagit estuary IMW is unique among IMWs in targeting estuary restoration for subyearling Chinook salmon. Monitoring estuarine habitats inhabited by small resident fish pose important challenges, and the success of this effort has hinged on a different set of approaches than other intensively monitored watersheds. First, Chinook salmon inhabit large river systems that are not amenable to replication. Whereas small creek systems can be independently monitored and reserved as treatments and references following staircase designs (Walters et al. 1988), there is no appropriate reference for the entire Skagit River system, or its estuary. Instead, we took advantage of the serendipitous planning of restoration to provide treatments (South Fork) and a reference (the North Fork) for BACI designs at a system level. This design will require careful revision as restoration projects shift to the North Fork, in order that appropriate comparisons are maintained and monitored.

A second reason the Skagit IMW differs from other IMWs is that individual migrant subyearling Chinook salmon cannot be readily marked and tracked. The sheer abundance of downstream migrants (in the millions) reduces the efficacy of mark-recapture techniques because recaptures at later stages are rare and would require huge effort to obtain. Most migrants are too small to tag with individual tags, and larger fish amenable to PIT or acoustic tagging are generally not estuarine-dependent. Furthermore, the bifurcating nature of the tidal delta complicates automated recapture or detection technologies such as antennas or hydrophones.

Instead of tracking groups of individuals to determine the benefits of restoration to populations, the entire cohort must be monitored, and biological measurements must be inferred at the cohort level. Hence, we do not have measures of individual residence time, growth, or survival, and instead must focus on changes in density, size, and timing of outmigration. Measures like timing are summarized annually, reducing the statistical power to detect some changes over time. These types of metrics are also sensitive to variation in the gear used to capture fish in the estuary and nearshore. Systematic estimation of gear efficiency using subgroups of batch-marked fish at small spatial scales has been critical to standardize datasets. In turn, the linking of monitoring at multiple stages (freshwater outmigration, tidal delta residency, and nearshore residency) has allowed us to make conclusions about changes in the abundance of particular life history types in the context of restoration activities.

Nevertheless, focusing on cohorts can result in counter-intuitive interpretation of the effects of restoration. Hence, while hypotheses related to project effectiveness monitoring state that restoration should result in increases in local densities of resident juveniles, our prediction for system-level effects is the opposite – restoration offers greater opportunities for diffusion of a cohort across the estuary system, thereby lowering average density. A second counter-intuitive result is the observation of declines in the length of fish over ~20 years of monitoring. While it is possible that fish in successive years are becoming smaller in size, it is also possible that additional restoration results in extended residence of more small fish, which are then sampled at greater frequency. An apparent decline in size would be the end result. We are planning to investigate this possibility using individual-based models that simulate sampling, and thereby track both individual and cohort changes.

Despite departures from the "typical" IMW design, the Skagit IMW has nonetheless provided insights into both project-specific and system-level monitoring of restoration. Project-specific monitoring has revealed that not all restoration project designs are equally effective at restoring capacity and connectivity. As noted recently by Bernhardt and colleagues (2005), effectiveness monitoring by itself has been underfunded, leaving many gaps in our understanding of whether the substantial monetary investment in habitat restoration has benefited habitat utilization by fish. An even larger information gap – which cannot be answered by effectiveness monitoring alone – is the cumulative benefits of multiple projects on the landscape and the benefits to populations using these habitats. It is this larger-scale issue that IMWs like that in the Skagit can be particularly valuable. Our results provide strong evidence for landscape-scale consequences of habitat restoration, and we expect that continued efforts will yield additional insights into the population benefits of these endeavors.

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