Review of Results to Date from the SRFB IMWs

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Preface

The SRFB-supported Intensively Monitored Watersheds (IMWs) were established in the early 2000s to determine the contribution habitat restoration can make to salmon recovery and to improve the effectiveness of habitat restoration programs in Washington. The SRFB first provided funding in 2004 to establish a program of IMWs in Washington. The funding was used to leverage existing long-term fish and habitat monitoring efforts conducted by WDFW, Lower Elwha Klallam Tribe, Northwest Fisheries Science Center (NOAA) and the Skagit River Systems Coop. Three freshwater IMWs were funded by the SRFB at this time: Strait of Juan de Fuca IMW, Hood Canal IMW, and Lower Columbia IMW. The Skagit IMW was included to provide an estuarine study site. The Asotin IMW received SRFB support shortly after the other IMWQs were established, providing a study site east of the Cascade Mountains.

IMWs concentrate restoration and monitoring efforts in a watershed, large stream reach or estuary. Concentration of effort enables enough data on physical and biological attributes of a system to be collected to develop a comprehensive understanding of fish and habitat response to the application of restoration treatments.

The purpose of this report is to examine IMW results to date to identify opportunities to improve the procedures being used to prioritize, design, and implement restoration treatments. The report consists of two sections. The first section is a summary of results and key findings to date of each IMW and a summary of findings on four questions that arose from the recent PNAMP IMW review (Bilby et al. 2022). Support for the findings in the summary section are provided in a series of appendices that include detailed descriptions of study site, methods, results and conclusions from each IMW.

Summary Report

Individual IMW Summaries

Asotin IMW (see Appendix A)

The Asotin IMW includes three Asotin Creek tributaries: Charley Creek, North Fork Asotin Creek (North Fork), and South Fork Asotin Creek (South Fork; hereafter referred to together as "study creeks"). All study creeks all have low large wood and debris jam frequency.

This IMW is evaluating the extent to which greatly increasing wood abundance can enhance instream complexity, frequency of overbank flow, and extent and function of floodplains and fish response to these habitat changes. Each study creek has at least one 4 km long treatment section and one or more control sections. Initial restoration treatments were completed in 2012, 2013, 2014, and 2016 resulting in 650 large woody debris (LWD) structures over 14 km (39% of the study area at a frequency of 3-5 structures/100m). The treatments used post-assisted log structures (PALS), which are inexpensive and do not require heavy equipment.

To date, modest, statistically significant, positive responses in geomorphology, habitat, LWD, debris jam frequency and several fish metrics has been detected. The increase in wood is forcing significant increases in geomorphic diversity in treatment areas compared to control areas by increasing bar and pool frequency and area. The positive changes in habitat are leading to relatively consistent, statistically significant, small-moderate increases in juvenile steelhead abundance (fish/km) and biomass (g/km) at some study sites but no significant changes in growth or survival. The number of Steelhead smolts produced by the treated reaches has increased significantly relative to the reference reaches at two of the three study creeks.

Key Findings

- Repeated wood additions at restoration sites were key to maintaining and increasing LWD densities.
- Establishing and maintaining high densities of large wood enhanced the retention of naturally-produced wood in treated reaches. Therefore, the formation of natural log jams was promoted, increasing geomorphic complexity, improving fish habitat, and increasing juvenile steelhead productivity.
- Changes in habitat that have occurred to date are mainly within the channel. We hypothesize that with ongoing treatments, reconnection of disconnected floodplains will occur and provide enhanced access to floodplain habitats, aid in the recharge of groundwater and contribute to higher summer base flows. Increased fish production may result. Additional monitoring will be required to evaluate this hypothesis.

- The PALS approach was an effective method of LWD placement at the Asotin IMW. This approach was less expensive than traditional methods of wood placement and avoided damage to riparian areas caused by heavy equipment.

Straits of Juan de Fuca IMW (see Appendix B)

The Strait of Juan de Fuca (SJF) IMW includes East Twin River, West Twin River (reference), and Deep Creek. The three contiguous watersheds are in the Lyre/Hoko basin (WRIA 19) and flow north into the SJF. They are relatively small watersheds (i.e., less than 45 km^2).

In-channel wood placement was the primary restoration approach because it influences many stream habitat-forming processes. Large wood forms pools, store gravels, and can reverse channel incision and improve floodplain connectivity. Increases in floodplain connectivity may also increase formation of floodplain habitats known to be critical over-winter habitats for juvenile Coho Salmon. Restoration treatments were implemented from 1998 to 2022 and focused on the lower portions of East Twin River and Deep Creek.

Repeated wood additions to sections of Deep Creek and East Twin River eventually resulted in observable habitat changes in some treated reaches. Deep Creek exhibited increased pool area, pool depth and increased sediment storage at several of the treated reaches. In addition, sections of lower Deep Creek developed side channels. Although habitat changes were generated at treated sites, significant trends in measured habitat attributes were not detected at the scale of the entire watershed. Unexpectedly high interannual variability in several habitat metrics were observed in all watersheds.

Parr-smolt survival for Coho Salmon and Steelhead has been greater in the treated watersheds than the control watershed. Deep Creek Coho Salmon smolt abundance tends to be greater than the other two watersheds. Steelhead smolt production estimates suggest similar levels for each of the watersheds.

Monitoring of Coho Salmon outmigrants using passive integrated transponder tags (PIT tags) revealed that many Coho Salmon left the study watersheds in the autumn. Some returning adult Coho Salmon were fall migrants rather than spring migrants. Our results indicate that traditional methods of spring-only smolt enumeration may underestimate juvenile survival and total smolt production, and overestimate spring smolt-to-adult return.

Key Findings

- Repeated, large-scale wood additions changed channel morphology, improving both spawning and rearing habitat, and had a positive effect on juvenile Coho Salmon survival.
- It was necessary to add wood multiple times to a stream to achieve the desired habitat response.
- Habitat and fish response to wood treatments took multiple years to be fully expressed. Therefore, long-term monitoring is required to evaluate restoration effectiveness.

Hood Canal IMW (see Appendix C)

Little Anderson, Big Beef, Stavis (reference watershed), and Seabeck creeks comprise the Hood Canal (HC) IMW. The four contiguous watersheds are in Kitsap County, Water Resource Inventory Area (WRIA) 15 and they flow north into Hood Canal.

Restoration efforts focus on improvement of salmon habitat by enhancing stream connectivity and complexity. Restoration projects typically have included more than one treatment type. For example, removal of an instream structure, bank contouring to increase floodplain connectivity, and large wood and engineered logjam placements may be implemented simultaneously at a treated reach. Disconnected floodplain habitats have been reconnected to the channel by removing dikes. LWD additions are intended to improve habitat complexity, resulting in more sinuous, multi-thread channels with a greater degree of variation in depth and velocity. The LWD also provides roughness to retain sediment.

Habitat conditions in the treated HC IMW watersheds have not changed as much as anticipated by restoration. Detecting changes in habitat condition was complicated by the discovery of high interannual variability in several habitat metrics. The interannual variability was often greater than changes anticipated from restoration treatments.

Reestablishing a dynamic equilibrium of sediment supply and transport appears to be a key need at several of the HC IMW watersheds. Severe bank erosion and subsequent deposition downstream frequently create barriers to migrating adult salmon and can bury placed and naturally recruited large wood.

Removal of a blocking culvert on Little Anderson Creek in 2002 was followed by a rapid increase in the production of smolts from this system. However, since 2014 smolt production in Little Anderson Creek has been variable and much lower than in the years immediately following barrier removal. Although replacement of an undersized culvert with a bridge represented a significant increase in passage over the former culvert, the bridge continues to limit salmon access. In recent years, a combination of substrate deposition near the bridge, low water and beaver activity underneath the bridge has limited fish passage upstream.

No fish population metric has responded positively to wood placements. Experiences at this and other IMWs suggest that effective treatment with LWD may require multiple placements and considerable time before habitat conditions improve. A single reach in Little Anderson Creek received LWD in both 2009 and 2016, providing some opportunity to test whether repeated treatments might generate an increase in smolt abundance. There was no fish response to the treatments. Perhaps despite the repeated wood additions, the treatments were not intense enough to elicit a fish response. Fish response also was impacted by the concurrent issues of low escapement and passage restriction at the bridge.

A large project implemented on Big Beef Creek from 2015 through 2017 appears, at least initially, to have had a positive effect on Coho Salmon parr to smolt survival. This project removed a levee, providing access to a large floodplain wetland and increased overwinter habitat. Relatively high overwinter survival in Big Beef Creek has been documented from 2019-2022.

Key observations from the HC IMW are that spawner abundance is frequently lower than the carrying capacity of the habitat and density-independent processes, such as scouring flows and migration barriers, often limit survival and production. In most years, there are too few fish to utilize available habitat. Therefore, providing additional habitat through restoration may have little effect on smolt production. However, restoration actions that address density-independent mortality factors, such as increased refugia from high flows or reduced frequency or intensity of scouring flows, might be effective.

Key Findings

- Increasing habitat quantity will likely only have modest effects on fish survival and production until escapement to these systems increases.
- Disruption of the movement of gravel and wood, often at undersized culverts, damaged and simplified salmon habitat in several of the HC IMW watersheds. In the near term, prioritizing projects that enhance connectivity and restore natural rates of transport of gravel and wood may have the most beneficial effect on salmon.
- Improving connectivity to floodplain habitats (Big Beef Creek) appears to have caused an increase in overwinter survival of Coho Salmon. This project was completed relatively recently, and additional monitoring is required to validate the response.
- The replacement of an undersized culvert with a channel spanning bridge near the mouth of Little Anderson Creek initially increased fish passage and generated a strong, positive response in Coho Salmon smolt production. However, after several years, fish passage under the bridge was restricted by sediment accumulation, low flow and beaver activity. Restoration treatments should be periodically revisited to ensure they are functioning as designed.

Lower Columbia River IMW (see Appendix D)

The Lower Columbia (LC) IMW includes Germany, Abernathy, and Mill (reference) creeks. The three contiguous watersheds are in Wahkiakum and Cowlitz counties in the Grays/Elochoman basin (WRIA 25) and flow south into the lower Columbia River between River Mile (RM) 53.8 and 56.2.

Restoration was initially planned for Abernathy and Germany creeks. However, in 2017, restoration planning, led by the Lower Columbia Fish Recovery Board (LCFRB), shifted the restoration focus solely to Abernathy Creek to reduce costs and enable concentrated restoration efforts. Thirteen projects were executed in the Abernathy Creek basin. Restoration efforts seek to improve salmon habitat by enhancing floodplain and stream connectivity and stream complexity. The prevalent restoration treatment has been the addition of wood to improve habitat complexity. Some undersized bridges and culverts have been replaced to improve passage of fish, wood, substrate, and water. All projects were completed by 2021.

Projects implemented in Abernathy Creek have impacted approximately 33% of accessible salmon and Steelhead habitat, including 11.8 kilometers (km) of instream habitat, 1.3 km of off-channel and side-channel habitat, 0.19 km^2 of riparian area, and 2.7 km of improved fish passage. These habitat treatments have occurred more recently than for other IMWs. Therefore, there have been only a few years of post-restoration monitoring. Other IMWs have found that full expression of habitat response to restoration treatments often requires multiple years. This fact, in combination with high interannual variability in habitat metrics, indicates that additional monitoring will be required at the LC IMW to determine habitat response to treatments.

Prior to the application of restoration treatments, Abernathy Creek, where most restoration has occurred, typically produced fewer Coho Salmon smolts than Mill Creek. Since 2018, however, Coho Salmon smolt production from Abernathy Creek has exceeded production from Mill Creek, suggesting a possible response to restoration treatments. Additional monitoring over the coming years will be required to verify this response. There has been no indication to date that restoration treatments have increased smolt production of Steelhead or Chinook Salmon.

A passage barrier removal on Sarah Creek, an Abernathy Creek tributary, in 2019 generated an immediate fish response. By 2021 this reach supported 64 spawning Coho Salmon. In 2020 and 2021 the area above the barrier supported 4% and 8%, respectively, of the watershed's Coho redds.

There is clear evidence that parr-smolt survival of Coho Salmon is density dependent, suggesting freshwater habitat is limiting productivity. Survival rates of juvenile Coho Salmon from parr to smolt decline sharply with increase in summer parr abundance. This pattern was observed in all three LC IMW watersheds.

Headwater reaches appear to be important rearing habitats for Coho Salmon in the LC IMW watersheds. Fish tagged in upper reaches of all 3 watersheds were more likely to emigrate as spring smolts than fish tagged lower in the watershed.

Nutrient enhancement treatments (i.e., Salmon Carcass Analogs), applied to Germany Creek, did not have a detectable effect on any fish population metric. Future evaluations of this technique should be implemented in watersheds with low nutrient levels and restoration treatments should include the development of features to help retain nutrients.

Key Findings

- Large-scale wood additions to improve spawning and rearing habitat concentrated in the headwaters of Abernathy Creek appear to be having a positive effect on juvenile Coho Salmon. Overwinter survival and smolt production both increased after restoration treatments, but further monitoring is needed as treatments were not completed until 2021. Steelhead and Chinook Salmon populations have not responded to treatments.
- Tributary and headwater reaches are important rearing habitat for Coho Salmon. Coho salmon tagged in upper reaches of the LC IMW watersheds were more likely be detected as spring smolts than Coho parr tagged lower in the watershed.
- Removal of a passage barrier on Sarah Creek implemented in 2019 in the Abernathy basin led to an immediate use of the blocked area by spawning Coho Salmon. By 2020-2022, 4-8% of the basin’s Coho Salmon redds were found in this previously blocked reach.
- There is strong evidence of density dependence for both Chinook and Coho salmon in the LC IMW, suggesting that, over time, both species should benefit from habitat improvements.
- The addition of salmon carcass analogs did not result in any improvement in Coho parr survival or smolt production. Future trials of nutrient enhancement should be implemented in nutrient-poor watersheds and in conjunction with restoration treatments that will help retain released nutrients in the watershed.

Skagit IMW (see Appendix E)

The Skagit IMW examines how Puget Sound Chinook Salmon use the Skagit tidal delta and how they respond to restoration. Estuary restoration projects have restored 255 hectares to tidal inundation since 2000. However, restoration gains have been partially offset by natural processes, resulting in only a net increase of 130 hectares to tidal inundation. Naturally occurring estuary habitats are not static and the area of Skagit tidal delta is exhibiting an overall decrease, primarily due to seaward edge erosion not being fully compensated by progradation.

The Skagit IMW demonstrated demographic changes associated with restoration actions that increase nursery habitat capacity. Restored areas in the delta supported lower juvenile densities overall than prior to treatment and restoration was associated with a decline in juvenile Chinook catches in nearshore marine waters. These findings suggest that greater nursery habitat capacity in the delta supported more juveniles but at lower densities, alleviating competitive effects on growth. The expanded habitat also accommodated more salmon when juvenile outmigrations were high, decreasing overflow of Chinook fry to nearshore environments. Thus, restoration appeared to reduce density-dependent constraints on rearing and growth.

Key Findings

- In the Skagit Delta, increasing connectivity expanded habitat capacity and enabled juvenile Chinook to utilize previously inaccessible areas of tidal marsh. Expansion of habitat led to multiple, positive fish responses. In this system, abundance of outmigrating Chinook Salmon fry exceeds habitat capacity. Therefore, increasing habitat capacity has been a successful strategy. In other systems outmigrants are not abundant enough to fully occupy available estuary habitat. In these estuaries restoration actions that focus on density-independent sources of mortality (e.g., predation) are likely to be more effective than actions intended to increase habitat capacity.
- Blind channels were found to be an important habitat for natural-origin Chinook Salmon. Increasing the availability of blind channels would be an effective restoration strategy.
- Our analyses suggest that large hatchery releases may increase the likelihood for systems to exceed capacity and increase competition for preferred prey. Further evaluation of the effect of various aspects of hatchery releases (e.g., number released, individual size, timing and location of releases) on natural origin juveniles is needed.

Cross-IMW Analyses

Fish and Habitat Responses to LWD at the Freshwater IMWs (see Appendix F)

Wood addition is often only one of several restoration actions implemented at a treated IMW site. However, the fact that wood placement was the dominant restoration action across all the SRFB freshwater IMWs provides an opportunity to contrast wood placements associated with a positive fish response with those that did not generate a detectable response. This comparison will help identify features associated with effective wood treatments.

Several of the IMWs reported that wood projects improved habitat conditions and generated positive responses in some salmon and Steelhead population metrics. The Strait of Juan de Fuca IMW found that the repeated wood additions enhanced capacity for some treated reaches to capture and retain wood and sediment being transported downstream. The result was increased wood loading and channel-spanning logjams, which contributed to deeper and more frequent pools, a reduction in streambed particle size, increases in sediment storage, reduced stream width, vegetation re-establishment in the riparian zone and increased development and maintenance of floodplain channels. The changes in habitat at Deep Creek increased juvenile Coho Salmon parr-smolt survival. There also are indications that Coho Salmon productivity (smolts per spawner) increased in Deep Creek.

Positive habitat and fish responses were also reported for the Asotin IMW. As with the SJF IMW, added wood was effective at capturing wood being transported downstream. The added and trapped wood formed new log jams within the treatment reach. The increase in wood is forcing significant increases in geomorphic diversity in treated areas compared to control areas by increasing bar and pool frequency and area. The positive changes in habitat are associated with relatively consistent, statistically significant, moderate increases in juvenile steelhead abundance (fish/km), biomass (g/km) and smolt production at some study sites.

At the LC IMW, LWD density increased at treated sites in Abernathy Creek following the application of treatments. Before wood additions, average annual production of Coho Salmon smolts was highest in Mill Creek, the reference watershed. After wood addition, Abernathy Creek produced 26% more Coho Salmon smolts than Mill Creek.

LWD addition has not been associated with a Coho Salmon response at the HC IMW. A LWD addition project was implemented in 2007 (25 structures total, mostly small wood) and 2 LWD projects placed wood within a 2 km reach upstream of the initial installation in 2009 and 2017. Wood treatments had no detectable effect on any monitored fish population metric.

The lack of fish response at the HC IMW is partially because there are insufficient numbers of Coho Salmon returning to these watersheds to produce enough offspring to occupy currently available habitat. Therefore, creating additional habitat by wood addition is unlikely to generate a fish response (see detailed discussion on this topic later in the report). Also, the wood projects at the HC IMW were not as intensive as those applied at the IMWs that did report a fish response.

Key Findings

- Intensive wood treatment appears to be often associated with a response in fish abundance. Positive fish responses achieved at the IMWs were all associated with wood treatments that included 10s to 100s of wood structures over a large area. Intensive treatment is required to ensure that sufficient wood is available to modify channel form and material transport and achieve floodplain connection. Achieving sufficient intensity of treatment often requires repeated wood additions at a site over several years. A large enough area must be treated in this manner to generate a fish response that can be detected at the watershed scale.

- Habitat and fish response to wood can require a significant amount of time. Wood treatments that are associated with fish responses create an area where transported materials (wood, sediment) can collect. Over time this accumulation of materials enhances in-channel habitat diversity and establishes a more continuous connection between the channel and floodplain. This result requires that wood treatments are applied in depositional reaches and avoid high energy transport reaches.
- Monitoring the response of habitat and fish to wood placement is a long-term proposition. Habitat response and biological response to changes in habitat can require multiple years to occur. The interannual variability in both habitat attributes and fish population metrics requires lengthy annual monitoring to be able to distinguish a response to treatment from natural variation.

Impact of low spawner escapement on fish response to habitat restoration (see Appendix G)

If escapement levels in a watershed are sufficiently low that not enough juvenile fish are produced to occupy available habitat, increasing habitat quantity through restoration may generate only small changes in abundance or survival. Therefore, detecting a fish response to restoration in watersheds with low salmon abundance can be very difficult. The IMW data provided the opportunity to analyze this issue. We based this analysis on the 7 watersheds in the HC IMW and LC IMW. Data at these two IMWs were the most suitable for this type of analysis.

We fit a series of stock-recruit models to describe variation in the strength of density dependence over time, between locations, and among life stages. We also utilized a series of hypothetical restoration response models to assess our ability to detect changes in fish productivity when density dependence is strong vs. when density dependence is weak.

Across all watersheds and years, we observed great variation in the strength of density dependence by year, stream and life stage. In the Hood Canal watersheds, we observed many years with weak density dependence, and few years with strong density dependence. The Lower Columbia watersheds had stronger density dependence than the Hood Canal watersheds in most years, and spawner values were typically in the range indicating enough juvenile fish were produced to occupy available habitat.

These results suggest that high adult abundance improves the likelihood of observing a measurable response to habitat restoration in Coho Salmon. When spawner abundances are consistently low, exhibiting weak density dependence, it reduces the potential mechanisms by which restoration can benefit salmon. For example, creating more rearing space for juvenile salmon through restoration is unlikely to help when abundances are too low to fully utilize habitat available prior to restoration. Implementing harvest management policies that ensure enough spawners to utilize available habitat would enhance effectiveness of habitat restoration efforts.

The strength of density dependence in a watershed should influence the restoration strategy. In systems with strong density dependence, restoration measures that increase the quantity of available habitat can increase smolt production. In systems with weak density dependence, however, implementing restoration treatments designed to increase habitat capacity are not likely to generate a detectable fish response. Rather, the goal in systems like these should be the implementation of measures that can reduce the severity of density independent mortality factors and, thus, enhance intrinsic productivity. Measures that improve water quality or reduce mortality from predation are examples treatments that could enhance intrinsic productivity. Therefore, determining the strength of density dependence for a watershed is an important foundational element for identifying limiting factors and developing an effective restoration strategy.

Key Findings

- Focus restoration efforts on watersheds that support enough adult salmon to benefit from an increase in habitat capacity. Many years the HC IMW watersheds do not have sufficient juvenile Coho Salmon to occupy available habitat. Increasing habitat quantity will likely only have modest effects on smolt abundance until escapement to these systems increases.
- In watersheds with weak density dependence restoration actions should focus on reducing the intensity of density-independent mortality factors.
- Determining juvenile capacity limits, and modifying restoration goals, accordingly, may be necessary to fully capture the benefits of habitat restoration.
- Integrating harvest and habitat actions in an “All-H” strategy remains a crucial goal for salmon recovery.

Correlations between habitat attributes and fish population metrics – Identification of limiting factors (see Appendix H)

Stream habitat restoration is usually preceded by efforts to identify the habitat conditions that limit the freshwater survival and productivity of salmon. The relatively modest fish response to restoration seen at many IMWs suggests that the factors that are controlling productivity and survival of fish populations are complex and not consistently addressed by restoration actions. The IMW studies provide a rare opportunity to directly assess relations between salmon productivity metrics (e.g., parr-smolt survival, smolt production) and fish habitat metrics (e.g., large wood density; pool frequency) over many years.

The analysis presented here is intended as an example of how these data might be used to investigate the relationships between habitat attributes and fish population performance. The habitat metrics we included in this analysis represent a subset of the attributes that might be influencing fish production and survival. There would be considerable value in a comprehensive evaluation of the relationship between survival and smolt production and the potential factors influencing fish. These factors are not limited to habitat condition. As discussed above, salmon and steelhead production in some watersheds may be limited by the number of returning adult fish.

We assessed relations between Coho Salmon parr-to-smolt survival and smolt abundance against four fish habitat metrics within each of the Hood Canal and Lower Columbia IMW streams from 2007 through 2022. Habitat metrics included instream very large wood density (LWD> 5 m long and > 0.3 m in diameter/100m), pool occurrence density, side channel occurrence density, and median wetted stream width.

As increasing wood, pools and floodplain habitats are common objectives of restoration efforts, positive correlations between salmon survival and productivity and these habitat metrics might be expected. Data pooled for all watersheds in each IMW revealed some fish-habitat correlations. Surprisingly, about half were negative, including some of the stronger correlations. Relationships for individual watersheds show some relatively strong correlations between parr-smolt survival and smolt production and habitat metrics. But there are also dramatic differences in fish-habitat relations among watersheds within IMW complexes.

This analysis was intended to be a preliminary evaluation of IMW data to help identify habitat features that are controlling salmon production. These results strongly indicate that limiting factors vary spatially (among watersheds) and temporally (among years). The weak, and sometimes counter-intuitive, relationships between parr-smolt survival and smolt production with the simple habitat metrics suggests that fish production is influenced by interactions among multiple habitat factors and this combination of factors changes through the period of freshwater rearing. Despite the apparent complexity of this problem, the comprehensive data sets compiled over the last two decades at the IMWs may enable us to develop more effective tools for identifying limiting factors. Additional attention should be focused on this task in the coming years as matching restoration actions with the key elements constraining salmon production and survival is the essence of an effective restoration strategy.

Key Findings

- The weak and inconsistent relationships found between fish population metrics and single habitat metrics suggest that fish are likely governed by complex, interacting habitat conditions that vary spatially and temporally. This complexity, coupled with complications related to strength of density-dependence, can make it difficult to accurately identify the habitat conditions with the greatest influence on salmon and Steelhead.
- Further analysis of the IMW data, possibly augmented with comparable data sets collected by other monitoring programs, could be used to develop more effective techniques for conducting limiting factors assessments.

Key Factors to Consider in Estuary Restoration (see Appendix I)

Greene et al (2021) examined fish-habitat relationships in four tidal river deltas of Puget Sound: the Nooksack, Skagit, Snohomish, and Nisqually with the goal of developing general principles characterizing rearing conditions for natural-origin juvenile Chinook Salmon that apply to other estuaries, The selected systems vary in landscape features and outmigrant population attributes (e.g., proportion of natural-origin vs. hatchery-origin juveniles) and thus represent the diverse characteristics expected in estuarine systems inhabited by juvenile Chinook Salmon across a broad geographic range within and beyond Puget Sound.

Greene et al (2021) found multiple lines of evidence for density dependence using stock recruit and bioenergetic modeling approaches. Specifically, estuary habitat capacity was often exceeded by juvenile Chinook Salmon cohorts in some estuaries and hatchery origin fish can contribute to density dependence. Density dependent responses can include reduced growth and prey selectivity. The study also found that landscape features within systems influence juvenile Chinook Salmon occurrence and density. In general, off channel habitats with higher landscape connectivity support higher fish abundance.

These findings provide a decision framework to help managers select appropriate estuary habitat strategies for any specific estuary system for Chinook Salmon.

- Strategy 1 - Maintain current habitat conditions: This approach applies to systems where (a) the current juvenile Chinook salmon outmigration is within the desired range, (b) the current outmigration does not exceed the indicators for density dependence derived from this study, and (c) the current estuary is well connected and diverse in terms of wetland and channel type complexity. Estuaries that fit this strategy would support high-quality habitats with Chinook salmon populations at levels where density dependence pressures are weak.

- Strategy 2 - Restore habitat connectivity and diversity: This strategy is appropriate for systems where (a) the current juvenile Chinook salmon (natural and hatchery) outmigration is within the desired range, (b) the current outmigration does not cause density dependence, but (c) the current estuary is not well connected and/or not diverse in terms of wetland and channel complexity. Estuaries that fit this strategy have reduced habitat extent but their Chinook salmon populations don't exhibit regular density dependence pressures within the estuary. Because the current population generally does not express density dependence, habitat restoration within these estuaries should not focus on restoring vast areas (i.e., capacity) but should work toward restoring connectivity and the diversity of wetland types and channel types.
- Strategy 3 - Restore habitat capacity, connectivity, and diversity: This approach is appropriate for systems where the current outmigration levels cause density dependence. Estuaries that fit this strategy have reduced habitat extent and their Chinook Salmon populations regularly exhibit density dependence within the estuary. Because of this, habitat restoration within these estuaries needs to focus on restoring large areas (i.e., capacity) as well as connectivity and diversity of wetland types and channel types.

Key Findings

- Implement restoration that increases landscape connectivity, allowing juvenile Chinook Salmon to access areas of tidal marsh otherwise inaccessible.
- Emphasize restoration of blind channels, given their observed importance to natural origin fish.
- Develop a restoration portfolio of habitat types that provide various benefits for temperature and inputs of terrestrial, freshwater, and marine prey. A variety of wetland habitats contribute to growth and survival. Addressing restoration from a portfolio perspective may provide improved resilience to climate impacts such as sea level rise and temperature increases.
- Re-evaluate the concept of restoring estuary habitat capacity. Habitat restoration is often gauged from the perspective of increasing capacity, an important concept in estuaries where outmigrating fish exceed habitat capacity. Many systems may only rarely experience these high levels of density except in the context of large, hatchery releases.
- Investigate in more detail the potential role of various aspects of hatchery releases (e.g., number released, individual size, timing, and location of releases) in affecting natural origin juveniles. Our analyses suggest that large hatchery releases may increase the likelihood for systems to exceed capacity and increase competition for preferred prey, but better documentation of potential causes is warranted.

Conclusions

The IMWs have documented that habitat restoration is contributing to salmon recovery. IMWs also are generating generated information that can help improve the effectiveness of habitat restoration efforts in Washington and suggest some new avenues for investigation that could further improve program effectiveness in the future.

The review of effectiveness of various wood placement projects provides new insights into how these wood projects can be better sited and designed. Wood projects need to be very intensive to produce a detectable habitat and fish responses. The review also identified the need to base restoration strategies on escapement levels as the relative strength of density dependence in a watershed or estuary provides an indication of the habitat restoration actions most likely to generate a positive fish response.

The Skagit IMW is providing a wealth of information on estuary restoration. As found at the freshwater IMWs, identification of priority estuary restoration actions should consider the strength of density-dependence. In estuaries that support high densities of juvenile salmon (like the Skagit) increasing the area of available habitat should be a priority. In contrast, in estuaries where abundance of juvenile fish is too low to fully occupy available habitat, restoration should focus on reducing the impact of density-independent mortality factors, like predation.

This review of IMW results to date provides strong evidence that fully characterizing habitat and fish response to restoration at the IMWs will require additional monitoring. The western Washington freshwater IMWs generated an estimate of the length of time required to detect a fish response to habitat restoration at the start of these projects. This estimate indicated that 10 years of post-treatment monitoring would be required to detect a 25% change in smolt production. This estimate may have been overly optimistic as the IMWs have found that habitat response to restoration treatments can take a long time to fully develop. Therefore, the 10 years required to assess response in smolt production would begin after habitat changes were fully developed. This lag is especially evident with wood projects. Placement of wood in the channel can have short-term effects on channel form. But the IMW results suggest that biological response to these types of changes tend to be relatively modest. Over time reaches treated with sufficient wood aggrade, accumulating additional wood and sediment, enabling the channel to interact more consistently with floodplains. Floodplain reconnection appears to have the potential to generate a much larger fish response than that associated with channel modification. At all four of the freshwater IMWs, reconnection of floodplains is just beginning to occur. Monitoring for multiple years after connection between channel and floodplain has been re-established will be required to determine the magnitude of the fish response to floodplain reconnection.

The IMW results indicate that identification of the factors controlling salmon and Steelhead production in a system can be very difficult. This understanding is necessary to implement effective restoration treatments. The evaluation of relationships between fish and habitat metrics included in this review was intended to determine if the IMW data could be used to help with this problem. The cursory assessment we conducted indicated that single habitat variables are not consistently related to fish population metrics. This finding suggests that factors controlling fish production are likely a combination of habitat attributes and these attributes vary both spatially and temporally. A more detailed investigation of this issue using the IMW data could provide a clearer understanding of the relationship between fish production and habitat condition.

An example of our incomplete understanding of the factors controlling salmon production is provided by comparing Coho Salmon smolt production across the ten watersheds in the western Washington freshwater IMWs. One watershed produces far more Coho Salmon smolts than the others (Fig. A). Big Beef Creek from 2005 through 2019 produced an average of about 850 smolts/km^2 of watershed area. No other IMW watershed produced more 280 smolts/km^2. This result is somewhat surprising, given that the density-dependence analysis done for this review indicates that Big Beef Creek habitat is not fully utilized by Coho Salmon, suggesting that the capacity to produce smolts is even higher. The cause of the high production capacity in Big Beef Creek is not known. But understanding why this system is so much more productive could enable the identification of watersheds that have high productive potential and provide information useful to developing restoration priorities.

Review of Results to Date from the SRFB IMWs

Introduction to Appendices

Many salmon populations in the Pacific Northwest have been assigned protection under the U.S. Endangered Species Act over the last 30 years (NWFSC 2015), initiating efforts to recover these populations. Various factors have contributed to the decline in naturally spawning salmon including impacts associated with fish harvest, hatcheries, hydropower, and freshwater and estuarine habitats. In addition, salmon and steelhead are impacted by temporal shifts in ocean productivity and climate change is degrading both freshwater and marine conditions (Mantua et al. 2009; Crozier et al 2008, Crozier et al. 2019). Improved understanding of the impact of each of these factors, and their interactions, on salmon and steelhead at all life stages will be required to successfully recover these fishes. Achieving this level of understanding requires monitoring and adaptive management programs that are integrated across all the factors impacting the fish.

A significant proportion of the resources spent on salmon and steelhead recovery has focused on restoration of freshwater and estuarine habitat (Katz et al. 2007). Hundreds of millions of dollars have been dedicated to habitat restoration over the last three decades (NMFS 2014). However, the contribution these efforts are making to salmon recovery is poorly understood (Cram et al. 2018, GSRO 2020). This knowledge gap is widely appreciated and has led to considerable expansion in monitoring programs in the region (Bilby et al. *in review*). One element of this expanded evaluation effort was the establishment of Intensively Monitored Watersheds (IMWs) in the early 2000s (Bilby et al. 2005; Bennett et al. 2015).

IMW Concept

The basic premise of an IMW is that the complex relationships controlling salmon response to habitat conditions can best be unraveled by concentrating habitat treatments and monitoring of habitat and fish response at a few locations. Evaluating biological responses is complicated, requiring an understanding of how various management actions interact to affect habitat conditions and how system biology responds to these habitat changes. The habitats required by a species of salmon change through the period of freshwater and estuarine rearing. The relative importance of each habitat type in determining fish survival also changes from year-to-year due to variations in weather and flow, the abundance of fish spawning within the watershed and other factors. For example, smolt production may be heavily influenced by spawning habitat stability during years when flood flows occur during incubation can greatly impact egg survival (Seiler et al. 2002). However, during years of more benign flow conditions during egg incubation, population performance may be more influenced by the availability of food during spring and summer or adequate winter habitat. Untangling the various factors that determine performance of salmon and how these factors respond to restoration efforts can only be accomplished with an intensive monitoring approach.

The data required to evaluate the response of fish populations to management actions that affect habitat quality or quantity must be collected over a considerable time and are difficult and expensive to collect. Focusing efforts on a relatively few locations enable enough data on physical and biological attributes of a system to be collected to develop a comprehensive understanding of fish and habitat response to the application of restoration treatments in freshwater or estuary ecosystems. Therefore, IWMs offer one option for achieving the level of treatment and sampling intensity necessary to detect fish responses to a set of management actions.

However, the IMW approach is not without flaws and complications (Bisson et al., *in review*). Some of these difficulties are associated with logistical challenges of implementing the original study design. Many IMWs were originally designed as a Before-After/Control-Impact (BACI) experiment. This design requires monitoring of all experimental units (e.g., watersheds) for several years before application of treatments to a subset of the units. Contrasting habitat and fish populations between the treated and reference sites, before and after treatment, enables evaluation of response to habitat treatments. However, the complexity of designing, permitting, funding and executing all restoration treatments within a short period of time, a requirement under the BACI design, was not feasible. A further challenge was the inherent differences in initial condition among the treated and reference IMW watersheds. The fact that the reference sites were, at best, an imperfect control for the treated watersheds complicated detection of treatment responses. Due to these challenges, we now better understand how to design and implement IMW studies. Despite these difficulties, IMWs have generated information useful for improving restoration strategies; the basic IMW approach remains one of the most effective tools available for quantifying the contribution habitat restoration can make to salmon recovery.

The purpose of this synthesis report is to examine IMW results to date to identify opportunities to improve the procedures being used to prioritize, design, and implement restoration treatments. A significant amount of data analysis and interpretation has been conducted at each of the IMWs individually. Much of this work has been captured in annual reports and publications. This synthesis will summarize results from each IMW to date, emphasizing outcomes of management relevance. There has been relatively little evaluation of the data from multiple IMWs combined, with the notable exception of the recent report by Kruger et al. (*in review*) examining overall trends in habitat conditions at the 10 watersheds included in the western Washington freshwater IMWs. Analyses utilizing data from multiple IMWs will form a section of this report, partially focusing on key uncertainties identified in the recent PNAMP IMW review (Bilby et al 2022).

History of the SRFB IMWs

IMWs grew out of several early 2000s policy initiatives to address concerns about the plight of salmon and aquatic ecosystems in Washington. In 2001, Governor Locke signed into law Substitute Senate Bill (SSB) 5637, an act relating to monitoring of watershed health and salmon recovery. This law required a Monitoring Oversight Committee (MOC) to develop a comprehensive statewide strategy for monitoring watershed health, with a focus on salmon recovery. The strategy also incorporated monitoring recommendations from the state Independent Science Panel in its report to the Governor and Legislature in December 2000. The law required development of a state agency action plan that was to be fully implemented by June 30, 2007.

One recommendation of the MOC was to create IMWs to determine the response of salmon to habitat restoration efforts (MOC 2002; https://rco.wa.gov/wp-content/uploads/2019/07/MonitoringStrat02V2.pdf). The primary policy driver for establishing IMWs was the need for accountability as stated in the SRFB's Strategic Plan: "Be accountable for board investments by promoting public oversight, effective projects, and actions that result in the economical and efficient use of resources." In 2003 the SRFB requested that the Washington State Departments of Fish and Wildlife and Ecology provide recommendations for a monitoring program capable of estimating changes in fish populations due to habitat restoration. A detailed monitoring framework to accomplish this goal was developed by the Monitoring Design Team for the Department of Natural Resources (MDT 2002). IMWs were included as a key component of this program as an effective method for empirically evaluating the relationship between habitat restoration and salmon production.

The SRFB provided funding in 2004 to establish four IMWs in western Washington. The funding was used to leverage existing long-term fish monitoring efforts conducted by WDFW, Lower Elwha Klallam Tribe, Northwest Fisheries Science Center (NOAA) and the Skagit River Systems Coop. Three freshwater IMWs were funded by the SRFB at this time: Strait of Juan de Fuca IMW, Hood Canal IMW, and Lower Columbia IMW. The Skagit IMW was included to provide an estuarine study site. The Asotin IMW received SRFB support shortly after the other IMWs were established, providing a study site east of the Cascade Mountains.

Collectively, the four freshwater IMWs include 13 watersheds or large experimental reaches. The IMW study areas range from 78 km^2 to 206 km^2 with individual watershed areas ranging from 13 km^2 to 75 km^2. Watersheds of this size are sufficiently large to provide all the habitat conditions required for the target species to complete freshwater rearing. The freshwater IMWs focused primarily on the response of Coho Salmon and Steelhead to restoration treatments. Chinook salmon are also monitored at the Lower Columbia IMW; this species is not found consistently at the other IMWs. Chinook Salmon are the focus of the Skagit IMW.

The IMWs were responsible for monitoring and data analysis but worked closely with Lead Entities to identify specific restoration projects in each watershed. Multiple power analyses indicated that detecting a 20-40% increase in average annual coho smolt production would require 10-12 years of post-treatment monitoring. If larger responses in Coho smolt production were to occur, the time required to detect a change would decrease. The timeline for several of the IMWs was extended due to the pace of project implementation, which was a function of available funding. Few projects were initiated at Hood Canal and Lower Columbia IMWs until after 2014, when approximately $2 million per year in dedicated funding was allocated to implement treatments at these IMW (based on a recommendation in the Stillwater report (Stillwater 2013).

Review of Individual IMW Results

Appendix A: Asotin Creek IMW

The Asotin Creek Intensively Monitored Watershed (IMW) project was established in 2008 in southeast Washington. Asotin Creek is managed as a wild Steelhead refuge, and Snake River summer-run Steelhead are the focal species of the IMW. Juvenile steelhead and sculpin are the most abundant fish species in the IMW study area, and there are small numbers of longnose dace, bull trout, Chinook, and Pacific Lamprey. The Asotin IMW also has the advantages of only one landowner (WDFW) and one focal species (steelhead) with minimal hatchery influence.

The IMW includes three Asotin Creek tributaries: Charley Creek, North Fork Asotin Creek (North Fork), and South Fork Asotin Creek (South Fork; hereafter referred to together as “study creeks”). The study creeks cover a range of sizes, gradients, and flow regimes, but all have low large wood and debris jam frequency. This IMW is evaluating the extent to which greatly increasing wood abundance can enhance instream complexity, frequency of overbank flow, and extent and function of floodplains and fish community response to these habitat changes.

Restoration Design and Actions

This IMW is evaluating the effectiveness of a novel approach to adding large woody debris (LWD) to stream channels; post-assisted log structures (PALS). The goal is to cost-effectively add wood and protect recovering riparian habitat. Each study stream has at least one 4 km long treatment section and one or more control sections. Initial restoration treatments were completed in 2012, 2013, 2014, and 2016 resulting in 650 (LWD) structures over 14 km (39% of the study area at a frequency of 3-5 structures/100m).

We expected that processes governed by in-channel LWD would be unlikely to be fully restored after one restoration treatment. Therefore, we added additional wood to treated sites if certain conditions were observed, including risk to infrastructure, decreasing LWD abundance or lack of progress towards process goals. Several thousand additional pieces of LWD were added to treatment sections following initial treatment to ensure continued progress towards habitat goals. Total restoration and maintenance costs to date are ~$523,200 total, or $37,400/km.

We predicted treatments would cause multiple short and long-term structure and habitat responses that could lead to fish responses and used these predicted responses to develop explicit restoration design hypotheses. We employed a staircase experimental design based on simulation models that demonstrated that staircase designs had more statistical power to detect changes than traditional before-after control impact (BACI) designs (Loughin et al. 2021). We monitored habitat with PACFISH INFISH Biological Opinion (PIBO) protocol from 2008-2009 and the Columbia Habitat Monitoring Protocol (CHaMP) from 2010-2017. We currently use a rapid monitoring protocol that encompasses metrics from both PIBO and CHaMP along with geomorphic units including planar (runs, rapids, cascades), convexity (bars), and concavities (pools). With these protocols we can construct a time series of basic channel characteristics (e.g., bankfull width, sinuosity, residual pool depth, substrate composition), LWD, debris jams, pool frequency, and geomorphic unit area, volume, and frequency. We also have LiDAR flown pre-restoration and recently collected high-resolution aerial imagery of the floodplain which we will use to assess changes in floodplain connection.

We also monitor stream temperature and discharge throughout Asotin Creek and the study sites. We monitored discharge at the mouth of Charley and the South Fork since 2009 and recently began monitoring discharge at the confluence of the South Fork and North Fork. The Lick Creek Fire in 2021 and floods in early summer 2022 caused damage to one of our stage height loggers on Charley Creek, leaving gaps in the Charley discharge data. In October of 2020, the USGS decommissioned the Forks gauge station, due to lack of funding. This data is critical to estimating the North Fork's discharge. We were able to get the site back up and running in April 2022 and are currently monitoring discharge at the site. Consequently, over a year of data was missed during the acquisition and set up of the Forks discharge site. We are currently working on updating our rating curves at each discharge monitoring site.

We have collected stream temperature data throughout the IMW study area since 2008. Currently we have 28 temperature loggers deployed. Every year, data is downloaded at the start of the summer sampling period and at the end of our fall sampling period. Throughout the years we've had loggers go missing due to spring high flows or get damaged from leaks in the logger's waterproof seal. Consequently, there are gaps in the temperature data that still need to be analyzed and sorted before evaluating any impacts restoration may have on stream temperature throughout the study creeks.

To assess fish populations, we partner with WDFW which operates an adult weir and smolt trap near the mouth of Asotin Creek. The fish-in fish-out operation provides life-history data as well as estimates of adult escapement and juvenile migrants (smolts and juveniles emigrating from Asotin Creek or tributaries).

In the three study creeks, we conduct two-day mark-recapture in the summer and fall and tag all unmarked juvenile steelhead ≥ 70 mm with 12 mm passive integrated transponder (PIT) tags. From the summer and fall PIT tagging data, we estimate site abundance (fish/km) and biomass (g/km). We then estimate annual growth (g/season), survival (by season), and production rates (g/km/season) across two seasons: summer to fall and fall to summer. We also estimate juvenile emigration and productivity (smolts/female) by estimating the age of PIT tagged juvenile steelhead from 10%~ subsample of scales, tag detections at PIT tag interrogation sites (of juveniles and adults), and the ratio of tagged/untagged juveniles in the study creeks. There are four PIT tag interrogation sites, two located at the mouth of each IMW study creek, and two located near the mouth of Asotin Creek.

We analyze most metrics with a linear mixed effects model specifically designed for the staircase experimental design. The resulting test evaluates the change in the treatment sections compared to the control sections. Because each stream was restored in a different year, the statistical test compares responses in the different streams in the same year after treatment (YAT). We provide 90% confidence intervals on the % change estimate, and when intervals do not cross zero on the y-axis, the response (either negative or positive) is considered significant at $p<0.1$. We then present the Least Square Mean estimate for each metric (e.g., fish/km, g/season, etc.) for YAT=0 (pre-restoration), YAT=$\geq$ 1 (post-restoration, and the difference (treatment -control).

Results to Date

To date, we have documented small to modest, statistically, positive responses in geomorphic, habitat, and fish responses. We suspect that these modest responses are due to most of the habitat changes occurring within the existing channel (i.e., limited floodplain connection) and the resistance of the banks to erosion and widening (i.e., the channel is locked in by vegetation). We are evaluating and adjusting the maintenance and enhancement of the restoration treatments to force greater geomorphic responses and increased floodplain connection with the hypotheses that this will lead to greater connection of side-channels, inundation at low flow, and ultimately more volume of stream/km of valley length. This may lead to larger fish responses.

As hypothesized, some of the wood from PALS moved and reformed as new log jams within the treatment section due to the high density of structures. We found that the number of new “natural” debris jams (combination of added LWD and natural recruitment) roughly equaled the number of PALS that moved. In addition, we documented increased natural wood recruitment resulting from bank erosion forced by PALS. LWD and debris jams frequency has increased dramatically in treatment sections compared to controls because of the restoration (Fig. 1A). The increase in wood is forcing significant increases in geomorphic diversity in treatment areas compared to control areas by increasing bar and pool frequency and area (Fig. 2A). Most of the geomorphic changes are happening within the existing channel; however, small increases in side-channel, back-water, and floodplain connection are occurring and increasing as we adapt our maintenance to focus on side-channel connection.

The positive changes in habitat are leading to relatively consistent, statistically significant, small-moderate increases in juvenile steelhead abundance (fish/km) biomass (g/km) at some study sites (Figs. 3A). We have not observed significant changes in growth or survival (Fig. 4A). Lack of response in growth and survival in treatment sections may be due to fry surviving in greater numbers because of the flow refugia and/or increased off-channel and edge habitat that increased LWD is providing. It is also possible that egg-fry survival has increased due to improved spawning sites. The increase in bars in treatment sections demonstrate that substrate is being mobilized and sorted more effectively in treated reaches, providing clean, less compacted spawning sites. In addition, many bars are located downstream of PALS, which provide protection to redds from spring freshets. Increased density of fry could increase competition for available resources, muting responses in growth and survival. Increased Steelhead density and biomass at treated sites is consistent with this explanation. Steelhead smolt production has increased significantly relative to the references reaches at two of the three study sites (Fig. 5).

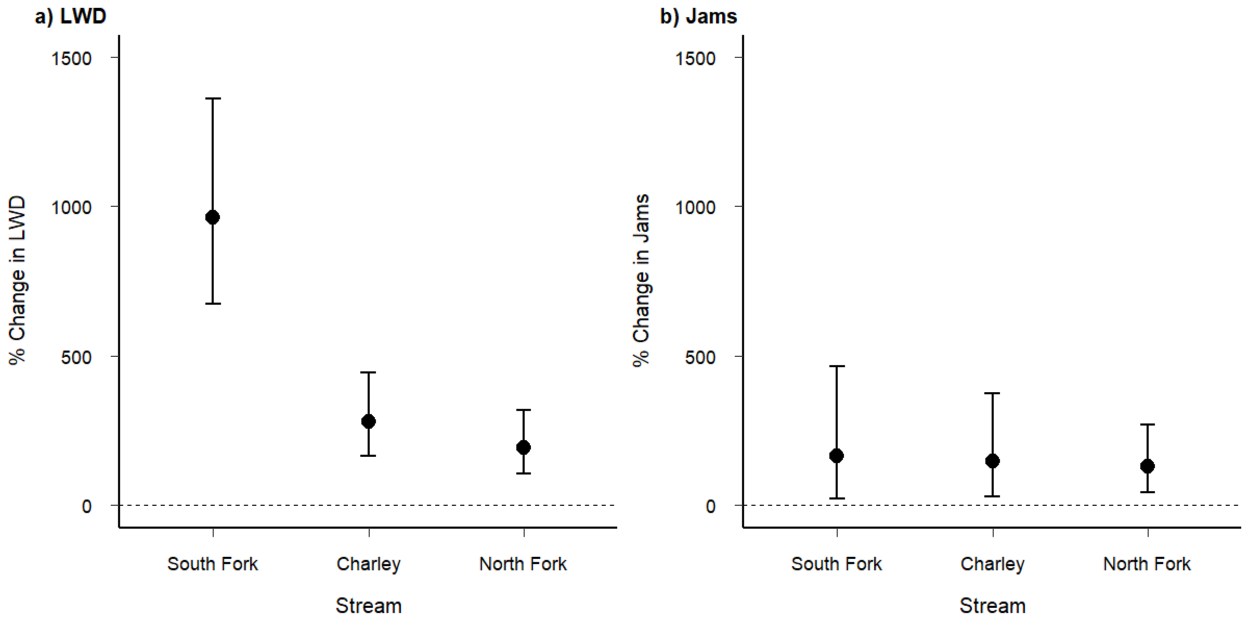

Figure 1A. *Percent difference (treatment-reference) in LWD and wood jam frequency at the treatment and control reaches of each study site.*

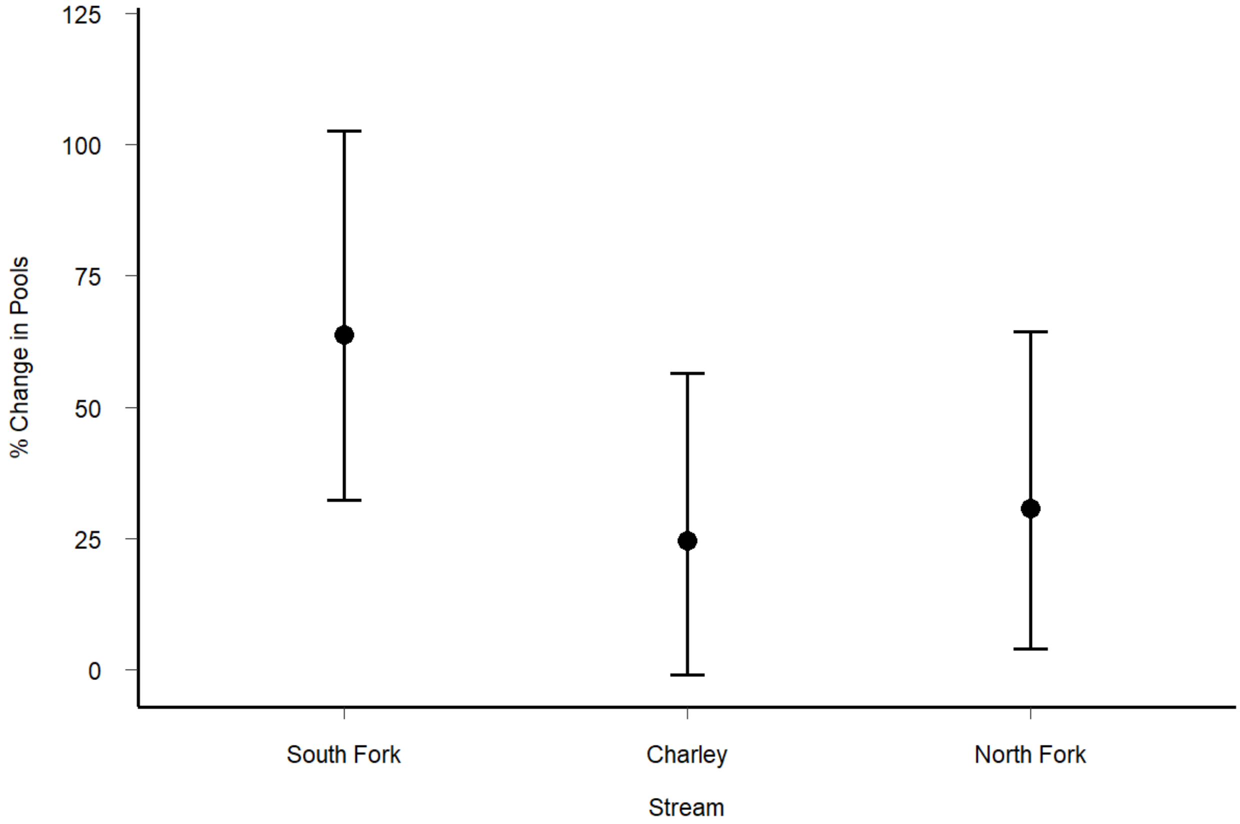

Figure 2A. *Percent difference (treatment-control) in pool area between treatment and control reaches at the three study sites.*

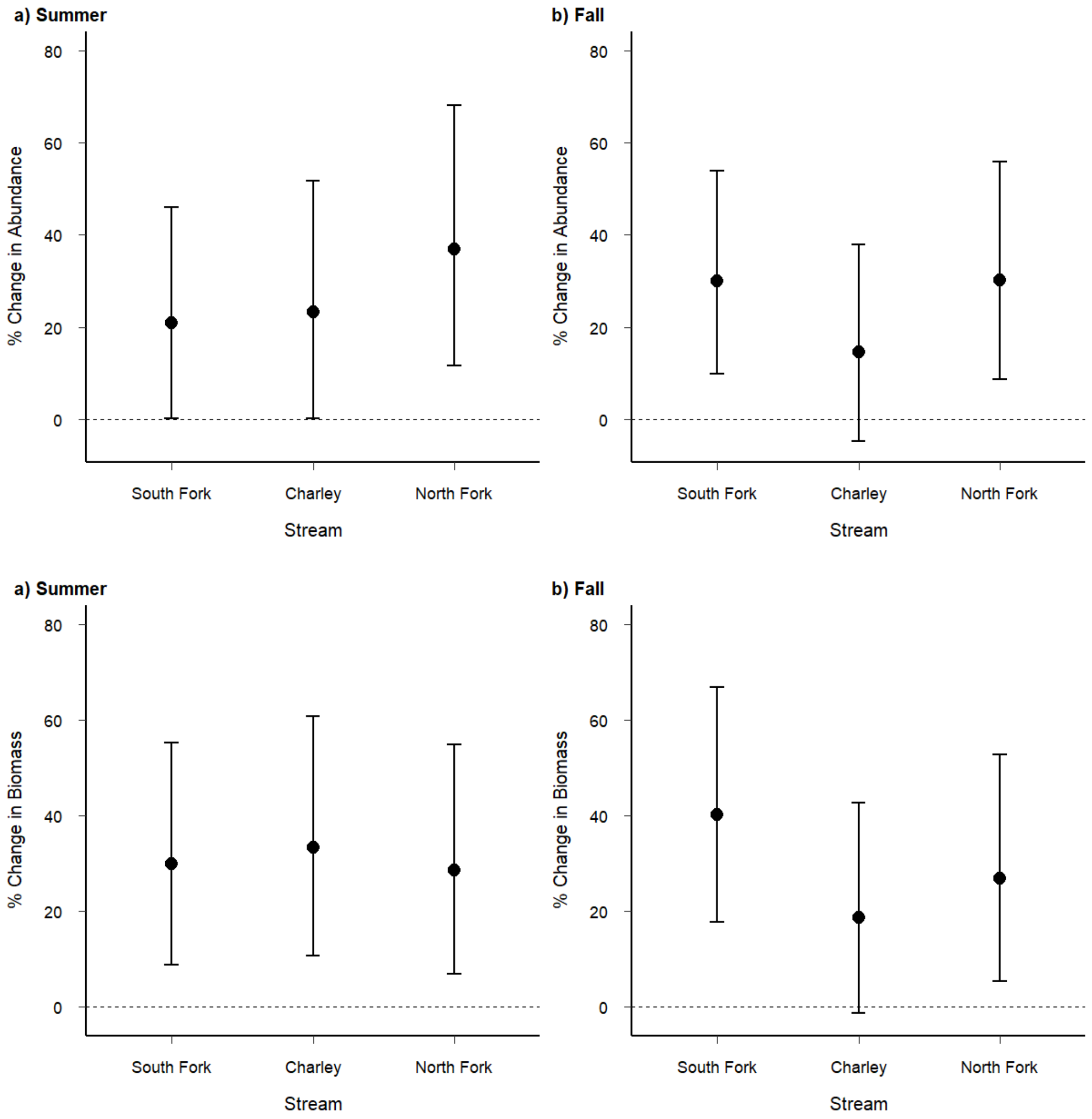

Figure 3A. *Percent difference (treatment-control) in juvenile steelhead abundance, biomass during the summer-autumn and autumn-summer seasons at the three study sites.*

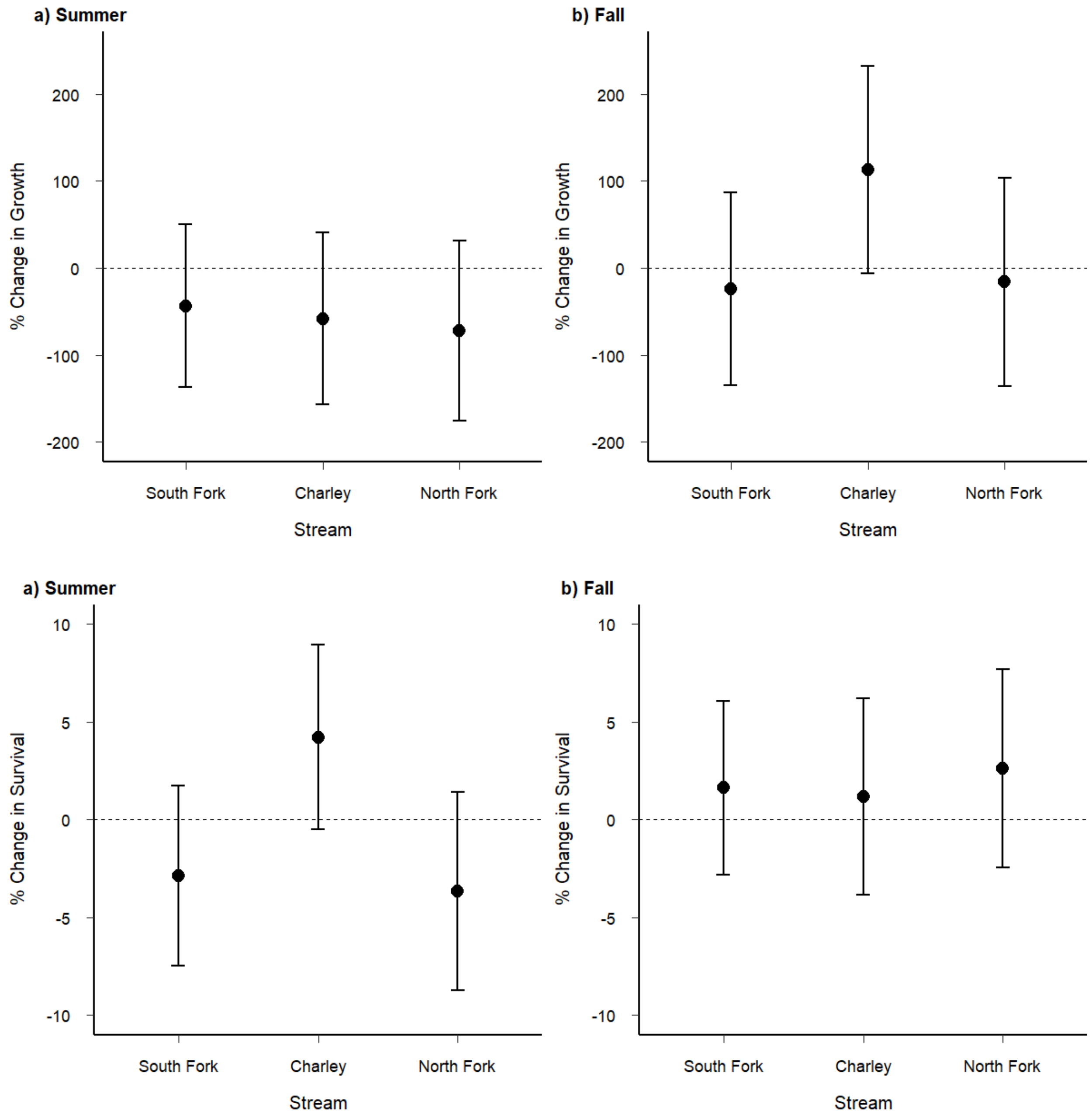

Figure 4A. *Percent difference (treatment-control) in juvenile steelhead growth and survival during the summer-autumn and autumn-summer seasons at the three study sites.*

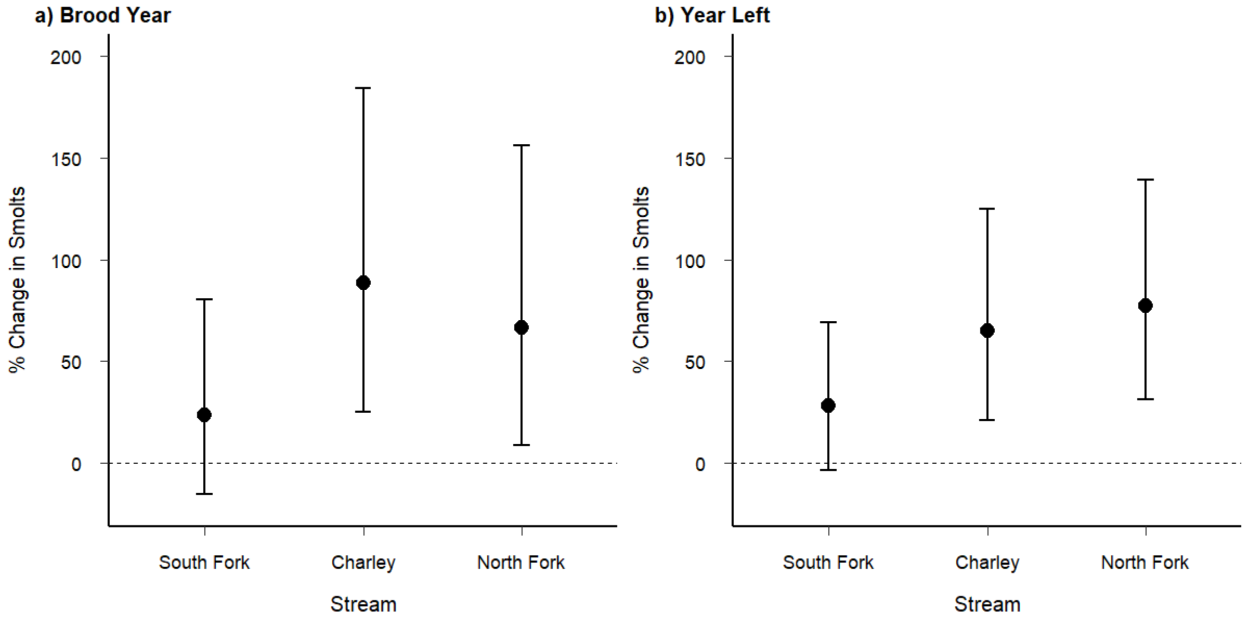

Figure 5A. *Percent difference in juvenile steelhead migrants (smolts/section) for a) brood year and b) year left from treatments compared to the controls pre- and post-restoration for: brood year 2008-2018, year left 2010-2020. Sections are 4 km long.*

The Nez Perce Tribe has been relocating adult Pacific Lamprey to Asotin Creek mainstem since 2007. Prior to 2016 most of the adult lamprey were relocated in the lower mainstem below Headgate dam which was considered a partial barrier. In 2016, Headgate dam was completely removed, and the Nez Perce started relocating lamprey higher up in the watershed, including within the IMW study area. We began detecting PIT tags from adult lamprey at the IMW interrogation sites in 2019 and caught some juvenile lamprey at the IMW study sites. In 2021, we conducted a survey that targeted lamprey and found ~ 100 juvenile lamprey in a short stretch of South Fork section 1. In 2022, we consistently captured juvenile lamprey in the North Fork and South Fork while conducting mark recapture surveys for steelhead (i.e., not targeting lamprey). The increase in incidental captures of juvenile lamprey suggests that adult lamprey may be regularly spawning within the IMW study area. We propose testing if juvenile lamprey are more abundant in IMW treatment sections compared to control sections. We hypothesize that the fine sediment that is sorted and trapped near PALS is creating ideal rearing areas for juvenile lamprey.

Results from the Asotin IMW are particularly applicable to wadeable streams (order 1-5) which typically make up 90% or more of the perennial stream network. We are developing a greater understanding of the mechanisms by which the habitat and fish are responding to restoration which will allow us to transfer lessons learned from the Asotin IMW to other wadable streams across the Pacific Northwest.

Key Findings

- Repeated wood additions at restoration sites were key to maintaining and increasing LWD densities.
- Establishing and maintaining high densities of large wood enhanced the retention of naturally-produced wood in treated reaches. Therefore, the formation of natural log jams was promoted, increasing geomorphic complexity, improving fish habitat, and increasing juvenile steelhead productivity.
- Changes in habitat that have occurred to date are mainly within the channel. We hypothesize that with ongoing treatments, reconnection of disconnected floodplains will occur and provide enhanced access to floodplain habitats, aid in the recharge of groundwater and contribute to higher summer base flows. Increased fish production may result. Additional monitoring will be required to evaluate this hypothesis.
- The PALS approach was an effective method of LWD placement at the Asotin IMW. This approach was less expensive than traditional methods of wood placement and avoided damage to riparian areas caused by heavy equipment.

Appendix B: Strait of Juan de Fuca IMW

The Strait of Juan de Fuca IMW includes East Twin River, West Twin River (reference), and Deep Creek. The three contiguous watersheds are in the Lyre/Hoko basin (WRIA 19) and flow north into the SJF. They are relatively small watersheds (i.e., less than 45 km^2), and are poorly drained by a dendritic-trellis drainage pattern and characterized by alluvium, glacial drift, volcanic and marine sedimentary rock that are susceptible to erosion, especially in areas of high topographic relief. The streams initiate in higher gradient uplands and have steep mid-reaches that decline in gradient near the outlet (i.e., ~3% down to <0.5%). Relatively high drainage densities suggest low base flows and rapid hydrographic responses to rainfall (Tab. 1B). Average annual rainfall is the highest of the three IMW complexes at about 190 cm/y. The watersheds are managed for timber production. Portions of the watersheds are public lands in the uplands (Olympic National Forest), as well as state lands (WA DNR), and privately owned timberlands dominate in the lower parts of the basin. Road crossings have restricted fish passage and impaired hydrological processes. Anthropogenically-caused landslides and road failures have produced a dramatic imbalance in sediment dynamics. Simple single thread channel forms are common throughout the study watersheds.

Table 1B. *Watershed areas, stream order, total reach length, maximum elevation, number of annual habitat surveys completed since 2007, mean number of annual habitat surveys, number of restoration projects, and number of intersections of restoration projects with annual habitat surveys and project monitoring surveys.*

Attribute	**East Twin River**	**West Twin River**	**Deep Creek**
Area (km^2)	36.2	33.9	44.0
Strahler stream order	5	4	4
Reach length (km)	89.7	92.8	103.8
Maximum elevation (m)	425	340	304
Total surveys (2007 – 2021)	291	295	265
Mean annual (2007 – 2021)	22.4	22.7	20.4
Survey sites	22	23	20
Projects	8	1	6
Intersects	22	0	19

Restoration Treatments

Starting in the mid-1990s the Lower Elwha Klallam Tribe (LEKT) developed and implemented a watershed-scale restoration plan for East Twin and Deep Creek Watersheds (United States Forest Service, Olympic National Forest et al., 2002). The restoration plan focused on reducing the rates of anthropogenic-caused landslides to background levels, recovering riparian forests to provide long-term supplies of in-channel wood, adding wood to offset losses due to land use impacts, and increasing floodplain habitats. These physical habitat objectives were linked to biological factors including fish abundance, growth, and productivity. For example, elevated landslide rates can cause mortality of juvenile salmonids due to scour-and-fill events, degradation of salmonid spawning habitat due to sedimentation, and loss of juvenile rearing habitat due to pool loss, floodplain disconnection, and overall channel simplification (Kemp et al., 2011). Reducing landslide impacts was a necessary first step in restoration to enable habitat-forming processes to recover naturally. Restoration projects were initiated beginning in 1998 and have continued through the present.

In-channel wood placement was an obvious tool for restoration treatment because it influences many stream habitat-forming processes that affect salmon life histories (Roni et al., 2008). Large wood is known to form pools, store gravels, and can reverse channel incision and improve floodplain connectivity (Abbe and Brooks, 2011; Wohl and Scott, 2017). Increases in floodplain connectivity may also increase formation of floodplain habitats known to be critical over-winter habitats for juvenile Coho salmon (Martens and Connolly, 2014).

Over half of the 30 projects that were completed over the last 24 years were wood placement efforts. Restoration treatments implemented from 1998 to 2022 were focused on the lower portions of East Twin and Deep Creek. The majority of wood placement focused on increasing low-gradient, mainstem habitat quality and quantity (Tab. 1B, Fig. 1B). Initial treatments were in-channel projects constructed of cut logs that relied upon ground-based placement techniques to create features such as log weirs, sills, and logjams. These treatments were generally of small size and of low profile, obstructing a relatively small percentage of the stream channel cross-sectional area. Some wood was placed to protect the toes of deep-seated landslides from further erosion.

In 2002-2003, the first helicopter wood placement projects were implemented using heavy-lift helicopters to fly in key pieces of wood to both previously ground-based treated reaches and into inaccessible habitats. This technology resulted in new or larger jams (adding to ground-based treatments) or individual key pieces. By 2008, there was a shift away from ground-based wood treatments to helicopter placement of wood.

Additional wood treatments did not occur for nearly a decade following the completion of the initial ground-based and initial helicopter treatments. This was due to a combination of factors including the inability to procure restoration funds and a focus on other project types (i.e., road decommissioning). Wood treatments were renewed from 2013-2022 and exclusively used helicopter placements. Thus, in-channel restoration in East Twin and Deep Creek was iterative and evolved over time in response to new techniques (Roni et al., 2015).

Both East Twin and Deep Creek restoration efforts were affected by natural disturbance events. For example, in upper Deep Creek, a high percentage of the relatively smaller, low-profile ground-based treatments began to degrade or move in response to large floods in the late 2000's (M. McHenry, personal observation). These movements resulted in larger aggregations of wood (i.e., full channel-spanning logjams) that had a greater effect on habitat features (i.e., conversion of stream channel types) downstream.

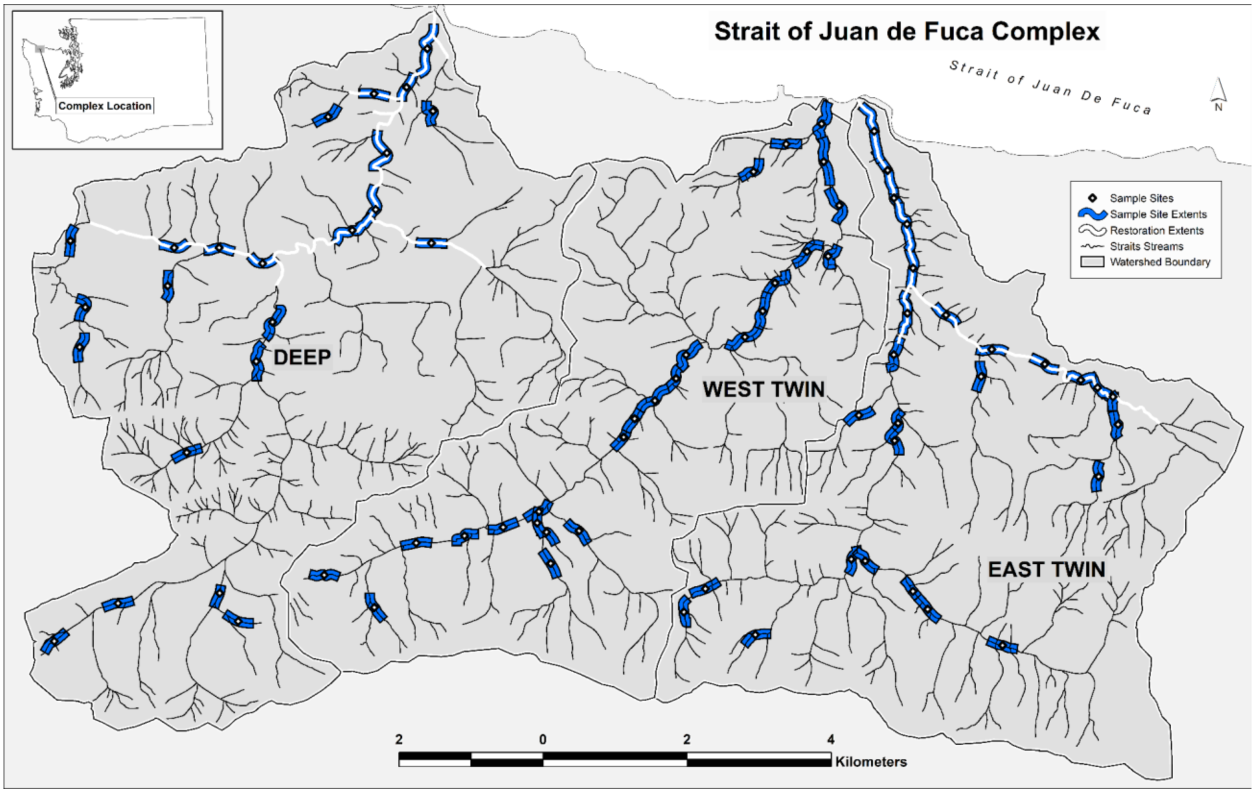

Figure 1B. *Map of East Twin River, West Twin River (reference), and Deep Creek depicting locations and spatial extents of frequently sampled sites and restoration sites.*

Table 2B. *Project (PRISM) identification number, project name, project status (C = completed, F = funded, P = proposed), year completed, and primary treatment types (OC = Off-Channel, SC = Side Channel, Floodplain Reconnection = FR, Instream Habitat Complexity = IHC, Fish Passage = FP, L = Landslide Treatments, RD = Road Decommissioning, R = Riparian).*

PRISM ID	Project Name	Project Status	Complete	Treatment
	East Twin River			
BIA	East Twin Off-Channel Pond/Riparian	C	2000-2001	OC, R
00-1884	East Twin River LWD Placement	C	2002-2006	IHC
05-1484	IMW Final Restoration Treatments	C	2007, 2009	IHC, FR
09-1529	Strait of Juan de Fuca IMW Restoration Treatments	C	2012-2014	IHC, FR
05-1485	Roads Decommissioning	C	2009	RD
16-1427	Strait of Juan de Fuca IMW Restoration Project	F	2020	IHC, FR
	West Twin River			
05-1485	Roads Decommissioning	C	2009	RD
	Deep Creek			
BIA	Initial Deep Creek Restoration Treatments	C	1998-2000	L, IHC, FR
05-1485	Roads Decommissioning	C	2009	RD
02-1583	Deep & SF Pysht River LWD Additions	C	2005-2006	IHC, FR
04-1546	Sadie and Susie Barrier Removals	C	2005	FP
09-1529	Strait of Juan de Fuca IMW Restoration Treatments	C	2011	IHC, FR
16-1427	Strait of Juan de Fuca IMW Restoration Project	C	2020	IHC, FR
PFMC	Upper Deep Helicopter Wood Projects	C	2019-2022	IHC, FR

Monitoring

Annual habitat survey methods are based on Lazorchak et al. (1998) and Roper et al. (2003) and are similar to those used by the Oregon Coastal Coho Survey (Anlauf et al. 2009) and Watershed Health Monitoring conducted by WA Department of Ecology (Watershed health - Washington State Department of Ecology). This sampling protocol was designed to provide a comprehensive assessment of habitat conditions for all stream reaches accessible to anadromous fishes in each watershed. Therefore, habitat survey locations were selected using a random, spatially balanced, stratified design (Stevens and Olsen 2004) and are conducted beginning in June through October. Surveys began in in 2005 and are ongoing. In 2006 we modified the design to annually resurvey sites and focus on reaches with anadromous fish presence, continuing the random spatially balanced design. Annually, we usually survey more than 25 sites, encompassing about 7 km in each watershed (Tab. 1B). More than 1,500 habitat surveys have been completed in the IMW to date.

The spatially extensive habitat surveys are augmented with monitoring at sites where restoration treatments were applied. Generally, the habitat survey methods described above are used. In some circumstances additional measurements may be taken at project sites, such as measuring stream gradient to assess deposition.

Tree canopy, visible surface water, and land cover have been described for each watershed using high resolution (i.e., 1-m resolution) imagery and changes in land cover, especially tree loss and development, are being monitored by WDFW Habitat Program's High Resolution Change Detection project (High Resolution Change Detection (arcgis.com). Stream flow and temperature data were collected by the WA department of Ecology near the stream outlets into the Strait of Juan de Fuca. We anticipate final habitat data collection in 2032.

Because wood addition is the most common restoration treatment being employed at the SJF IMW, a wood budget survey was conducted in 2020 in the lower 5.5 kilometers of Deep Creek to quantify how wood accumulation and associated stream channel characteristics changed in response to wood placement. Wood budget surveys were subsequently carried out in 2021 and 2022 in East Twin and West Twin Creeks. We organized the survey by reference point and proceeded from downstream to upstream over a period of eight survey days in August and September. The wood survey attempted to locate all pieces of large wood within the current active channel. We identified all wood that had been placed in the system, as well as those pieces naturally recruited All placed wood was mapped and individually tagged with a numbered 2" aluminum disk the same year it was placed. Wood was measured as either single pieces (snags) or aggregations of wood (logjams). We used a minimum piece size of 30 cm in diameter and >3 m in length for both snag and logjam measurements. Logjams were classified as any aggregation of wood with a piece count greater than two.

We used a Trimble Geoexplorer XT with individual data dictionaries to record wood and stream channel habitat metrics during the survey. For snags, we recorded the tree species, basal diameter, top diameter, root diameter, total length, decay factor, and tag number if present. For logjams, we identified the type (channel-spanning, meander, bar apex, bar top), size (surface area and volume), number of wood pieces, and origin of individual pieces (natural versus restoration). Differences between restoration and naturally recruited wood was determined by a combination of presence of tags, species and characteristics of wood observed. Wood added during restoration was all conifer and consisted of sawn logs (both ends cut) and rootwads. Rootwads were cut on one end and were either Douglas fir (*Pseudotsuga menziesii*), Sitka spruce or western hemlock and were consistently ~15 m in length with diameters ranging from 46-81 cm. All wood not meeting these criteria were considered of natural origin. Other information collected focused on the function of the wood encountered, including whether the individual piece (or multiple pieces or jams) was contributing to channel functions. Those criteria include no effect, storing gravel, forming pools, creating off-channel habitat, and contributing to floodplain connectivity.

During the stream channel morphological survey, we recorded pool location, surface area, maximum depth, outlet depth, and pool-forming factor (bedrock, roots of standing tree, channel bed, snag, and logjam). We calculated residual pool depth for each pool by subtracting the outlet depth from the maximum depth for each pool. For floodplain channels, we recorded their location using GPS and classified its type (side-channel, overflow channel, alcove, or excavated pond). We also classified the floodplain channel forming function (natural wood, restoration wood, other). The wood and morphological metrics used allowed us to assess how wood impacted stream morphology. We summarized metrics of pool size and logjam intensity for 500-m reaches. We also used scatter plots to look for potential correlations. We avoided formal statistical analysis because of the small sample size (N=11 reaches).

We utilized a life cycle monitoring approach to assess fish response to restoration. We enumerated returning adult Coho salmon and Steelhead, collected and PIT (Passive Integrated Transponder) tagged juvenile salmonids at the end of summer, monitored PIT tagged fish migrations at river mouths, and used fence-weir traps in each of the watersheds to enumerate smolt outmigration. This life cycle approach allowed us to understand the overall abundance, productivity, and survival for both Coho salmon and Steelhead. The restoration response in the three basins was assessed using metrics of abundance and survival at various life stages.

Annual estimates of adult escapement to the SJF watersheds are made for Coho salmon and Steelhead. Coho salmon escapement estimates are based on redd surveys conducted during the spawning season from late November to late January. The survey reaches were based on a stratified random sample where strata were defined by habitat type. The number of redds per habitat type is totaled and then applied to unsurveyed reaches within the watershed. In contrast, for Steelhead, WDFW conducts main stem surveys for redds beginning in mid-March and ending in late June. These surveys are only in the main stem of each watershed and do not include tributaries, which are assumed to support relatively minor amounts of spawning habitat.

We used three-pass and single-pass electroshocking to collect, enumerate, and PIT tag juvenile Coho salmon and Steelhead from 2004 to 2017. All juvenile coho 55 mm or larger and Steelhead 60 mm and larger were tagged with 12 mm PIT tags. Each year we sampled 10 sites in each of the three watersheds that were chosen based on a generalized random tessellation stratified (GRTS) sample procedure design (Stevens and Olsen 2004; Bilby et al. 2005b). Some additional collections were conducted in lower East Twin to increase the number of total tagged fish. For some years and sites, only a single pass was used. Estimates in this case are based on a regression between the first pass and three pass estimates for sites with three passes. Collected fish were anesthetized, measured, weighed, PIT tagged, placed in a recovery tub in the stream for 15 or more minutes, and released into their habitat of origin.

Stationary multiplex PIT tag readers were installed approximately 600 and 300 m from tidewater in the East Twin and West Twin Rivers, respectively, and 200 m from tidewater in Deep Creek. The PIT tag readers identify individual migration in either direction and allow quantification of estimated survival from tagging date and determination of migration timing (e.g., age at migration and seasonal timing). To maximize our probability of detecting PIT tagged fish, each reader included two antenna arrays composed of three antennas that spanned the stream channel at most flows. The two arrays in each stream were positioned with the downstream array approximately 3 to 5 m below the upstream array. This configuration allowed for the detection of PIT tagged fish migrating from the watersheds to the marine environment and vice versa. Survival from tagging (August and September) to outmigration (parr to smolt) was based on PIT tag detections of outmigrating fish, corrected for PIT tag reader efficiency.

Smolt trapping began in 1998 in Deep Creek and in 2000 in the East Twin and West Twin Rivers[1]. All sites use fence weirs and target the outmigration of Coho, Steelhead and Cutthroat trout. The traps are installed in late April and fished through mid to late June. Traps are checked daily and captured fish are identified, counted, interrogated for PIT tags, and released downstream of the trap. Trap efficiency tests are conducted throughout the season using mark-recapture techniques. Total catch is summarized, and the total outmigration adjusted based on trap efficiency trials. Summer parr abundance for Coho and Steelhead is estimated from the ratio of PIT tagged to total captures in the smolt trap and the parr-smolt survival rate. We anticipate final fish data collection in 2027.

Key Results to Date

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[1] Smolt trapping was not conducted in IMW streams in 2020 because of Covid.

The repeated wood additions to sections of Deep Creek and East Twin River created observable habitat changes in treated reaches. For example, the lower 4 km of Deep Creek exhibited increased pool area, pool depth and increased sediment storage at several of the treated reaches (Fig. 2B). In addition, sections of lower Deep creek went from single thread to multi-thread channel types (Fig.2B). However, extensive habitat surveys did not identify any significant trends in any measured habitat attributes at the scale of the entire watershed. (Kruger et al. 2022). Unexpectedly high interannual variability in several habitat metrics were observed in all watersheds and at many survey sites. Implications of high interannual variability to restoration are especially important; at many sites interannual variability was greater than the estimated effects of restoration. As a result, the substantial restoration effort in these watersheds often change habitat less than habitat varies from year to year (Krueger et al. 2022).

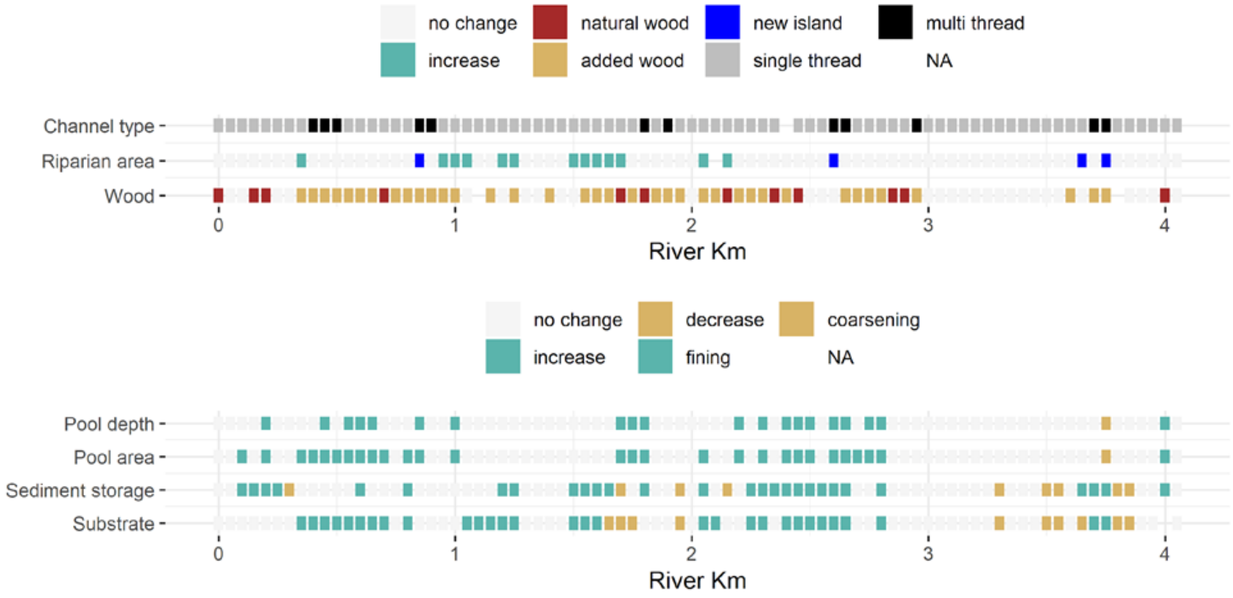


Figure 2B. *(a) Representation of the changes to reach-scale elements of Deep Creek from 1997 to 2020 using photo points from rkm 0.0 to 4.0. (b) Representation of the changes to in-channel elements of Deep Creek from 1997 to 2020 using photo points from rkm 0.0 to 4.0.*

Parr-smolt survival for Coho salmon and steelhead has been greater in the treated watersheds relative to the control watershed – West Twin River (Fig. 3B). Most of the wood additions in both treatment watersheds occurred from 2000 through 2014. East Twin juvenile Coho salmon survival was higher in 10 of the 17 years monitored, while East Twin juvenile steelhead survival was greater than the control watershed in 15 of the 17 years (Fig.3B). Deep Creek juvenile Coho salmon survival surpassed West Twin River starting in 2014 and dropped below West Twin twice since 2014. Deep Creek steelhead had relative survival estimates greater than the control watershed in 7 of the 12 years (Fig. 3B).

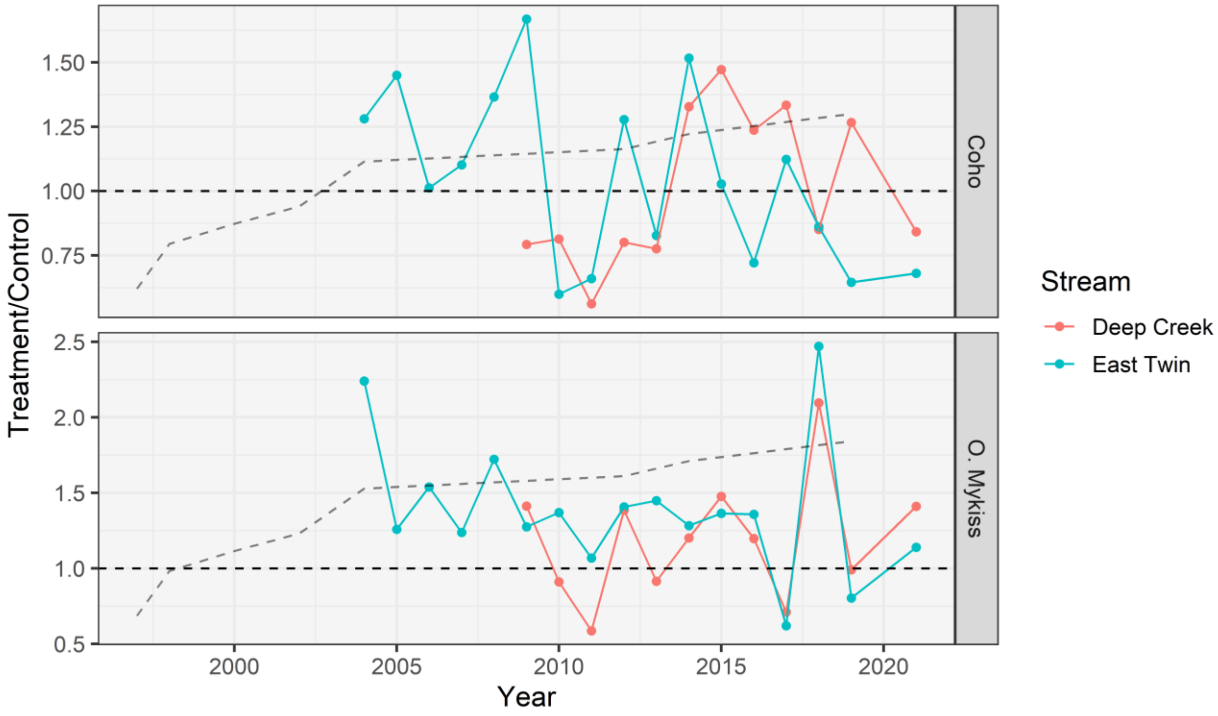


Figure 3B. *Difference between estimated (a) juvenile coho salmon and (b) steelhead survival from tagging to outmigration across passive integrated transponder (PIT) antennas by year. Hashed line denotes the level of wood additions over time. Solid dots and solid line denote mean survival differences between either East Twin River or Deep Creek and West Twin River.*

Smolts trends for Coho Salmon and steelhead suggest that Deep Creek Coho Salmon smolt production tends to be greater than the other two populations (Fig. 4B). Steelhead smolt production is similar for each of the watersheds (Fig. 4B).

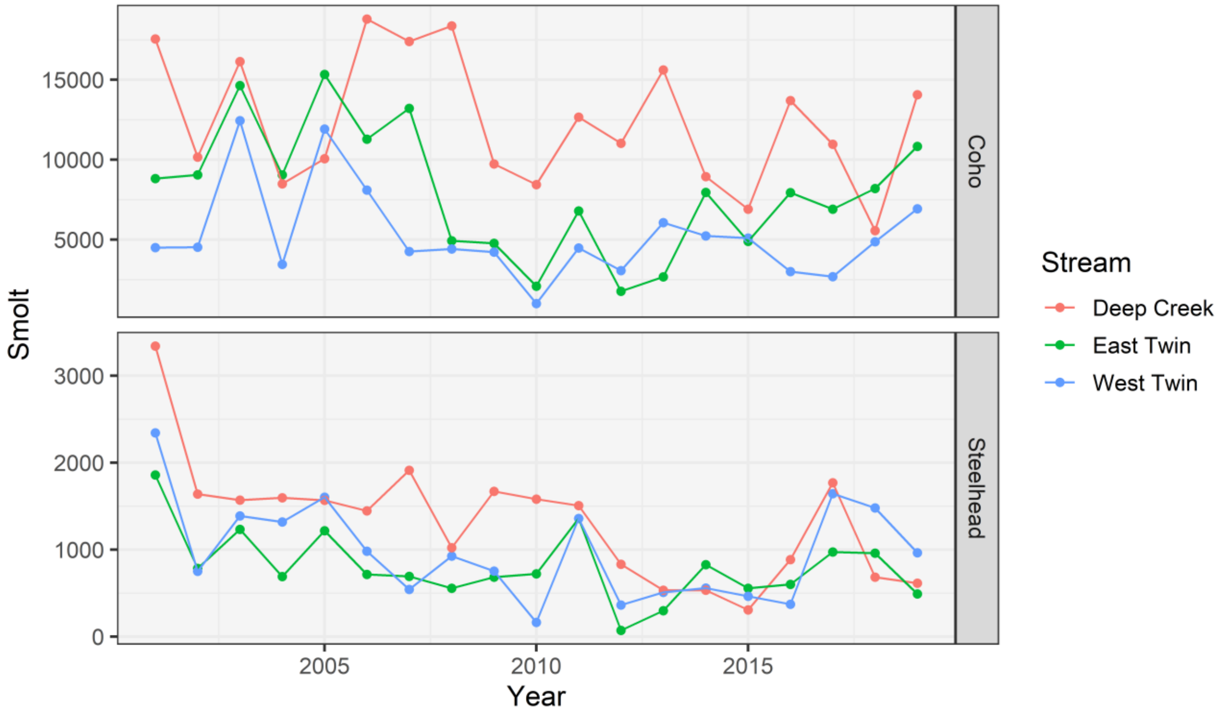


Figure 4B. *Coho salmon and steelhead Smolt abundance estimates from 2001 to 2019 East Twin River, Deep Creek, and West Twin River.*

Comparing abundance of returning adult Coho and Steelhead at the treated watershed against the reference watershed indicates there may be some increase beginning to occur at the treated sites (Fig. 5B), although differences are not yet statistically significant. Coho salmon returning to Deep Creek began to increase relative to returns to West Twin River in about 2008. A comparable change in Coho returns has not been observed at East Twin River. Steelhead returns to Deep Creek have been consistently greater relative to the reference watershed since the inception of the study (Fig. 5B). However, there is little evidence of an increase in steelhead returns to this system over the study period. East Twin River Steelhead returns have been comparable to West Twin River throughout the study period. As with Deep Creek, there is no indication of a temporal trend in Steelhead returns during the study period.

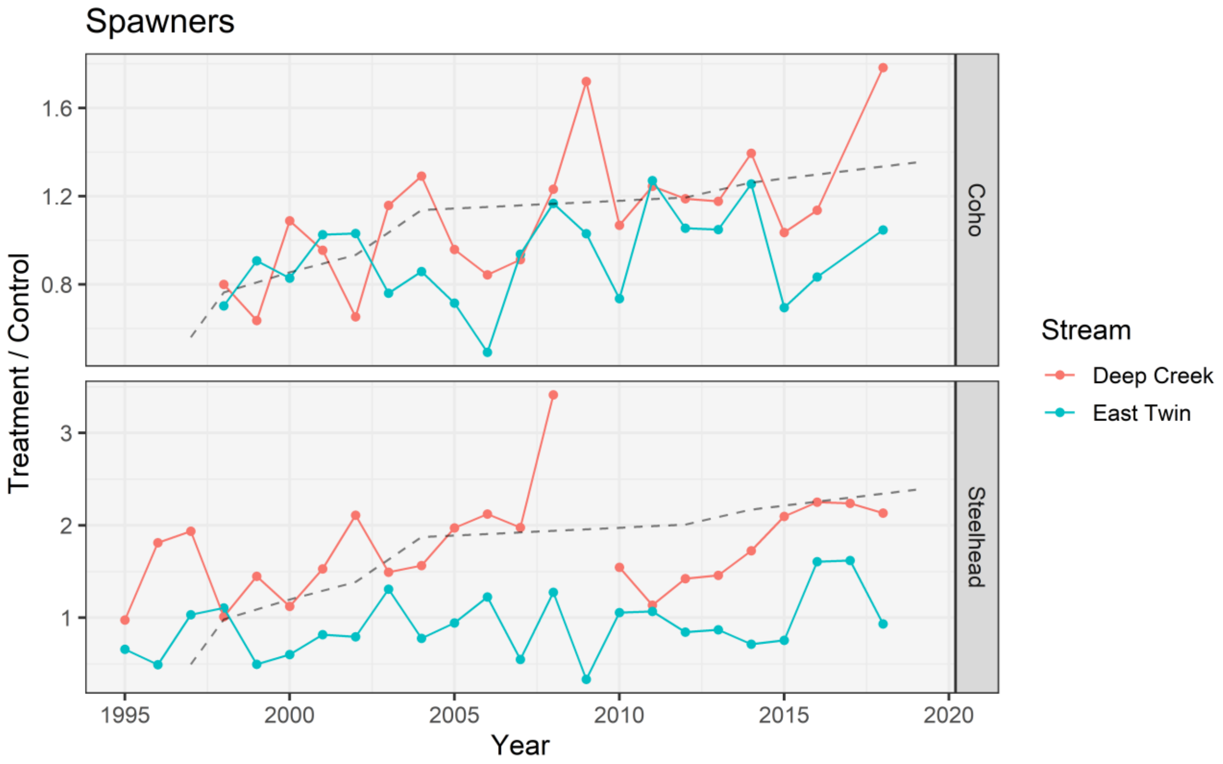


Figure 5B. *Ratio (treatment/control of adult coho salmon and steelhead returns over time in the Strait IMW watersheds 1995 to 2019. Hashed line denotes the level of wood additions over time.*

One of the more interesting results to date because of the long-term monitoring is the identification and quantification of the variety of life history strategies that contribute to the overall population of Coho salmon and steelhead (Fig. 6B) (Bennett et al.2014, Hall et al. 2016). Long-term monitoring of juvenile coho salmon outmigrants using passive integrated transponder tags (PIT tags) from each of the Strait watersheds documented returning adult Coho salmon that were fall/winter migrants rather than traditional spring migrants (Bennett et al. 2014). Our results indicate that traditional methods of spring-only smolt enumeration may underestimate juvenile survival and total smolt production, and also overestimate spring smolt-to-adult return (SAR) (Bennett et al. 2014).

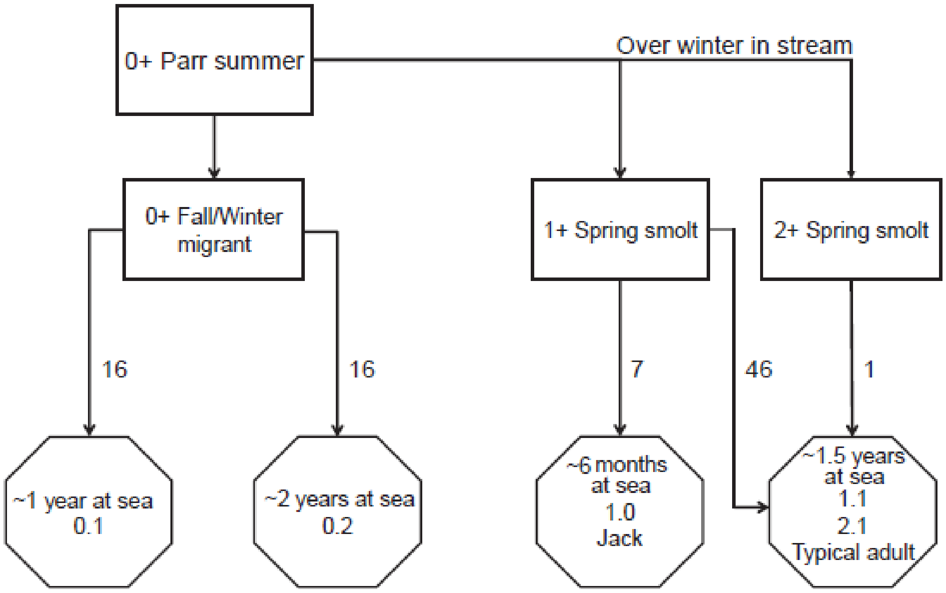


Figure 6B. *Life history pathways exhibited by coho salmon in the East Twin River, West Twin River, and Deep Creek. From Bennett et al. (2014).*

Similar life history diversity data collected for steelhead suggests that fish attaining a large enough size early in life to survive over the winter but not big enough to trigger migration at age 0 were more likely to remain in the river to become age-1 migrants, which were more likely to produce a returning adult steelhead (Hall et al. 2016). Long-term monitoring associated with PIT tag data of steelhead also that density-dependent growth may influence juvenile steelhead migration patterns and production of migrants as evidenced by increasing contributing-adult steelhead escapement being negatively related to average cohort body size, probabilities of fish being detected as migrants, and production of age-1 and older migrants (Hall et al. 2016). Increases in juvenile habitat capacity due to restoration treatments such long-term, intensive wood placement can help alleviate some of these density-dependent effects.

Key Findings

- Repeated, large-scale wood additions changed channel morphology, improving both spawning and rearing habitat, and had a positive effect on juvenile Coho Salmon survival.
- It was necessary to add wood multiple times to a stream to achieve the desired habitat response.
- Habitat and fish response to wood treatments took multiple years to be fully expressed. Therefore, long-term monitoring is required to evaluate restoration effectiveness.

- PIT tags and smolt traps enabled the identification of multiple freshwater life histories for Coho Salmon. Fall-migrant Coho Salmon made a significant contribution to returning adults but survived in the ocean at a lower rate than spring migrants.

Appendix C: Hood Canal IMW

The Hood Canal IMW includes Little Anderson, Big Beef, Stavis (reference), and Seabeck creeks. Coho Salmon (*Oncorhynchus kisutch*) are the focal species of the Hood Canal IMW. The study streams have experienced repeated industrial logging, removal of instream large wood, and ongoing rural residential development. Road crossings have restricted fish passage and impaired hydrological processes. This caused a dramatic imbalance in sediment dynamics, with some reaches (frequently but not always those upstream of undersized culverts) serving as deposition zones and other reaches becoming deeply incised. Single-thread, plane-bed channels with uniform depth profiles are common throughout the study streams. In especially acute deposition zones, stream flow is often subsurface during the summer, resulting in a series of isolated pools.

Study Design and Area

Little Anderson, Big Beef, Stavis (reference watershed), and Seabeck creeks comprise the HC IMW Complex. The four contiguous watersheds are located in Kitsap County, Water Resource Inventory Area (WRIA) 15 and they flow north into Hood Canal. These small watersheds are low elevation and have relatively little topographic relief (Tab. 1C). Glacial (Vashon) till and alluvium is the dominant geology and subsurface flow across clay layers creates locations of erosion, especially where crossed by stream channels and roads (Booth and Jackson 1997). Average annual rainfall is about 105 cm/y. Substantial flooding occurred in 2004 and 2007 causing road crossing failures and continuing channel geometry variability. These streams initiate in a relatively flat upland plateau with associated wetlands and have relatively steep mid-reaches that decline in gradient near the mouth (Booth et al. 2003). The few relatively high gradient stream reaches are likely sources of bedload that is deposited in lower gradient reaches. The Hood Canal IMW watersheds were some of the first to be commercially logged in Washington and most of the area has been logged more than once. Most of these watersheds is forested and ownership is a patchwork of public and private land. However, rural residential development is continuing in all watersheds and urban development is occurring in the Little Anderson Creek watershed.

Table 1C. *Watershed areas, stream order, total reach length, maximum elevation, number of annual habitat surveys completed since 2007, mean number of annual habitat surveys, number of* *restoration projects, and number of intersections of restoration projects with annual habitat surveys and project monitoring surveys.*

Attribute	**Little Anderson**	**Big Beef**	**Seabeck**	**Stavis**
Area (km^2)	12.9	36.6	13.3	17.4
Strahler stream order	3	3	4	4
Reach length (km)	28.4	58	35.1	32.3
Maximum elevation (m)	117	151	113	126
Total surveys (2007 – 2021)	357	398	393	367
Mean annual (2007 – 2021)	25.5	28.2	27.8	26.2
Survey sites	27	30	31	27
Projects	6	4	7	2
Intersects	11	10	8	1

Restoration Treatments

Restoration planning in the Hood Canal IMW watersheds has been funded by several SRFB grants, including an orthophoto analysis effort to help plan to reduce peak flows in 2000, an assessment by Stillwater Sciences and WDFW in 2008 (Stillwater Sciences 2008), and designs for lower Big Beef Creek in 2011 and 2014. WDFW provided a watershed assessment for Seabeck Creek in 2008 and a watershed-scale plans for Little Anderson, Big Beef, and Seabeck Creek were developed by the Hood Canal Salmon Enhancement Group with assistance from the IMW Technical Oversight Group in 2018. A persistent challenge in the Hood Canal IMW study has been a lack of financial support for restoration, many of our proposed projects remain unfunded. Overall, a larger magnitude of restoration would increase the likelihood of detecting a response to restoration.

Restoration efforts seek to improve salmon habitat by enhancing stream connectivity and complexity. Restoration projects typically have included more than one treatment type. For example, removal of an instream structure, bank contouring to increase floodplain connectivity, and large wood and engineered logjam placements may be implemented simultaneously at a treated reach (Table 2C, Krueger et al. 2022). Replacing undersized culverts with larger spans aims to improve passage for fish, woody debris, and sediment. Previously isolated floodplain habitats have been reconnected to the channel by removing dikes. This action is intended to provide fish access to overwinter habitat in wetlands and allows for more natural patterns of channel migration. Large woody debris (LWD) additions are intended to improve habitat complexity, resulting in more sinuous, multi-thread channels with a greater degree of variation in depth and velocity. The LWD also provides roughness to retain sediment, thereby helping to address the sediment dynamic imbalance. In some cases, individual restoration projects employ a combination of these treatment types.

At Little Anderson Creek a culvert was replaced with a bridge in 2002 and LWD additions occurred in 2007, 2009 and 2016. The LWD additions cover a substantial portion of the channel network accessible to anadromous fishes (Fig 1C, Tab. 2C). In Big Beef Creek restoration treatments have been concentrated in the lower 2 km of the watershed, with a much lower density of treatment extending upstream for another 4 km. A large restoration project was implemented in three phases during 2015-2017 on Big Beef Creek that included reconnecting a wetland to the channel by removing a levee. Relatively little restoration has occurred in Seabeck Creek; the primary action was the replacement of an undersized culvert with a bridge on the mainstem in 2021, whereas the other Seabeck projects listed in Table 2 were relatively small scale or in reaches rarely used by Coho salmon.

Table 2C. *PRISM identification number, project name, project status (C = completed, F = funded, P = proposed), year project was completed, and primary treatment types (OC = Off-Channel, SC = Side Channel, Floodplain Reconnection = FR, Instream Habitat Complexity = IHC, Fish Passage = FP). KCPW = Kitsap County Public Works, KCD = Kitsap Conservation District. Table adapted from Lamperth et al. (2021).*

PRISM ID	Stream	Project Name	Project Status[b]	Construction Complete[b]	Primary Treatment
		Little Anderson Creek			
KCPW	AND	Anderson Hill Rd Culvert to Bridge replacement	C	2002	FP
14-1889	AND	Little Anderson Ck IMW Stream Enhancement	C	2016	IHC, OC/SC
Private	AND	Little Anderson Creek BDA (Beaver Dam Analog)		2019	IHC
05-1665	AND	IMW Treatments in Hood Canal - Phase 1 "2"	C	2007-2009	IHC, FR
		Big Beef Creek			
KCPW	BIB	Holly Arch Scour Repair		2012	IHC
14-1284	BIB	Lower Big Beef Creek Restoration- Construction	C	2015	IHC, FR, OC/SC
15-1203	BIB	IMW-Lower Big Beef Creek Restoration Phase 2	C	2016	IHC, FR, OC/SC
16-1477	BIB	Big Beef Creek Restoration Phase 3 Construction	C	2017	IHC, FR, OC/SC
		Seabeck Creek			
HCSEG	SEA	NW Dragonfly Dr	C	2003	FP

KCPW	SEA	Seabeck Holly @ Foley Lane Culvert Replacement	C	2010	FP, IHC
KCPW	SEA	NW Hite Center Rd	C	2012	FP
KCPW	SEA	Miami Beach Rd NW	C	2013	IHC, FR
KCD	SEA	Lower Seabeck Creek Habitat Enhancement	C	2022	IHC, OC/SC
19-1600	SEA	Seabeck Creek Culvert Replacement	C	2021	IHC, FP
Stavis Creek					
KCPW	STA	NW Seabeck Holly Road Culvert Replacement	C	2010	FP
KCPW	STA	Stavis Bay Road Bridge Replacement	C	2011	FR

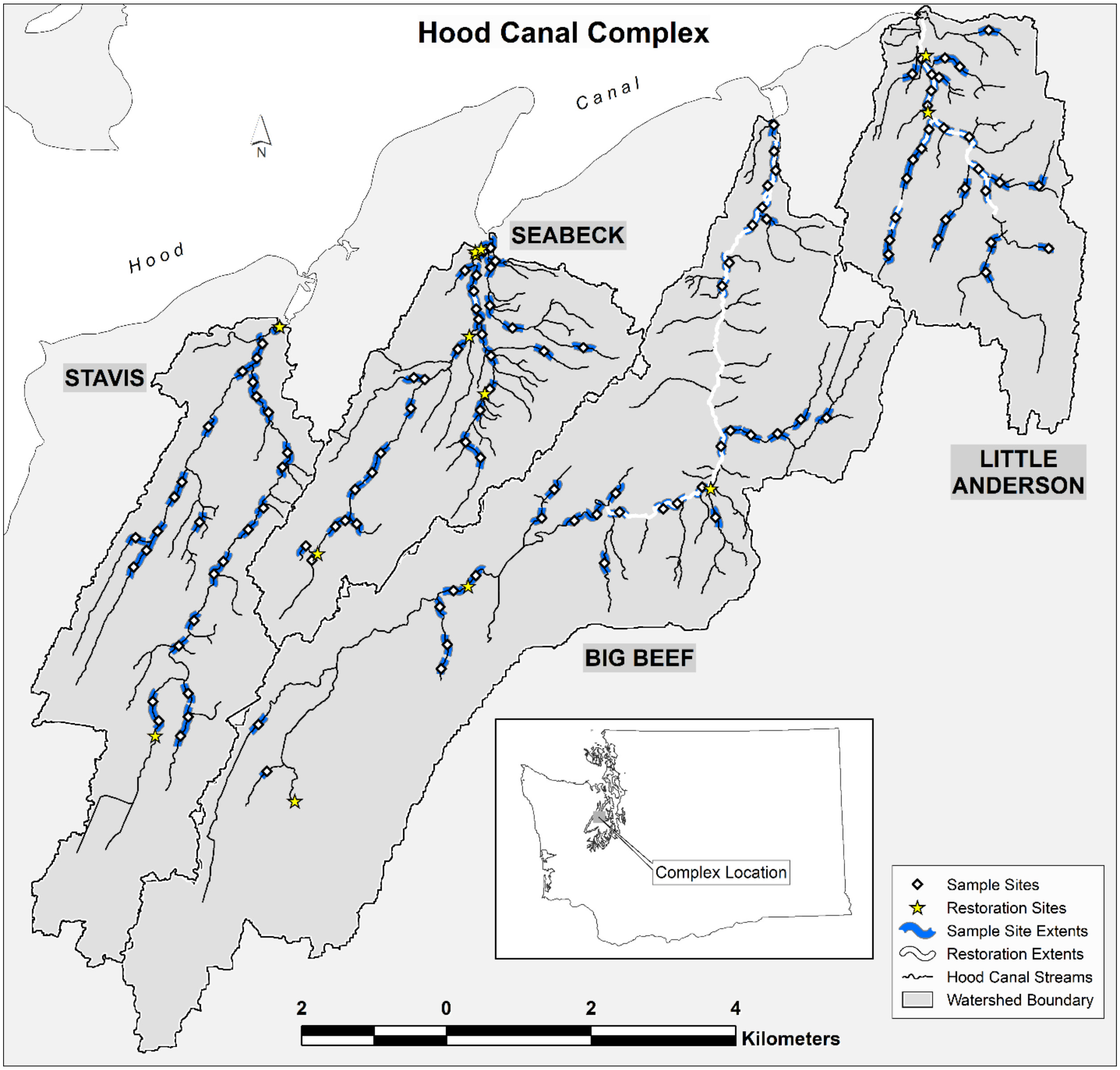


Figure 1C. *Map of Little Anderson, Big Beef, Seabeck, and Stavis creeks depicting locations and spatial extents of frequently sampled sites and restoration sites. Restoration sites depict locations of small, but possibly important projects such as bridge replacements whereas restoration extents depict locations of extensive projects such as some large wood placements.*

Monitoring

Annual habitat survey methods are based on Lazorchak et al. (1998) and Roper et al. (2003) and are similar to those used by the Oregon Coastal Coho Survey (Anlauf et al. 2009) and Watershed Health Monitoring conducted by WA Department of Ecology (Watershed health - Washington State Department of Ecology). Habitat survey locations were selected using a random, spatially balanced, stratified design (Stevens and Olsen 2004) and are conducted from June through October. Surveys began ibn 2005 and are ongoing. In 2006 we modified the design to annually resurvey sites and focus on reaches with anadromous fish presence, continuing the random spatially balanced design. Annually, we usually survey habitat at more than 25 sites and across more than 7 km in each watershed (Tab. 1C). More than 1,500 habitat surveys have been completed in the HC IMW since 2007.

Tree canopy, visible surface water, and land cover have been described for each watershed using high resolution (i.e., 1-m resolution) imagery and changes in land cover, especially tree loss and development, are being monitored by WDFW Habitat Program's High Resolution Change Detection project (High Resolution Change Detection (arcgis.com)). Stream flow and temperature data were collected by the WA Department of Ecology near the stream outlets until 2013. WDFW supplemented those data using water level loggers until 2017. Now, Kitsap County collects some flow data at a station on Big Beef Creek.

The spatially extensive habitat surveys are augmented with monitoring at sites where restoration treatments were applied. Generally, the habitat survey methods described above are used. In some circumstances additional measurements may be taken at project sites, such as measuring stream gradient to assess deposition.

We estimate Coho Salmon abundance at three distinct life stages: adults, stream rearing age-0 parr, and outmigrating age-1 smolts. Additional response variables include survival between life stages, body size and growth, and the spatial distribution of spawners. We also count other salmonids when they are encountered. Cutthroat Trout, fall Chum Salmon, summer Chum Salmon and Steelhead are captured at one or more stream.

In Big Beef Creek, we are tracking the fish response to a large magnitude floodplain reconnection and LWD restoration project that occurred in 2015-2017. The restoration appears to have provided substantial overwinter habitat for coho salmon, so we have hypothesized that parr to smolt survival will increase.

We anticipate habitat and fish monitoring at this IMW will continue through 2034.

Key Results to Date

Habitat conditions in the treated HC IMW 3watersheds have not responded as anticipated (Krueger et al. 2022). There is little evidence that any of the measured habitat variables are trending in a positive direction, despite extensive restoration treatments in some of the IMW watersheds (Fig. 1C). Perhaps most importantly, we quantified unexpectedly high interannual variability in several fish habitat metrics in all watersheds and at many survey sites. Implications of interannual variability to restoration are especially important – at many sites interannual variability was greater than the estimated effects of restoration (Pittman and Krueger 2012). As a result, the substantial restoration effort in these watersheds often change habitat less than habitat currently varies across several years (Krueger et al. 2022).

Results to date clearly indicate that removal of barriers can increase Coho salmon smolt abundance. Replacement of a blocking culvert with a bridge on Little Anderson Creek in 2002 was followed by a rapid increase in the production of smolts from this system (Fig. 2C; Anderson et al. 2019). The response was presumably due to an increase in accessibility of spawning and rearing habitat for Coho Salmon. However, since 2014 smolt production in Little Anderson Creek has been variable ranging from very few smolts in some years and in some cases abundance comparable to years immediately following the culvert replacement. Years of low smolt production are related to two issues. Although the replacement of an undersized culvert with a bridge represented a significant increase in the opening over the former culvert, the bridge remains a constriction. In recent years (2018 to present), a combination of low water during the time of spawning coupled with beaver activity underneath the bridge has restricted fish passage upstream. In addition, very few adults spawn in this watershed some years, resulting in extremely low coho salmon adult, parr and smolt abundances. A combination of a long-term decline in marine survival (Zimmerman et al. 2015[b]) and harvest affect the abundance of spawning adults in the Hood Canal IMW. Overall, we observed very few smolts in Little Anderson Creek (average = 160) in the four outmigrant years (2019 - 2022) since the Anderson et al. (2019) evaluation, among the lowest of the entire time series (Fig. 2C)

Although we observed slightly more smolts after LWD addition than before it, this difference was not statistically significant and not consistent across life stages (Anderson et al. 2019). Experiences at other IMWs suggest that effective treatment with LWD may require multiple placements and considerable time before habitat conditions improve (Pess et al. 2022; see sections on Straits and Asotin IMWs). A single reach in Little Anderson Creek received LWD in both 2009 and 2016, providing some opportunity to test fish response to repeated treatments. There was no fish response to the treatments. Perhaps despite the repeated wood additions, the treatments were not intense enough to elicit a fish response. Fish response also was impacted by the concurrent issues of low escapement and passage restriction at the bridge.

The large project implemented on Big Beef Creek from 2015 through 2017 appears to have had a positive effect on Coho parr to smolt survival (Fig. 3C). We have observed several years of relatively high overwinter survival in Big Beef Creek from 2019-2022. This project removed a levee, providing access to a large floodplain wetland and increasing overwinter habitat. However, several additional years of monitoring will be required to be able to attribute this increase in survival to the restoration.

Finally, a key result from the Hood Canal IMW is that spawner abundance is frequently lower than the carrying capacity of the freshwater habitat. Spawner to smolt stock-recruit plots indicate that density dependence is weak in many years, well below the level where habitat capacity restricts productivity (Fig. 4C). Small population size combined with factors external to freshwater habitat, such, as a long-term decline in marine survival (Zimmerman et al. 2015^{b}; Crozier et al. 2019) and harvest (Hood Canal 2003-2021 average = 49%, BackFRAM model), may limit Coho salmon response to some types of habitat restoration in watersheds at the HC IMW. However, access for fish throughout the watersheds, especially Seabeck and Little Anderson creeks, is often constrained by sediment deposition and other obstructions. Correcting these problems also will be necessary to increase fish populations in these systems.

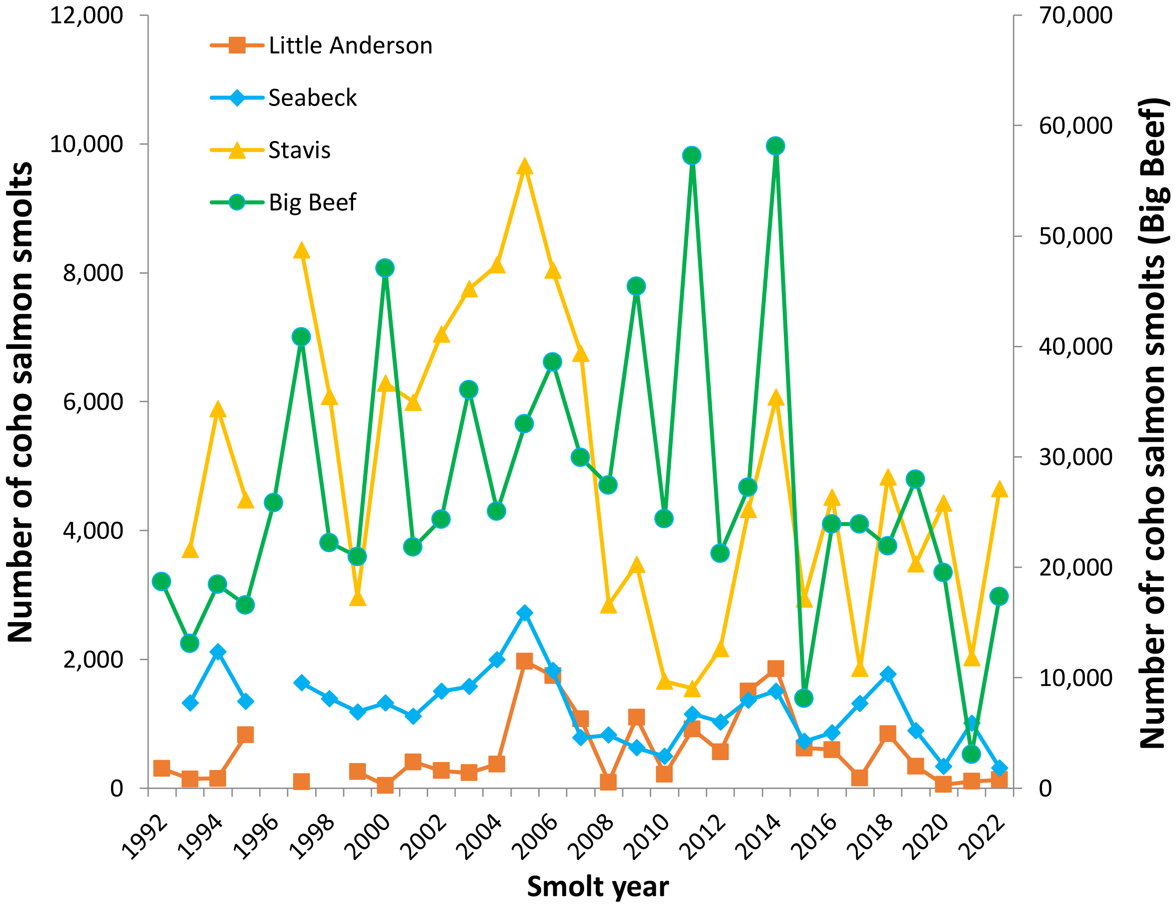


Figure 2C. *Smolt abundance time series from the Hood Canal IMW. Note Big Beef Creek is plotted on the right y-axis, all other streams on the left y-axis.*

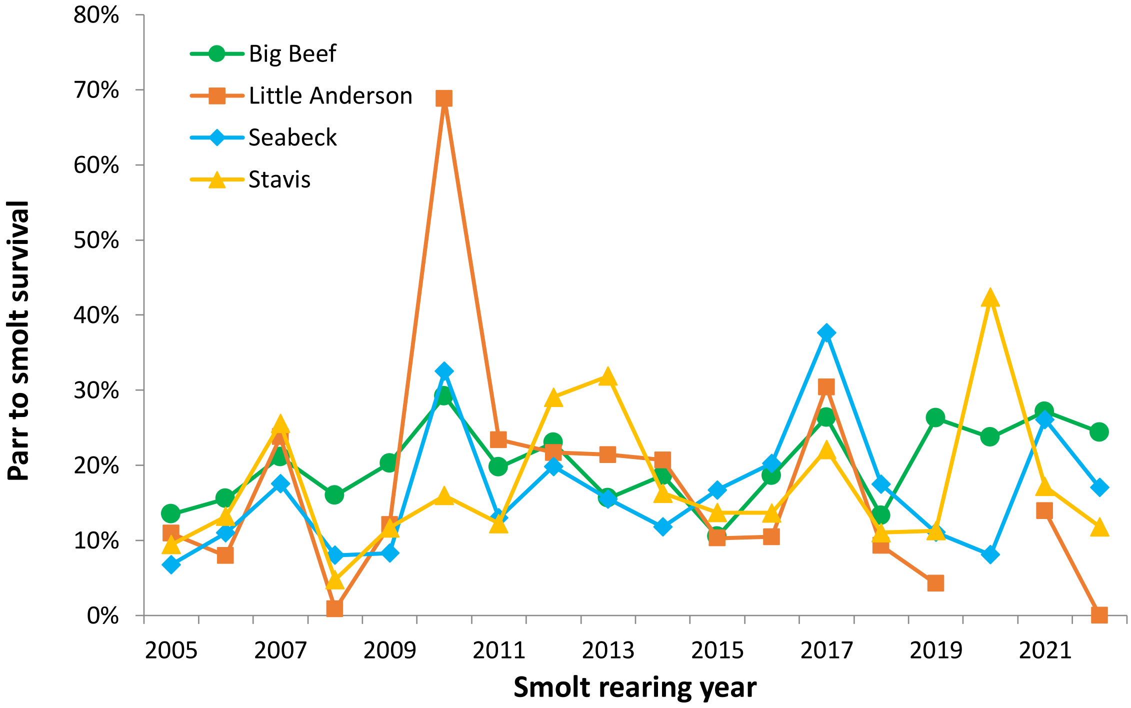


Figure 3C. *Parr to smolt survival time series from the Hood Canal IMW.*

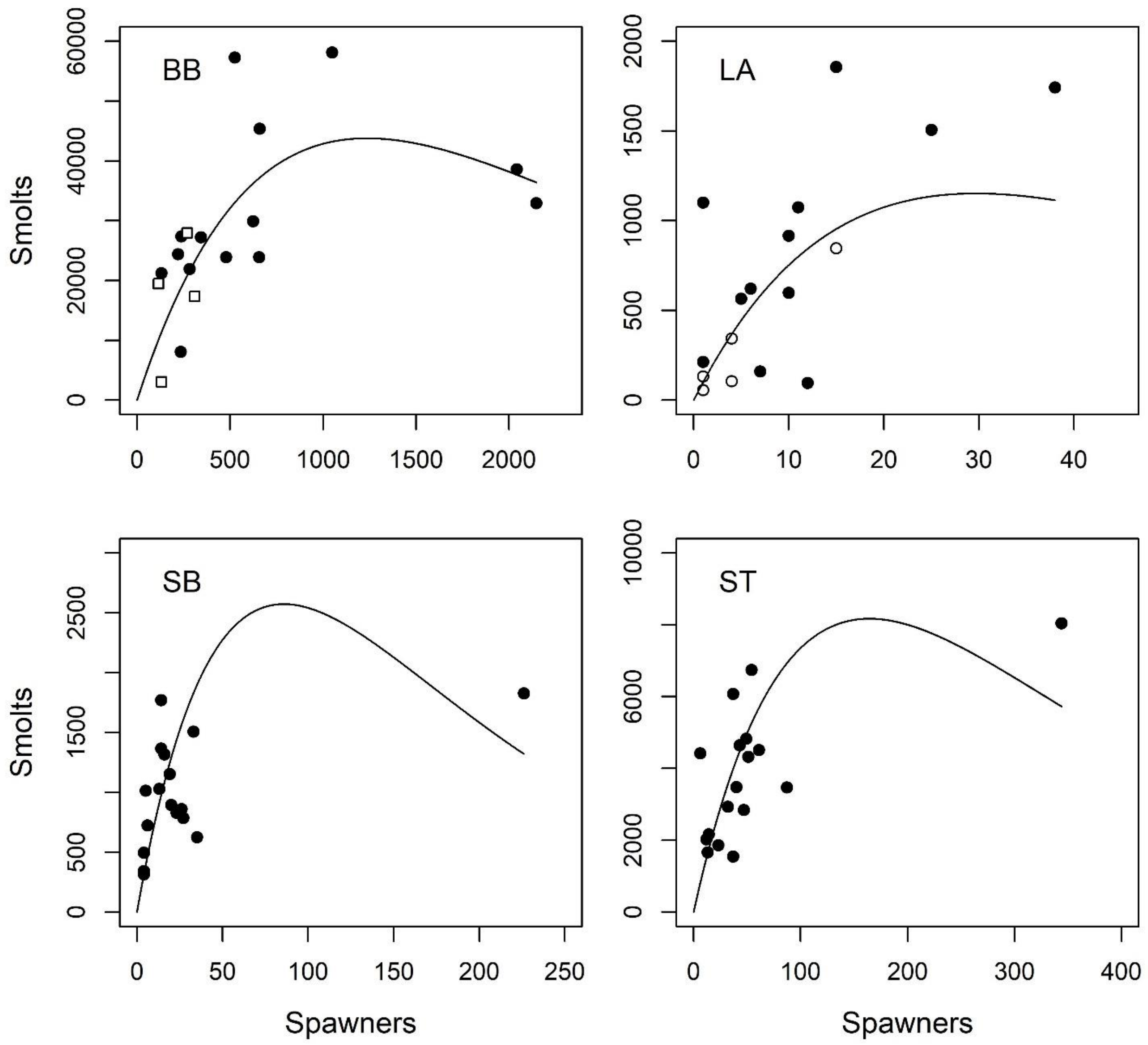


Figure 4C. *Spawner to smolt plots of coho salmon in Big Beef (BB), Little Anderson (LA), Seabeck (SB) and Stavis (ST) creeks, 2004-2022. The line is a Ricker stock-recruit model fit to each stream. The open circles denote coho salmon cohorts that experienced stream conditions after the floodplain reconnection and LWD placement in Big Beef Creek (smolt years 2019-2022) and after the most recent LWD placement in Little Anderson Creek (smolt years 2018-2022).*

Key Findings

- Increasing habitat quantity will likely only have modest effects on fish survival and production until escapement to these systems increases.
- Disruption of the movement of gravel and wood, often at undersized culverts, damaged and simplified salmon habitat in several of the HC IMW watersheds. In the near term, prioritizing projects that enhance connectivity and restore natural rates of transport of gravel and wood may have the most beneficial effect on salmon.
- Improving connectivity to floodplain habitats (Big Beef Creek) appears to have caused an increase in overwinter survival of Coho Salmon. This project was completed relatively recently, and additional monitoring is required to validate the response.
- The replacement of an undersized culvert with a channel spanning bridge near the mouth of Little Anderson Creek initially increased fish passage and generated a strong, positive response in Coho Salmon smolt production. However, after several years, fish passage under the bridge was restricted by sediment accumulation, low flow and beaver activity. Restoration treatments should be periodically revisited to ensure they are functioning as designed.

Appendix D: Lower Columbia River IMW

The Lower Columbia IMW (LC) includes Germany, Abernathy, and Mill (reference) creeks. The three contiguous watersheds are in Wahkiakum and Cowlitz counties in the Grays/Elochoman basin (WRIA 25) and flow south into the lower Columbia River between River Mile (RM) 53.8 and 56.2 (Figure 1D). They are characterized by sequences of upper Tertiary volcanic (~85%) and Columbia River Quaternary sedimentary (~13%) rock and steep slopes that result in frequent erosion and mass wasting events. Average annual rainfall is about 160 cm/yr. The Lower Columbia IMW watersheds initiate in relatively steep uplands and flow through relatively confined channels in a dendritic drainage pattern. Watersheds are small and drainage density is high (Tab. 1D). Coho salmon (*Oncorhynchus kisutch*), Chinook Salmon (*O. tshawytscha*), and Steelhead (*O. mykiss*) are the focal species. We anticipate final data collection in 2032.

Most of the area in these watersheds has been managed for wood production for over a century with approximately 10% rural residential. Over 80% of the complex is early seral stage forest. Much of the Mill and Abernathy creek watersheds are publicly owned, while most of the Germany Creek watershed is privately owned (Sierra Pacific Industries). Road crossings have restricted fish passage and impaired hydrological processes. Historic logging practices included splash dams, removal of wood from the channels and harvesting of riparian trees, which depleted future sources of large wood. Splash dams coupled with a lack of wood led to channel scour, incision, isolation of floodplains and simplification of channel structure. Single-thread, plane-bed channels are common throughout the study watersheds.

Table 1D. *Watershed areas, stream order, total reach length, maximum elevation, number of annual habitat surveys completed since 2007, mean number of annual habitat surveys, number of restoration projects, and number of intersections of restoration projects with annual habitat surveys and project monitoring surveys.*

Attribute	**Germany**	**Abernathy**	**Mill(ref)**
Area (km^2)	58.6	75	75.8
Strahler stream order	4	5	5
Reach length (km)	204.8	252.4	215.4
Anadromous habitat (km)	19.9	36.5	39.2
Total surveys (2007 – 2021)	343	366	349
Mean annual (2007 – 2021)	24.4	25.9	25
Survey sites	25	26	24
Projects	12	17	3
Intersects	19	21	1

Restoration Treatments

The Lower Columbia IMW Treatment Plan identifies habitat restoration opportunities in the Abernathy and Germany creek watersheds (HDR Inc and Cramer Fish Sciences 2009). The Treatment Plan was developed in 2009 and updated in 2016 with support from four grants administered by the Recreation and Conservation Office (RCO), IMW habitat monitoring results, and input from the IMW Technical Oversight Group (LCFRB 2016). Restoration was initially planned for Abernathy and Germany Creeks. However, in 2017, restoration planning led by the Lower Columbia Fish Recovery Board (LCFRB) shifted the restoration focus solely to Abernathy Creek to reduce costs. The restoration implementation plan identified 13 projects in Abernathy Creek. All 13 projects were completed by 2021.

Restoration efforts seek to improve salmon habitat by enhancing floodplain and stream connectivity and stream complexity. The primary restoration treatments are large woody debris (LWD) additions intended to improve habitat complexity. Undersized bridges and culverts have been removed to improve passage of fish, wood, substrate, and water. We anticipate that these treatments, in combination, will result in an increase in sinuous, multi-thread channels with a greater degree of variation in depth and velocity. The LWD also provides roughness to retain sediment, which over time will promote reconnection of floodplain habitats to the channel

Thirteen restoration projects on Abernathy Creek were completed between 2012 and 2021 (Tab. 2D). Restoration projects typically included more than one treatment type, for example, removal of a passage barrier, bank contouring to increase floodplain connectivity, and large wood and engineered logjam placements (Lamperth et al. 2021). The projects are in the mainstem and large tributaries and primarily consist of LWD additions with additional work addressing stream sinuosity and fish passage concerns. Despite restoration focus moving away from Germany Creek, four projects were completed in the mainstem of this system from 2019-2022 (Tab. 2D). One additional project is planned that will impact instream habitat in upper Germany Creek. In Mill Creek, the reference watershed, two culverts were replaced which likely could expanded available habitat for salmon in this watershed (Fig. 1D).

In addition, a watershed-scale nutrient enrichment study was conducted from 2011-2013 in Germany and Abernathy creeks. Salmon carcass analogs (SCAs) were added in the fall to Germany Creek (2011-2013) and in the spring to Abernathy Creek (2013-2015) with the goal of increasing nutrients available to stream food webs during juvenile rearing (Sturza 2017). Treatments consisted of 5,987 kg to 18,144 kg of SCA additions, equivalent to densities ranging from 0.08 and 0.13 kg m^{-2}.

Table 2D. *PRISM identification number, project name, project status (C = completed, F = funded, P = proposed), year project was completed, and primary treatment types (OC = Off-Channel, SC = Side Channel, Floodplain Reconnection = FR, Instream Habitat Complexity = IHC, Fish Passage = FP). Table adapted from Lamperth et al. (2021).*

PRISM ID	Project Name	Project Status[b]	Construction Complete[b]	Primary Treatment
		Abernathy Creek		
10-1300-01	Abernathy Creek Tidal Restoration	C	2013	OC/SC
11-1329	Abernathy Creek Bridge Removal Project	C	2012	FR
11-1386	Abernathy Creek Two Bridges	C	2012	FR
12-1333	Abernathy Creek 5A Side Channel Project	C	2015	OC/SC
PCSRF[c]	Abernathy Sitka Spruce	C	2015	IHC
14-1296	Abernathy Creek Davis Site	C	2017	OC/SC,IHC
PCSRF[c]	Abernathy Creek Wisconsin Site Project	C	2016	IHC
14-1311	Abernathy Creek Cameron Site	C	2016	IHC
14-1310	Abernathy Creek Midway Project	C	2016	IHC
15-1127	Abernathy Creek Headwaters Implementation	C	2020	IHC
16-1533	Sarah Creek Habitat & Passage Enhancement	C	2019	FP,IHC
17-1115	Erick Creek Instream Habitat Restoration	C	2020	IHC
18-1397	Abernathy Creek Mainline Restoration IMW	C	2021	IHC
21-1506	Erick Creek Fish Passage Project	P	Future	FP
		Germany Creek		

09-1378	Germany Creek Conservation and Restoration 2	C	2012	IHC
15-1039	Germany Creek Restoration Smith Site	C	2020	IHC
15-1040	Germany Creek Restoration Andrews Site	C	2020	IHC
17-1027	IMW Godinho Restoration	F	2021	IHC
19-1225	Germany Creek Stream Restoration Kosiba	F	2022	IHC
21-1078	Upper Germany Creek Restoration Project	F	2023	OC/SC,FP,IHC
22-1181	Riparian Buffer Stewardship[c]	F	2026	Riparian

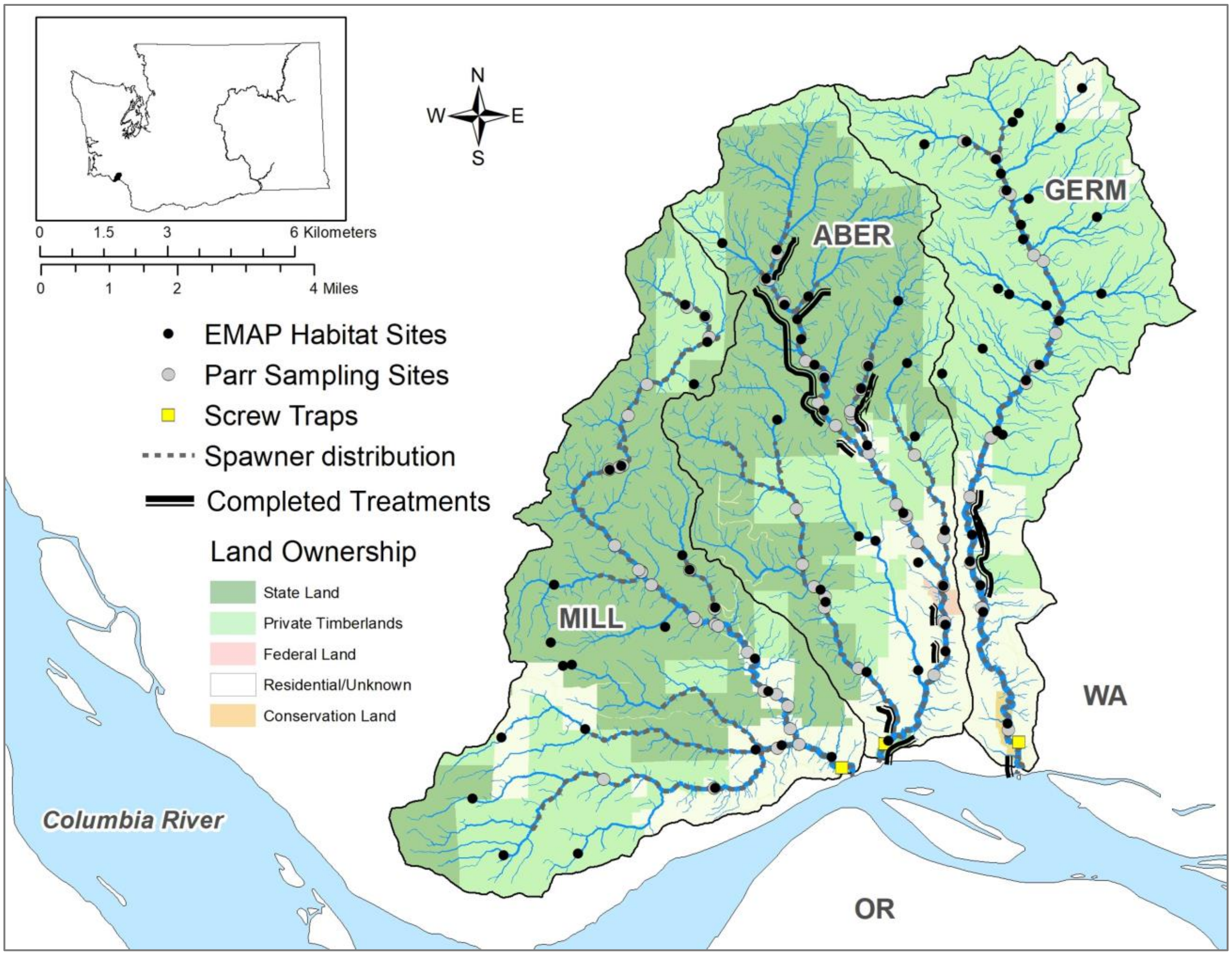


Figure 1D. *Map of the Lower Columbia Intensively Monitored Watershed complex in southwest Washington. The map shows monitoring sites, completed habitat restoration treatments as of 2022, and land ownership within the complex.*

Monitoring

Annual habitat survey methods are based on Lazorchak et al. (1998) and Roper et al. (2003) and are similar to those used by the Oregon Coastal Coho Survey (Anlauf et al. 2009) and Watershed Health Monitoring conducted by WA Department of Ecology (Watershed health - Washington State Department of Ecology). Habitat survey locations were selected using a random, spatially balanced, stratified design (Stevens and Olsen 2004) and were conducted from June through October in each year beginning in 2005. In 2006, the design was modified to annually resurvey sites and focus on larger reaches, continuing the random spatially balanced design. Annually, habitat was surveyed at about 24 sites across more than 7 km in each watershed. More than 1,000 habitat surveys have been completed in the LC IMW since 2007.

The spatially extensive habitat surveys are augmented with monitoring at sites where restoration treatments were applied. Generally, the habitat survey methods described above are used. In some circumstances additional measurements may be taken at project sites, such as measuring stream gradient to assess deposition.

Tree canopy, visible surface water, and land cover have been described for each watershed using high resolution (i.e., 1-m resolution) imagery and changes in land cover, especially tree loss and development, are being monitored by WDFW Habitat Program's High Resolution Change Detection project (High Resolution Change Detection (arcgis.com).

Stream flow and temperature data are collected by the WA Department of Ecology at the lower end of each watershed within 2 km of their confluence with the Columbia River. Flow data have been useful for interpreting habitat changes and were used in the assessment of the nutrient enhancement treatment. Flow data is also critical for conducting spawning ground surveys and screw trap operations.

Annually, abundance is estimated and biological data collected from three different life stages of salmon and steelhead including adult spawners, summer rearing parr, and out-migrating juveniles (i.e., smolts) using common monitoring protocols (Crawford et al. 2007a; Crawford et al. 2007b; Volkhardt et al. 2007). Population response metrics include adult abundance (Coho and Chinook salmon and Steelhead), smolt abundance (Coho, Steelhead, and Chinook), summer parr abundance (Coho), summer parr density (Coho and Steelhead), survival between life stages (Coho, Steelhead, and Chinook), body size and/or growth (Coho, Steelhead, and Chinook), age (Coho, Steelhead, and Chinook) and spatial distribution of spawners (Coho, Steelhead, and Chinook). Data also are collected from other species encountered including Chum Salmon, Coastal Cutthroat Trout, and Pacific Lamprey.

Key Results to Date

The projects implemented in Abernathy Creek have impacted approximately 33% of accessible salmon and Steelhead habitat, including 11.8 kilometers (km) of instream habitat, 1.3 km of off-channel and side-channel habitat, 0.19 km^2 of riparian area, and 2.7 km of improved fish passage (Fig. 1D and Fig. 2D).

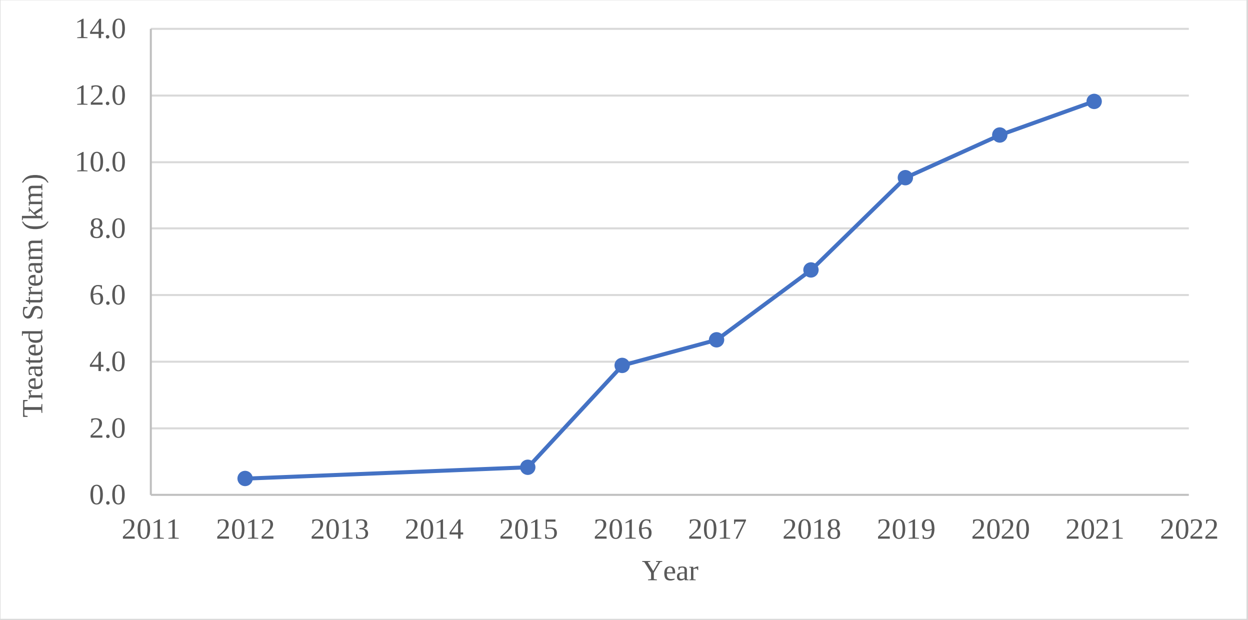
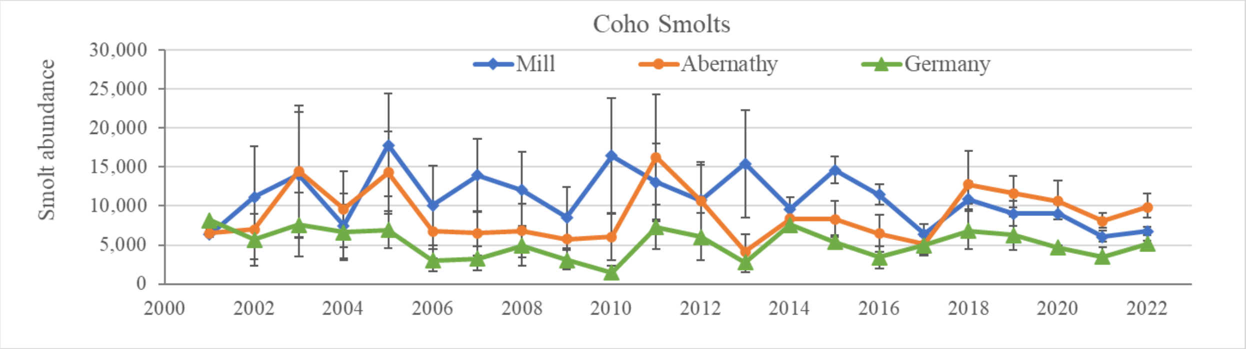
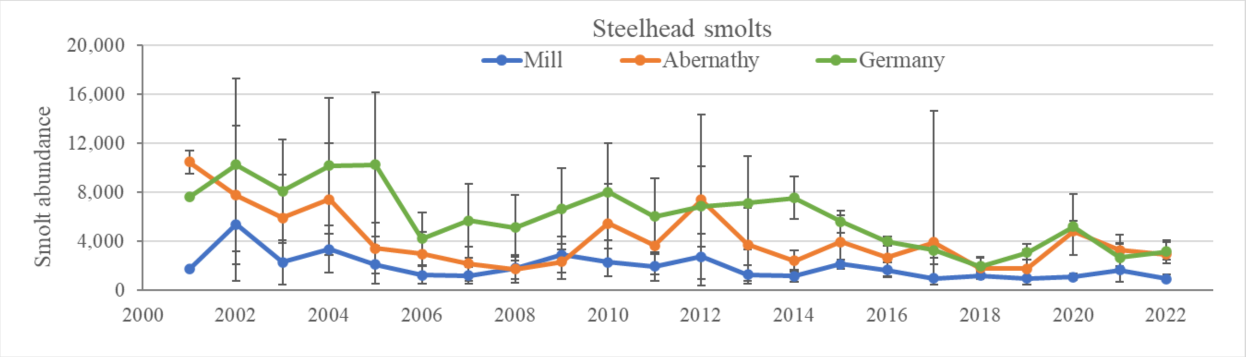


Figure 2D. *Cumulative amount of stream length treated in the Abernathy Creek basin. Fourteen projects were completed in the Abernathy Creek basin between 2012-2012, impacting nearly 12 km or approximately 33% of the habitat available to salmon and steelhead.*

Habitat treatments at the LC IMW have occurred more recently than for other IMWs supported by the SRFB. Significant restoration treatments at Abernathy Creek began in 2016 and continued through 2021. Therefore, there has been only a few years of habitat monitoring that have occurred post-restoration. Given that other IMWs (Asotin, Straits) have found that full expression of habitat response to restoration treatments often requires a long period, it is not surprising that habitat monitoring at LC IMW has not detected a positive habitat response to date. In addition, habitat monitoring at all IMWs has indicated unexpectedly high interannual variability in several fish habitat metrics in all watersheds and at many survey sites. At many sites, interannual variability was greater than the estimated effects of restoration. As a result, the anticipated habitat change from restoration treatments is often less than habitat varies among years due to natural processes. This variability may be masking habitat response to restoration at the LC IMW even though over 30% of the stream length accessible to salmon and Steelhead has received restoration treatments.

Prior to the application of restoration treatments, Abernathy Creek, where most restoration has occurred, typically produced fewer Coho smolts than Mill Creek. Since 2018, however, Coho smolt production from Abernathy Creek has exceeded production from Mill Creek (Fig. 3D), suggesting a possible response to restoration treatments, although there is not yet enough data to statistically verify that that an increase in smolt production has occurred. Additional monitoring over the coming years will be required. For steelhead, Germany Creek has produced the most smolts annually in the time series among the three basins. However, starting in 2017, smolt output in Abernathy Creek has matched the output in Germany Creek. There has been no indication to date that restoration treatments have increased Chinook production relative to the reference watershed (Fig. 3D).





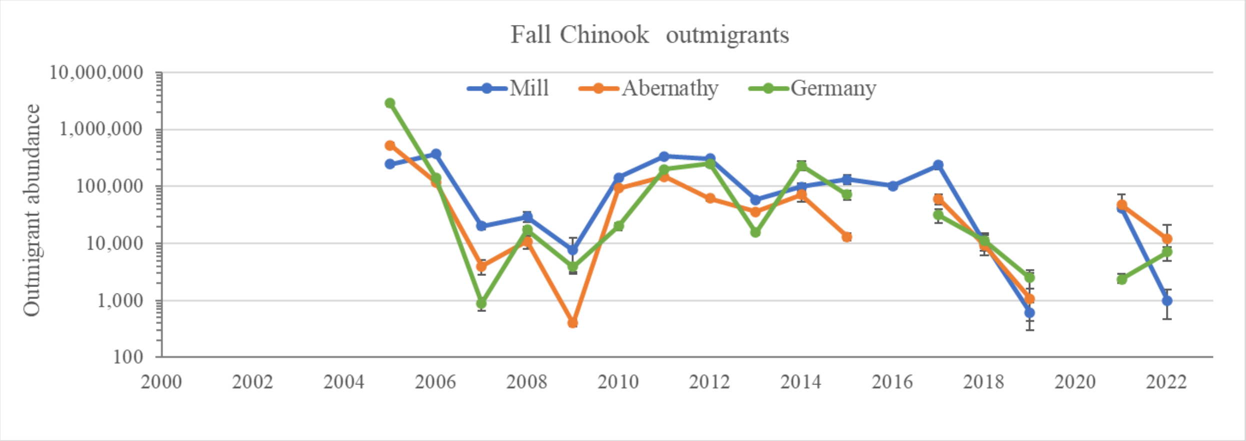


Figure 3D: *Time series of Coho, Steelhead and Chinook smolts from the three Lower Columbia IMW watersheds.*

As with results at the other IMWs, barrier removal was found to generate an immediate and substantial fish response. In the Abernathy Creek basin, a passage barrier was removed on Sarah Creek in 2019. The barrier was a natural feature and passage for salmon and Steelhead was provided by constructing an engineered log jam to raise downstream water level. In 2020, 13 live Coho Salmon and 12 redds were observed above the barrier. The number of spawning fish in this reach increased to 64 in 2021. Redds observed in 2020 and 2021 above the barrier represented 4-8% of the basin's total Coho Salmon redds.

There is clear evidence that parr-smolt survival of Coho Salmon is density dependent, suggesting freshwater habitat during summer and winter is limiting productivity (LCRB 2016, Lamperth 2021, Anderson this volume). Survival rates of juvenile Coho Salmon from parr to smolt decline sharply with increase in summer parr abundance. This pattern was observed in all three LC IMW watersheds (Fig. 4D), although the evidence of density dependence appears stronger in Abernathy and Germany creeks than it is in Mill Creek.

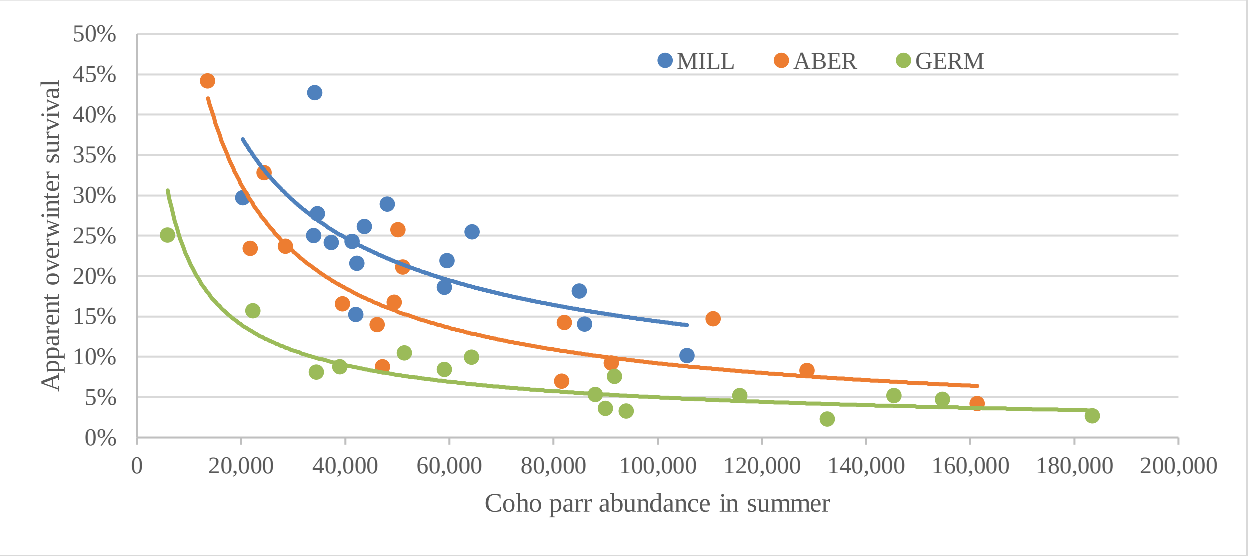


Figure 4D. *Juvenile coho apparent overwinter survival as a function of parr abundance, brood years 2004-2019. This plot demonstrates density-dependent survival of coho that overwinter in the LC-IMW Streams. Density dependent relationships suggest habitat is limiting productivity.*

Chinook Salmon also exhibit strong density dependence. Chinook Salmon, may emigrate from the IMW watersheds as either fry, leaving shortly after emerging from the gravel, of as parr, spending a month or more in the study watersheds before emigrating. The proportion of fish leaving as parr decreases as juvenile density increases (Fig. 5D). As with Coho, this pattern suggests that habitat in the IMW watersheds is limiting Chinook productivity.

The presence of strong density dependance in the LC IMW watersheds indicates that are capacity of these systems to rear juvenile salmon and Steelhead is being limited by the amount of suitable habitat. Therefore, if restoration is successful at providing additional suitable habitat, we would expect to see a positive fish response (Roni et al. 2010).

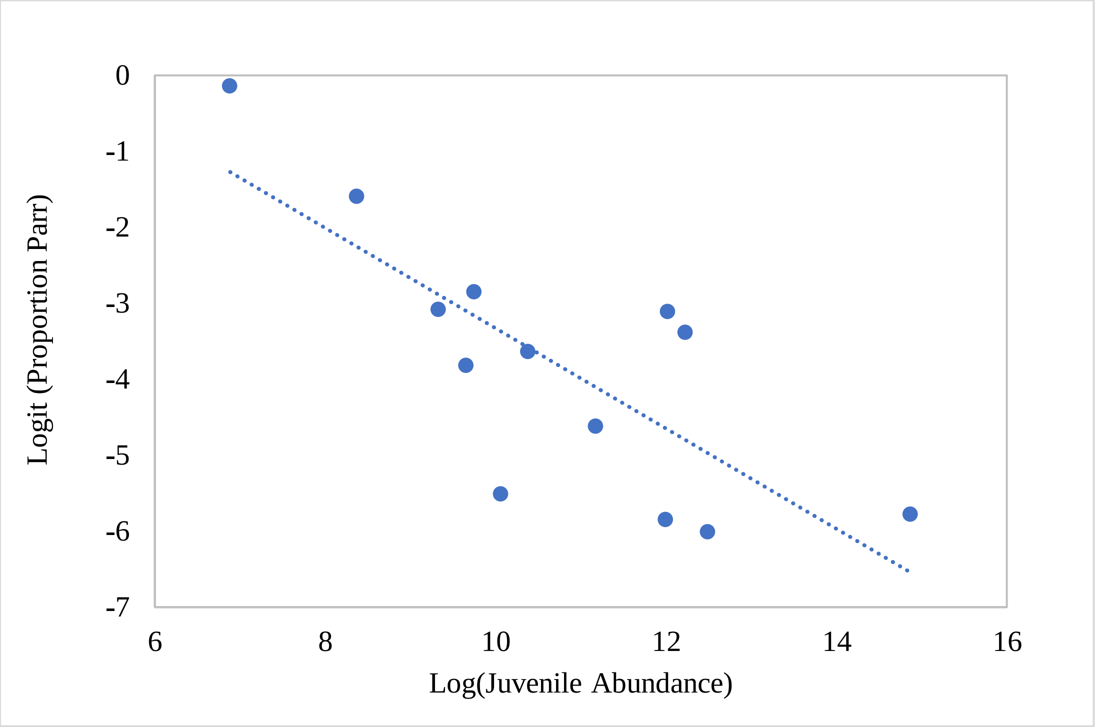


Figure 5D. *The relationship between the proportion of subyearling Chinook that exhibit extended residency in the natal stream (parr) and the total abundance of Chinook juveniles (fry + parr) in Germany Creek, brood years 2004-2017. This plot demonstrates a density-dependent relationship that affects migratory life history expression of fall Chinook. Density dependent relationships suggest habitat is limiting productivity.*

Juvenile Coho Salmon emigrate from the LC IMW watersheds during three periods. A large proportion of Coho emigration occurs as fry, the fish leaving the system within 2 months of emergence and at a small size (around 40mm). A second peak in emigration occurs in autumn. Fewer fish emigrate during this period than as fry. These fish have grown over the summer and range in size from 80mm to 90mm. The third emigration peak occurs the following spring. This consists of fish that have overwintered in the IMW watersheds and range in size from 110mm to 120mm. The relative proportion of juvenile Coho Salmon exhibiting these life histories appears to be influenced by habitat conditions (Lamperth et al. 2021).

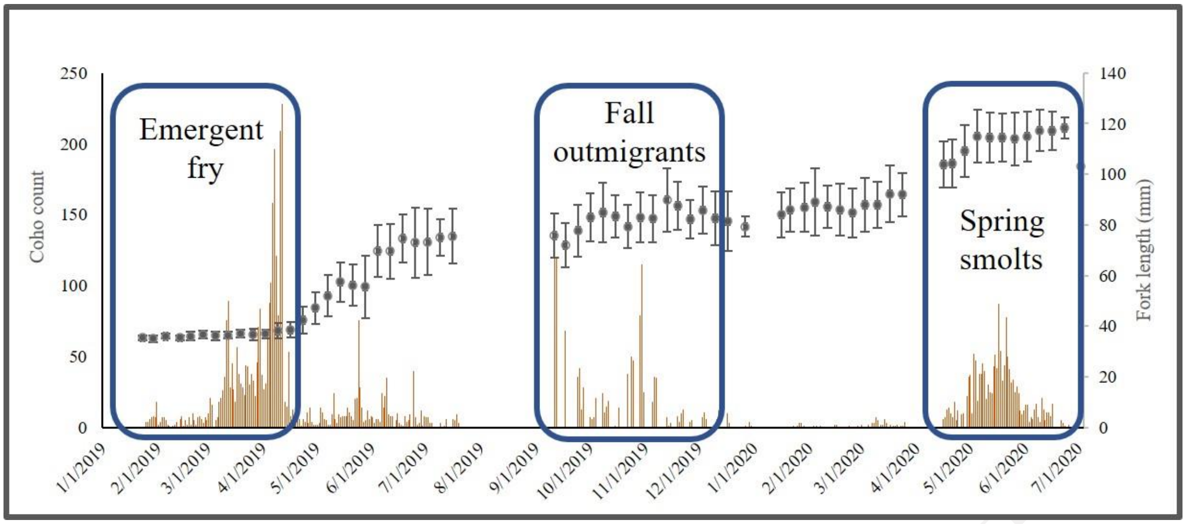


Figure 6D. *Daily counts (bars) and weekly mean ± 1SD fork length (circles with error bars) of Coho captured in the Abernathy smolt trap showing major movement periods (brood year 2018). Fall outmigrants are emigrating from their natal stream during the first year of freshwater residency. The emigration of sub-yearling Coho in fall may partially explain the overwinter survival patterns we have seen, suggesting that the expression of this life history may be affected by habitat conditions in the basin. Further investigations are warranted to better understand the fall outmigration of juvenile coho and how this life history affects our understanding of overwinter survival in natal streams, and the contribution of this life history to adult escapement.*

Tributary and headwater reaches appear to be important rearing habitats for Coho Salmon in the LC IMW watersheds (Zimmerman et al. 2015[a]).   Fish that were tagged in upper reaches of all 3 watersheds were more likely to emigrate as spring smolts that fish tagged lower in the watershed (Fig. 5D). Size of fish at tagging also had an effect of probability of a fish emigrating as a spring smolt (Fig.5D).   Spring smolts survive to adult at higher rates than fall or fry emigrants and size at smolting is positively associated with marine survival (Roni et. Al. 20011; Jones et al. 2014). These findings suggest that focusing restoration efforts in headwater areas may be an effective strategy for increasing Coho Salmon abundance.

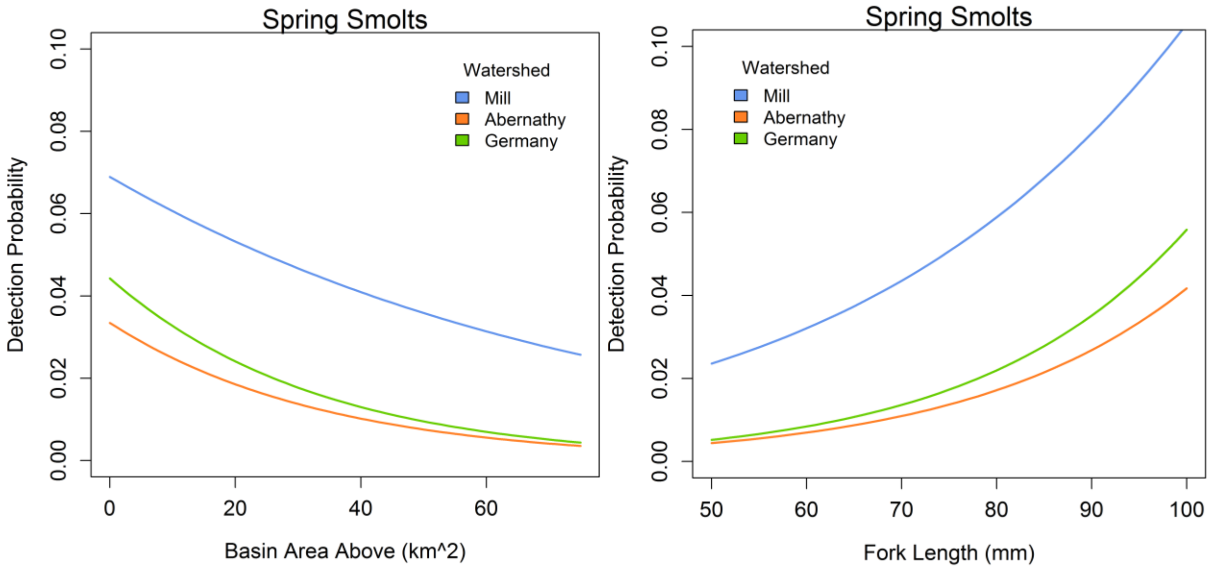


Figure 5D. *Probability of detection as a spring smolt for coho salmon based on rearing location (watershed area above sampling location) and growth (fork length in mm) the previous summer in the Mill, Abernathy, and Germany creek basins. This plot shows that the upper reaches of the LC-IMW basins are more likely to produce spring smolts, and coho that are larger at the end of the summer are more likely to be detected as spring smolts. This plot provides evidence that tributary and headwater reaches are important rearing habitats for coho.*

Marine derived nutrients from the analogs were detected in the food web following treatments and slight increases in Coho length and weight were apparent following spring additions. However, comparisons of juvenile Coho sizes and abundances between years with and without SCA application and between fertilized and unfertilized watersheds indicated that neither the fall or spring treatment had a significant effect on coho growth and survival. Many SCAs disintegrated or were washed downstream during the study, suggesting that nutrient enhancement benefits to the trophic food web were hindered by lack of retention. Future evaluations of this technique should be implemented in watersheds with nutrient retention features or coupled with other restoration treatments (e.g., beaver dam analogs) to help retain nutrients within the food web (Sturza 2017; https://cedar.wwu.edu/wwuet/597/).

Key Findings

- Nutrient enhancement treatments (e.g., Salmon Carcass Analogs, SCAs) should be implemented in watersheds with nutrient retention features or coupled with restoration treatments (e.g., beaver dam analogs) to help retain nutrients within the system. Nutrient enhancements in the form of SCAs resulted in short-term growth increases in juvenile Coho Salmon following spring treatments but did not translate to increased survival or smolt production, possibly because the nutrient subsidy did not persist in the system.

- Large-scale wood additions to improve spawning and rearing habitat concentrated in the headwaters of Abernathy Creek appear to be having a positive effect on juvenile Coho Salmon. Overwinter survival and smolt production both increased after restoration treatments, but further monitoring is needed as treatments were not completed until 2021. Steelhead and Chinook Salmon populations have not responded to treatments.

- Tributary and headwater reaches are important rearing habitat for Coho Salmon. Coho salmon tagged in upper reaches of the LC IMW watersheds were more likely be detected as spring smolts than Coho Salmon parr tagged lower in the watershed.

- Removal of a passage barrier on Sarah Creek implemented in 2019 in the Abernathy basin led to an immediate use of the blocked area by spawning Coho Salmon. By 2020-2022, 4-8% of the basin’s Coho Salmon redds were found in this previously blocked reach.

- There is strong evidence of density dependence for both Chinook and Coho salmon in the LC IMW, suggesting that, over time, both species should benefit from increasing habitat area.

- The addition of salmon carcass analogs did not result in any improvement in Coho parr survival or smolt production. Future trials of nutrient enhancement should be implemented in nutrient-poor watersheds and in conjunction with restoration treatments that will help retain released nutrients in the watershed.

Appendix E: Skagit IMW

People have invested considerable resources into restoring estuary habitats in efforts to increase capacity for migrating juvenile Chinook Salmon, but comparatively little work has evaluated outcomes for populations. The Skagit IMW examines how threatened Puget Sound Chinook Salmon use the vegetated Skagit tidal delta and how they have responded to its cumulative restoration. While the study evaluates juvenile Chinook Salmon population response to estuary habitat change, it also puts in context the effect of estuary restoration with pre-existing estuary habitat conditions. Specifically, estuary restoration projects have restored 255 hectares to tidal inundation since 2000. However, restoration gains have been partially offset by natural processes, resulting in only a net increase of 130 hectares to tidal inundation. This result illustrates the facts that (1) naturally occurring estuary habitats are not static and (2) the area of vegetated Skagit tidal delta is exhibiting an overall decreasing trend, primarily due to seaward edge erosion not being fully compensated by progradation (Hood et al 2016). Additionally, Skagit exhibits unique sub-delta trends in tidal habitat trajectory. Sub-delta trends vary due to a combination of causes primarily relating to differences in (a) the amount of restoration completed and (b) exposure to natural processes causing net habitat gains or losses. Understanding the overall and sub-delta trends are important for gaining realistic expectations of past salmon recovery efforts and more wisely planning future restoration actions to achieve sustainable long-term benefits.

The Skagit IMW is one of the first studies of its kind to demonstrate demographic changes associated with restoration actions that increase nursery habitat capacity. Leveraging three decades of monitoring before, during, and after delta restoration; in restored and unrestored forks within the delta; and in locations landward, within, and seaward of the delta; the Skagit IMW has found that:

1. Restored areas in the delta supported lower juvenile densities overall and greater juvenile densities when conspecific abundances were high. (Fig. 1E, panel A)
2. Within catches, individual juveniles using restored areas were smaller overall and their lengths declined less when conspecific competitors were more abundant. (Fig. 1E, panel B)

The study also monitored juvenile salmon in nearshore waters seaward of the delta. Following delta restoration:

3. juvenile catches in nearshore marine waters declined relative to landscape abundances (Fig. 1E, panel C), and
4. the prevalence of fry (<~45 mm) in the nearshore — a life history type thought to benefit more from delta nursery habitats — decreased overall (Fig. 1E, panel D).

Together, these findings suggest that greater nursery habitat capacity in the delta allowed salmon to spread out and accommodated higher salmon densities when juvenile emigrations were especially high. They also suggest that restoration promoted the use of delta habitats by smaller fish while alleviating competitive effects on growth. Furthermore, they suggest that greater delta habitat capacity supported more juveniles, decreasing overflow to nearshore environments, especially for the smallest, most vulnerable salmon that presumably benefit most from growth before entering nearshore waters. Thus, restoration appeared to alleviate density-dependent constraints on rearing and growth.

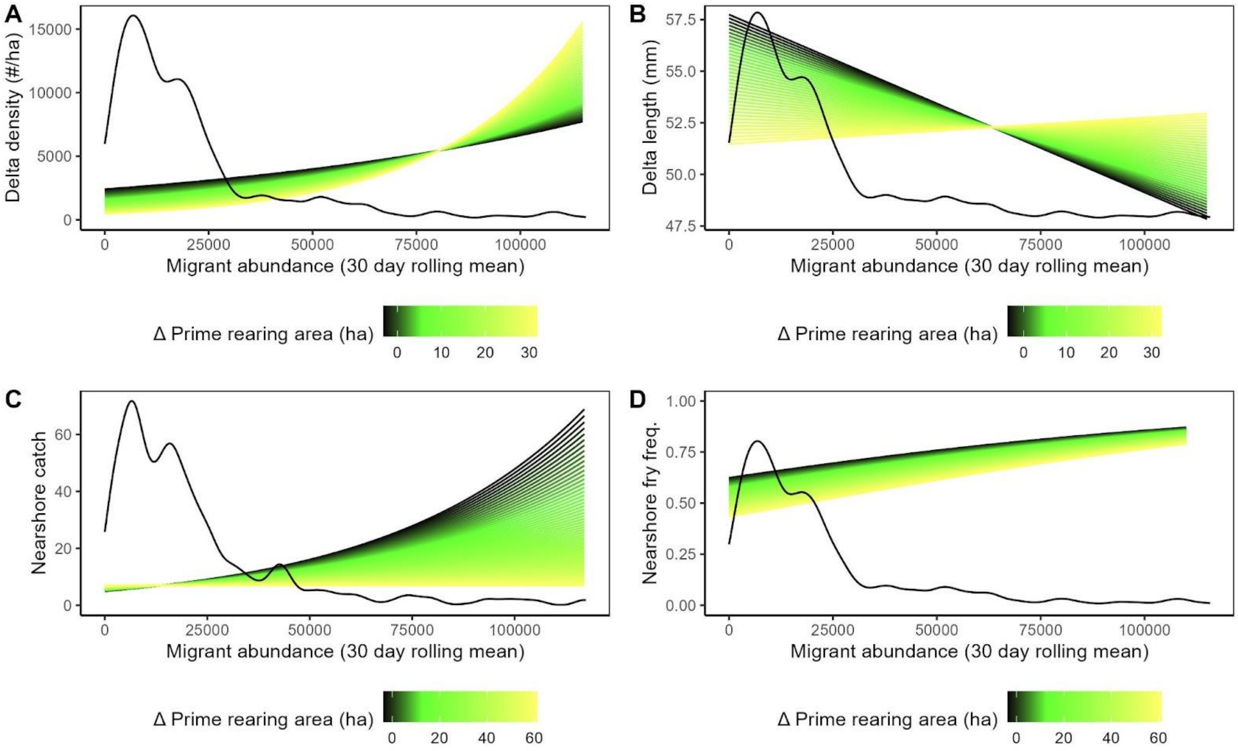


Figure 1E: *Colored lines: predictions from statistical models that examined the influence of habitat expansion (including from restoration) on juvenile salmon demographics. Models make predictions holding confounding factors such as time of year, water temperature, and spatial variation constant. The top panels demonstrate changes in populations characteristics within the tidal delta including reductions in density (A) and average body length (B). The bottom panels demonstrate demographic change of migrants captured in nearshore waters of Skagit Bay including declines in overflow abundance of Chinook (C) and the frequency of fry (≤ 45 mm) in the nearshore population (D). Black lines indicate the distribution of outmigrant abundance observations that informed the models. (Y axis for black lines not shown, but area under the line sums to one). Of note, migrant abundances were among the lower range for the overwhelming majority of observations, meaning predictions at the higher range reflect rare instances and less replication.*

These findings provide empirical support for restoring estuaries in human-stressed landscapes to rehabilitate nursery habitat functions for salmon, at least for watersheds with estuaries that are capacity limited. Replicating these findings across systems in Puget Sound and elsewhere in the Pacific Northwest is difficult for many reasons. Despite wide-spread habitat loss in tidal deltas (Brophy et al. 2021), many Chinook salmon populations have declined, thereby creating situations in which estuarine capacity limitations currently do not exist relative (Greene et al. 2021). Even within the Skagit delta, observations at the high end of the range of densities were relatively rare, making predictions of response at these high levels more uncertain (Fig. 2E). Many systems lack extensive restoration in tidal deltas or good spatial comparisons (i.e., treatment and reference areas on a demographic scale), thereby making estuary change difficult to detect. Most importantly, most watersheds lack the long-term monitoring of outmigrants, tidal delta residents, and nearshore migrants required to demonstrate potential population responses.

Of the many coastal watersheds in Washington, only one other system meets the conditions required for detection of demographic effects of estuary restoration: the Snohomish estuary. Based on the same analytic approach used for the Skagit, analysis of monitoring data from the Snohomish replicated several findings from the Skagit IMW. Of the four changes identified in the Skagit, the Snohomish revealed evidence for the latter three. Hence, in other watersheds exhibiting the combination of habitat limitations and strong density dependence, estuarine wetland restoration is likely to improve capacity through the population responses that we identified on natural-origin juvenile Chinook salmon.

Key Findings

- Increasing connectivity In the Skagit Delta expanded habitat capacity and enabled juvenile Chinook to utilize previously inaccessible areas of tidal marsh. Expansion of habitat led to multiple, positive fish responses. In this system, abundance of emigrating Chinook Salmon fry exceeds habitat capacity. Therefore, increasing habitat capacity has been a successful strategy. In other systems outmigrants are not abundant enough to fully occupy available estuary habitat. In these estuaries restoration actions that focus on density-independent sources of mortality (e.g., predation) are likely to be more effective than actions intended to increase habitat capacity.
- Blind channels were found to be an important habitat for natural-origin Chinook Salmon. Increasing the availability of blind channels would be an effective restoration strategy.
- Our analyses suggest that large hatchery releases may increase the likelihood for systems to exceed capacity and increase competition for preferred prey. Further evaluation of the effect of various aspects of hatchery releases (e.g., number released, individual size, timing, and location of releases) on natural origin juveniles is needed.

Cross-IMW Analyses

Appendix F: Effective Wood Placement Projects

There was variation in both habitat and fish response to large wood treatments among the IMWs included in the PNAMP review. The SRFB supported freshwater IMWs have detailed data on wood abundance and habitat response to wood addition. We reviewed these data for the purpose of better understanding where and how to add wood to maximize the probability of generating a positive fish response.

Wood is typically added to streams to influence hydraulics and sediment dynamics and to provide cover for fish. Wood often enhances habitat features like quantity and depth of pools and reduced width-to-depth ratios. Evaluation of wood addition projects over the last 30 years has demonstrated that this treatment can generate positive fish response. However, the PNAMP IMW review (Bilby et al. 2022) found that fish response to wood placement at IMWs in the Pacific Northwest was inconsistent. Some IMWs did report positive responses in one or more fish population metric to wood addition but other IMWs reported no detectable fish response. Because wood placement is one of the most common restoration treatments, understanding how to best utilize this restoration technique would enhance the effectiveness of regional restoration efforts.

Fish and Habitat Responses to LWD at the Freshwater IMWs

The SRFB IMWs also experienced variable responses to wood treatments. Although wood addition is often only one of several restoration actions implemented at a treated IMW site, the fact that wood placement was the dominant restoration action at a majority of treated reaches across all the SRFB freshwater IMWs provides an opportunity to contrast those wood placements associated with a positive fish response with those that did not generate a detectable response. This comparison will enable the identification of features associated with an effective wood treatment.

Several of the IMWs reported that wood projects enhanced habitat conditions and generated positive responses in some salmon and Steelhead population metrics. The Strait of Juan de Fuca IMW found that the repeated wood restoration treatments implemented over a 23-year period in a 6 km stretch of Deep Creek resulted in beneficial changes to habitat and fish populations. The wood additions enhanced capacity for the treated reaches to capture and retain wood and sediment being transported downstream. The result was increased wood loading and channel-spanning logjams, which contributed to deeper and more frequent pools, a reduction in streambed particle size, increases in sediment storage, reduced stream width, vegetation re-establishment in the riparian zone and increased development and maintenance of floodplain channels (Pess et al 2022).

Fish responses to the changes in habitat included increased juvenile Coho Salmon from less than 0.5 to over 1.25 times the survival of juvenile Coho Salmon in the West Twin River, the reference watershed (Fig. 1F). There also are indications that Coho productivity (smolts per spawner) increased in Deep Creek (Fig 2F). Further monitoring is required to verify this result. In addition, the proportion of yearling steelhead migrants in Deep Creek increased over time relative to West Twin River, suggesting greater survival (Hall et al. 2016).

Positive habitat and fish responses were also reported for the Asotin IMW. As with the SJF IMW, added wood was effective at capturing wood being transported downstream. The added and trapped wood formed new log jams within the treatment reach. LWD and debris jams frequency increased dramatically in treatment sections compared to controls. The increase in wood is forcing significant increases in geomorphic diversity in treated areas compared to control areas by increasing bar and pool frequency and area. Most of the geomorphic changes are happening within the existing channel; however, small increases in side-channel, back-water, and floodplain connection are occurring. The positive changes in habitat are leading to relatively consistent, statistically significant, small-moderate increases in juvenile steelhead abundance (fish/km), biomass (g/km) and smolt production (Fig. 3F) at some study sites. There have not been significant changes in growth or survival. These results suggest that the untagged portion of the population (i.e., steelhead fry <70 mm) are benefitting from the LWD additions, potentially from flow refugia or improved spawning conditions due to increased sediment storage and sorting.

Positive responses have also been reported at the Lower Columbia IMW. At Abernathy Creek, the primary treatment basin¸ thirteen restoration projects have been completed, impacting roughly 30% of the drainage network accessible to anadromous fishes. Nine of these projects relied on improving instream habitat complexity through wood addition. Habitat monitoring of treated reaches in Abernathy Creek indicated that LWD density increased following treatments and has been maintained through 2022, despite high flow events and some redistribution of wood. Before wood additions (brood years 2004-2015), average annual production of Coho smolts was highest in Mill Creek, the reference watershed (11,852 ± 2,979 SD) (Fig. 2F). After wood addition treatments (brood years 2016-2020), average annual coho production in Abernathy Creek, the main treatment watershed, increased by 26% to 9,589 ± 1,846 SD and became the most productive stream for Coho smolts in the LC-IMW complex. Meanwhile, average annual coho production in the reference watershed decreased by 29% to 8,390 ± 2,000 SD.

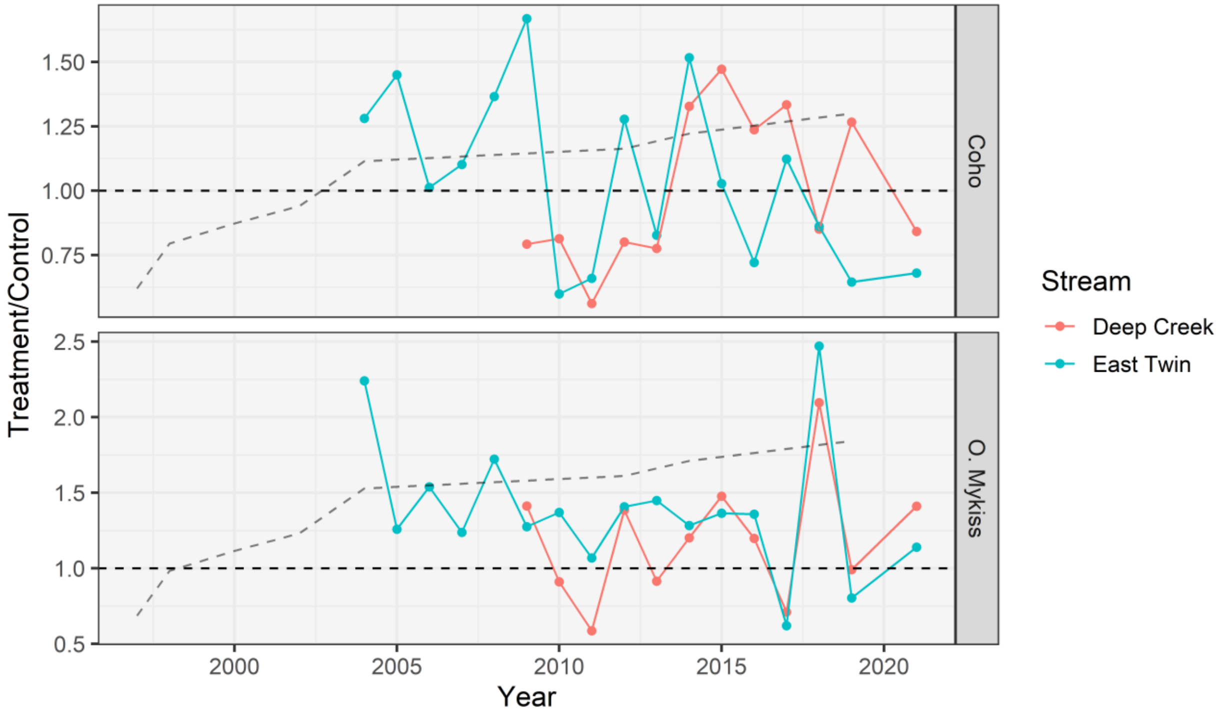


Figure 1F. *Difference between estimated (a) juvenile coho salmon and (b) steelhead survival from tagging to outmigration across passive integrated transponder (PIT) antennas by year. Hashed line denotes the level of wood additions over time. Solid dots and solid line denote relative survival differences between either East Twin River or Deep Creek and West Twin River.*

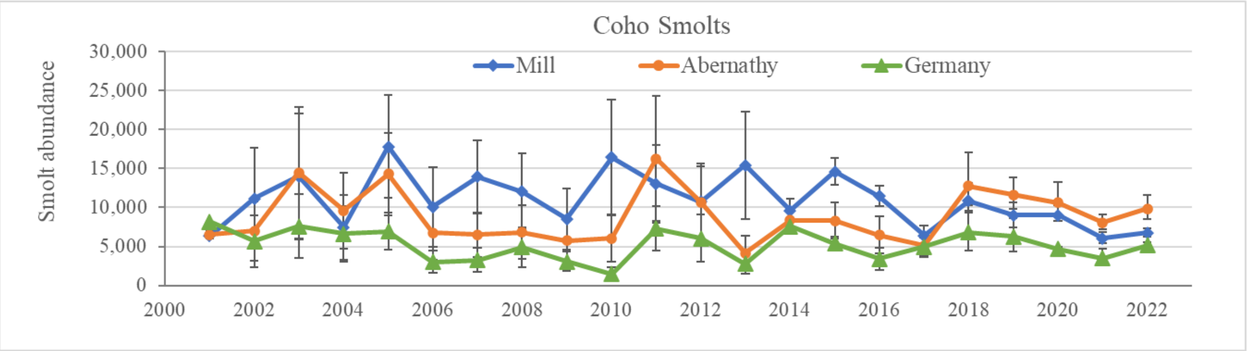


Figure 2F. *Time series of Coho smolt production from the three Lower Columbia IMW watersheds.*

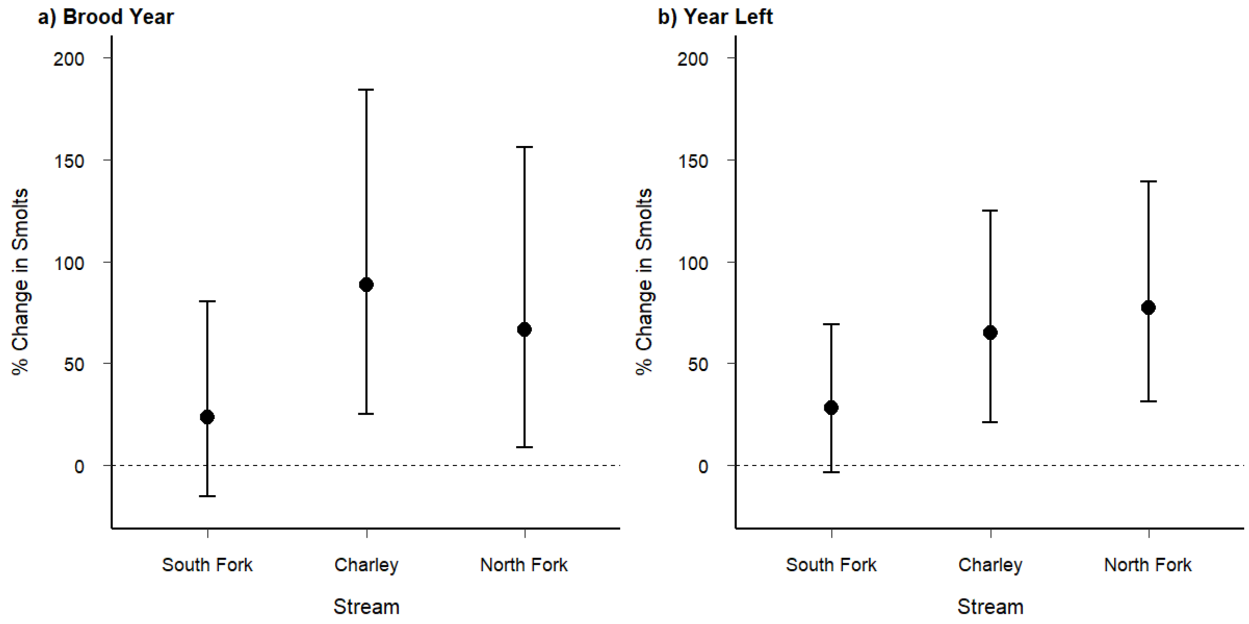


Figure 3F. *Difference in juvenile steelhead migrants (smolts/section) for a) brood year and b) year left from treatments compared to the controls pre- and post-restoration for: brood year 2008-2018, year left 2010-2020. Sections are 4 km long.*

Another IMW that has reported some success with wood treatments, although it is not a SRFB-supported IMW, is the Entiat. Responses at this IMW proved to be scale dependent. Observed effects differed from habitat scale (i.e., pool, riffle, glide) or the reach scale (i.e., hundreds of meters to kilometers). Positive Chinook Salmon responses were seen at the habitat scale at study sites in both the lower Entiat and the middle Entiat. However, fish response at the reach scale was temporary (lower Entiat) or a response was not detected (middle Entiat). This result suggests that achieving a large-scale fish response with wood treatments requires intensive treatment at large scale. This result is consistent to fish responses observed at the SJF IMW and Asotin IMW.

LWD addition has not been successful in generating a positive response from Coho Salmon at the HC IMW (Fig. 4F). However, Little Anderson Creek exhibited a very significant increase in Coho smolt production following replacement of a barrier culvert with a channel spanning bridge in 2002 (Anderson et al. 2019). Coho smolt abundance tripled from 275 ± 222 smolts for brood years 1990-2001 (mean ± SD) to 910 ± 623 for brood years 2002-2015. A LWD addition project was implemented downstream of the bridge in 2007 (25 structures total, mostly small wood) and

2 LWD projects placed wood within a 2 km reach upstream of the bridge in 2009 (10 LWD structures) and 2017 (14 LWD structures). Wood treatments applied after the culvert was replaced, however, had no detectable effect on smolt production, suggesting that these wood projects did not address the factors that were limiting Coho smolt production in this system.

Little Anderson Creek experienced a dramatic decline in Coho smolt production beginning with brood year 2017. Smolt abundance averaged 160 ± 110 fish for brood years 2017-2020, even less than the period from 1990-2001 before the culvert was replaced and far below the production levels attained in the years immediately following the culvert replacement. This decrease in production appears to have been caused by conditions near the new bridge. Although the bridge represented a significant improvement in passage compared to the culvert, it still serves as a constriction of the floodplain due to the large road fill used to construct the bridge. Since 2017, a combination of low water during autumn and beaver activity underneath the bridge has restricted upstream passage of adult salmon. No Coho Salmon redds were observed upstream of the bridge in spawning years 2018, 2020, 2021 or 2022. As a result, the LWD placement project installed above the bridge in 2017 had very little direct effect on Coho Salmon. This result emphasizes the need to inspect previously-installed projects to ensure they are still functioning as intended and periodically reassess the factors limiting salmon and Steelhead production.

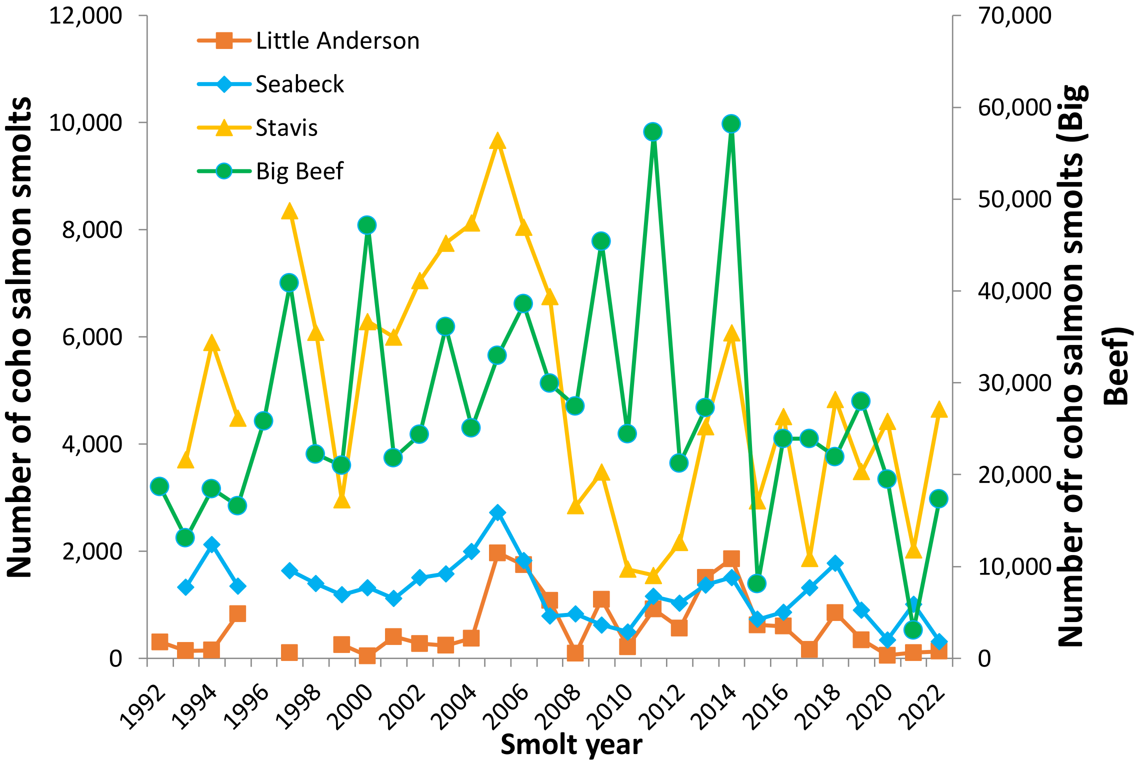


Figure 4F. Smolt abundance time series from the Hood Canal IMW. Note Big Beef Creek is plotted on the right y-axis, all other streams on the left y-axis.

Analyses of habitat metrics at the 3 western Washington freshwater IMWs found temporal trends in habitat conditions ranged from positive to none to negative, even in stream reaches with substantial restoration (Kruger et al. 2022). This result is surprising given the amount of restoration treatment applied at many of the IMW watersheds. There are several possible explanations for the lack of a consistently positive trend in habitat condition. Habitat quality may be declining as a legacy of past land use actions. For example, numerous projections of wood input suggest that the buffers on streams on commercial forest land, required since the 1980s, will not begin to make significant contributions of wood for several more decades (Welty et al. 2001). As a result, decline in habitat quality may be occurring more rapidly than can be offset by habitat improvement from restoration. Therefore, channel complexity continues to decline even in watershed receiving restoration treatments. High natural variability in some habitat metrics also may make a habitat response to restoration difficult to detect. Ranges of habitat metric values among years often exceeded estimated effects attributable to restoration. This dynamic nature of regional watersheds suggests that success is most likely if restoration actions are focused on locations with the highest potential to contribute to increased salmon production. This variation also indicates that long periods of monitoring are required to detect impacts from restoration efforts.

Key Findings

- Intensive wood treatment appears to be often associated with a response in fish abundance. Positive fish responses achieved at the IMWs were all associated with wood treatments that included 10s to 100s of wood structures over a large area. Intensive treatment is required to ensure that sufficient wood is available to modify channel form and material transport and achieve floodplain connection. Achieving sufficient intensity of treatment often requires repeated wood additions at a site over several years. A large enough area must be treated in this manner to generate a fish response that can be detected at the watershed scale.
- Habitat and fish response to wood can require a significant amount of time. Wood treatments that are associated with fish responses create an area where transported materials (wood, sediment) can collect. Over time this accumulation of materials enhances in-channel habitat diversity and establishes a more continuous connection between the channel and floodplain. This result requires that wood treatments are applied in depositional reaches and avoid high energy transport reaches.

- Monitoring the response of habitat and fish to wood placement is a long-term proposition. Habitat response and biological response to changes in habitat can require multiple years to occur. The interannual variability in both habitat attributes and fish population metrics requires lengthy annual monitoring to be able to distinguish a response to treatment from natural variation.

Appendix G: Impact of low spawner escapement on fish response to habitat restoration

Habitat restoration in the Pacific Northwest has frequently been focused on low abundance populations, in large part because of greater funding opportunities for population segments listed as threatened or endangered under the U.S. Endangered Species Act. However, if escapement levels in a watershed are sufficiently low that not enough juvenile fish are produced to occupy available habitat, increasing habitat quantity or quality through restoration may generate only small changes in abundance or survival. Therefore, detecting a fish response to restoration in watersheds with low abundance can be very difficult. The IMW data provided the opportunity to analyze this issue. We based this analysis on the 7 watersheds in the HC IMW and LC IMW. Data at these two IMWs were the most suitable for this type of analysis.

Density dependence, the ecological process by which population abundance influence rates of survival and productivity (e.g., smolts per spawner), may affect how salmon respond to restoration, or whether they respond at all. Under strong density dependence, abundance exceeds the total habitat capacity for spawning or rearing, and limitations on space or food reduce production of smolts. Under weak density dependence, total available space and food is ample to provide for the fish in the system and there are minimal habitat limitations on productivity. Density dependent processes may mask a fish response to restoration. In other words, restoration that effectively increases habitat capacity may not ultimately yield more fish if low population abundance rarely reaches the level that habitat capacity limits productivity.

Below, we examine how population abundance affects fish response to stream restoration. Using coho salmon abundance estimates from the Hood Canal and Lower Columbia Intensively Monitored Watersheds (IMWs), we fit a series of stock-recruit models to describe variation in the strength of density dependence over time, between locations, and among life stages. We test for differences in productivity and density dependence before vs. after restoration, albeit with few observations after restoration. Finally, we present a series of hypothetical restoration response models that assess our ability to detect changes in fish productivity when density dependence is strong vs. when density dependence is weak.

Methods

Study watersheds

Within the Lower Columbia IMW, Abernathy (AB) and Germany (GY) creeks are designated as treatment streams targeted for stream restoration, whereas Mill (ML) Creek is a reference stream to account for natural environmental variation unrelated to restoration. In the Hood Canal IMW, Big Beef (BB), Little Anderson (LA) and Seabeck (SB) creeks were treatment streams, and Stavis (ST) Creek was the reference stream. In both IMWs, restoration aims to improve channel complexity through LWD addition, enhance lateral connectivity to the floodplain through dike removal and improve longitudinal connectivity (passage for fish, wood and sediment) by culvert replacement. Further details on habitat conditions and a timeline of restoration actions are available in the IMW summary section above and in annual reports from both IMW complexes.

Table 1G. *Attributes of streams included in the analyses.*

Watershed	**Type**	**First year of restoration period**	**ESA status of coho salmon**
Big Beef	Treatment	2018	Not listed
Little Anderson	Treatment	2017	Not listed
Seabeck	Treatment	2022	Not listed
Stavis	Reference	NA	Not listed
Abernathy	Treatment	2017	Threatened
Germany	Treatment	2022	Threatened
Mill	Reference	NA	Threatened

Population monitoring

We estimated the abundance of coho salmon at three distinct life stages. Adult abundance in both IMWs was estimated by enumerating salmon redds via spawner surveys conducted throughout the anadromous zone. Summer juvenile parr abundance was estimated by mark-recapture. In each stream, coho salmon parr were captured at 10 spatially balanced sites sampled by electrofishing or seining in August, marked with either an adipose fin clip or PIT tag; marks were interrogated at smolt traps the following spring.   In Hood Canal, smolts were captured by channel spanning weir, providing a census count of smolt abundance. In Lower Columbia, smolts were captured by rotary screw trap, and mark-recapture approach techniques estimated smolt abundance. Additional details on monitoring methods are available in annual reports and study plans from both IMW complexes.

Stock-recruit analysis

We examined patterns of density dependence using the Ricker model, a stock-recruit model commonly used to assess fish productivity. This approach compares the abundance at one life stage (stock) to abundance at a subsequent life stage (recruit). Our comparisons addressed both the spawner to parr and parr to smolt stock-recruit relationships. In brief, the base Ricker model estimates both intrinsic productivity (ratio of recruit abundance to stock abundance) under a scenario of no density dependence, and the rate at which productivity declines with increasing stock size (density dependence).

Our analysis had three components. First, we evaluated the overall pattern of density dependent productivity by comparing the Ricker model to a density independent model that did not account for density dependence. Additionally, for each site and each year, we calculated the strength of density dependence as the proportional deviation from the intrinsic productivity accounting for density dependence, as predicted by the Ricker model at the observed stock abundance (Fig 1G, panel C). Visual inspection of the resulting Ricker stock-recruit curves provided an additional means of assessing the annual variation in the strength of density dependence. Observations on the linear portion of the curve near the origin indicate weak density dependence, whereas observations at or near the maximum number of recruits (Rmax) indicate stronger density dependence (Fig 1G, panel B).

Second, we tested for response to restoration by examining whether there was evidence for changes in intrinsic productivity and density dependence according to Ricker curves before vs. after restoration. This test was performed for both the spawner to parr and parr to smolt life stages but restricted to the three watersheds with at least three years of “after restoration” observations (Big Beef, Little Anderson and Abernathy creeks). To determine whether the reference streams improved model performance, we compared restoration response models with and without residuals from the base Ricker fit to either Stavis (Hood Canal) or Mill (Lower Columbia) creeks.

Finally, to visualize our ability to detect changes in the stock-recruit curve attributable to restoration, we compared base Ricker fits from the before restoration period to two different hypothetical curves. The first hypothetical scenario was a 30% increase in density independent intrinsic productivity. The second scenario was a 30% increase in Rmax, where restoration increased habitat capacity. We calculated 90% confidence intervals from the standard error of the base Ricker fits, and then applied the same standard error estimates to create 90% confidence intervals around the hypothetical curves. We inferred that comparisons with *separation* between the confidence bands of the before restoration base Ricker and the curves presented a greater opportunity to detect a response to restoration than curves with more *overlap*. Under this approach, cases where either A) the Ricker model did not fit the observed recruit data well (lots of noise) or B) ranges of stock (x-axis) abundance with few observations, would tend to produce wider confidence bands, and hence reduce the ability to detect a restoration response.

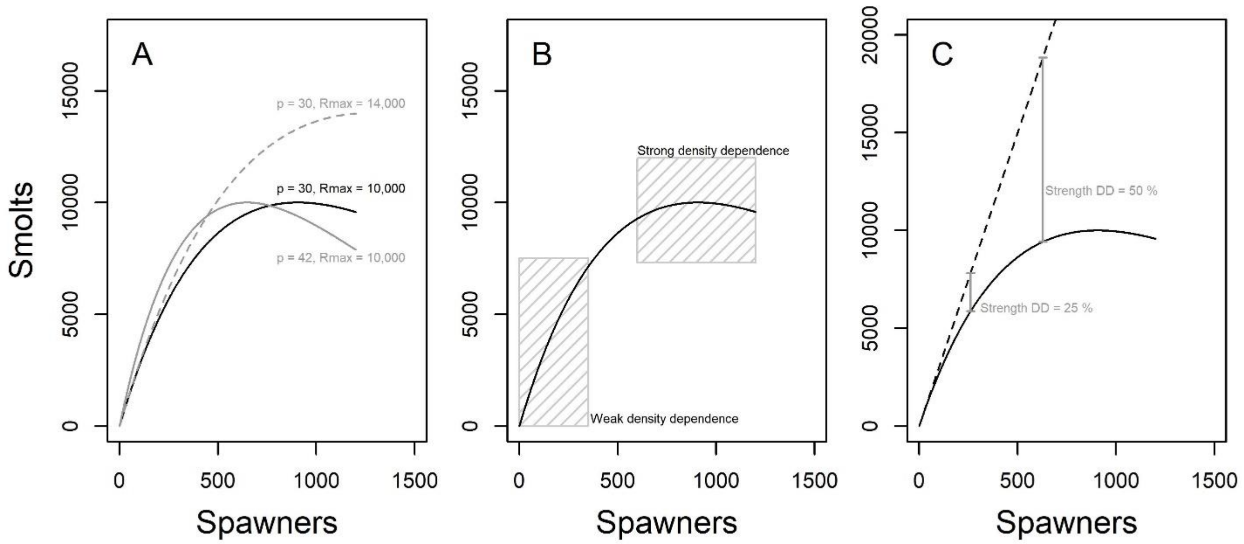


Figure 1G. *Conceptual diagram of stock-recruit curve, expressed in terms of a) intrinsic productivity p and maximum number of recruits Rmax b) b0 and b1 parameters and c) strength of density dependence.*

Results

Across all watersheds and years, there was strong support for the Ricker density dependent model over the density independent model for both the spawner to parr and parr to smolt life stage transitions (Tab. 2G, Figs. 2G, 3G). However, we also observed great variation in the strength of density dependence by year and stream. Annual estimates of density dependence were stronger in Lower Columbia than Hood Canal at both the spawner to parr and parr to smolt life stages (Fig 4G). The exception was Little Anderson parr to smolt, which was comparable in strength to the Lower Columbia estimates. Within each complex, the median annual strength of density dependence was similar between life stages, although the range across years was greater at the parr to smolt life stage (Fig. 4G).

The Hood Canal and Lower Columbia complexes also had some notable differences in the appearance of the observed data relative to the base Ricker stock-recruit curves (Fig 2G, 3G). At both the spawner to parr and parr to smolt stages, annual observations in Hood Canal BB, LA, SB, and ST tended to be located on the portion of the base Ricker model characterized by weak density dependence (Figs. 2G, 3G). By contrast, observations in the Lower Columbia watersheds were more often located along the curvilinear portion of the base Ricker model indicating that density dependence reduced per capita productivity (Fig 2G, 3G). The BB, SB, and ST spawner to parr and SB parr to smolt curves appeared to have only one or two observations anchoring the density dependence portion of the stock-recruit curves (Figs. 2G, 3G). The BB parr to smolt curve was nearly linear in appearance (Fig 3G) indicating little evidence of density dependence.

Table 2G**.** *Tests for density dependence across all watersheds. Within each stream and life stage, models with the lowest Akaike's Information Criterion (AIC) have the most statistical support.*

Life stage	**Model**	**AIC**	**ΔAIC**
Spawner to parr	Ricker	255.3	--
Spawner to parr	Density independent	279.4	24.1
Parr to smolt	Ricker	156.3	--
Parr to smolt	Density independent	244.1	87.8

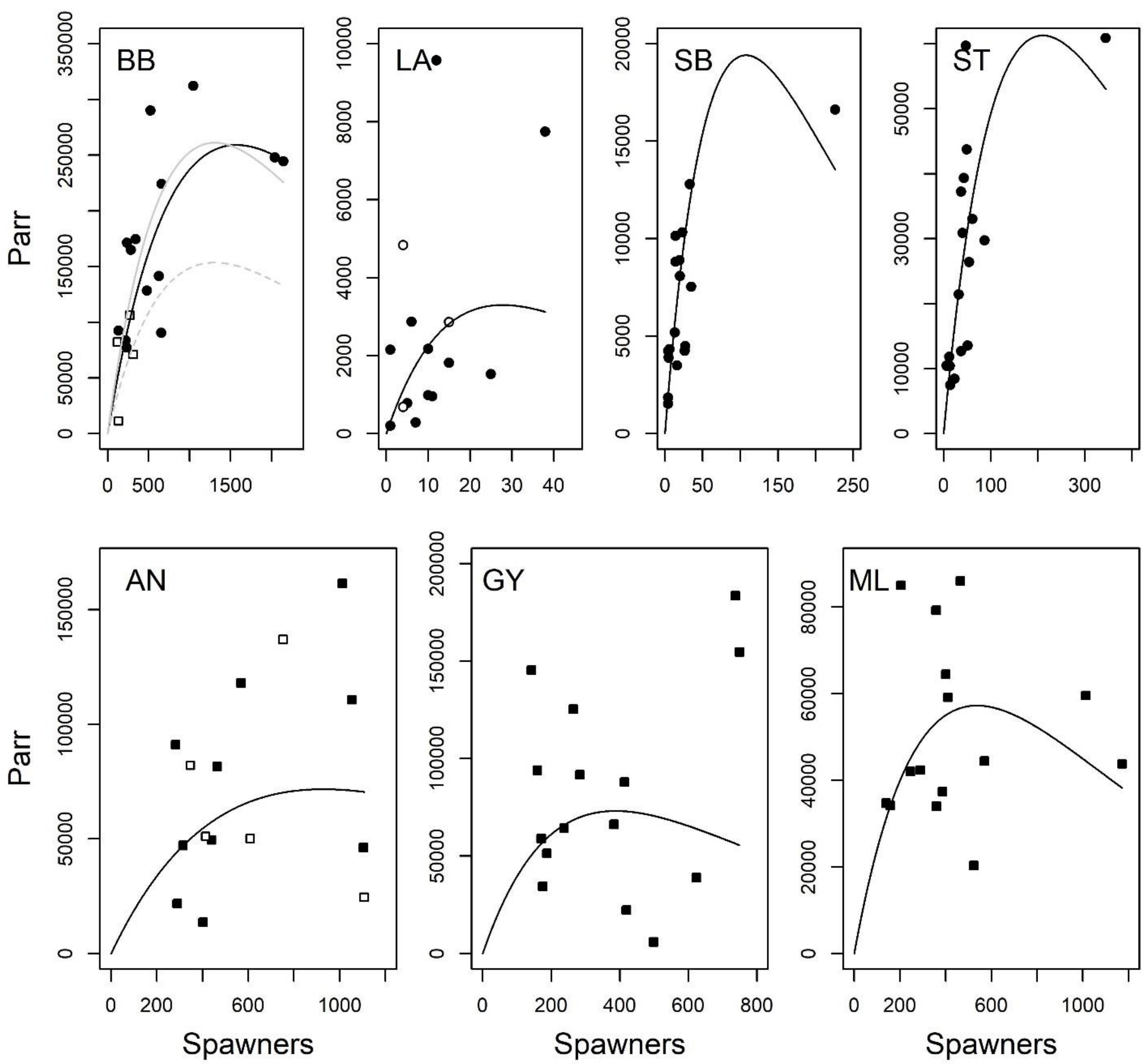


Figure 2G**.** *Spawner to smolt stock-recruit in Big Beef (BB), Seabeck (SB), Little Anderson (LA), Stavis (ST), Germany (GY), Abernathy (AN) and Mill (ML) creeks . The black line represents the base ricker model fit to all years. Filled symbols represent years before restoration, open circles represent years after restoration. Solid gray line represents the top restoration model before restoration, with the dashed line the fit after restoration.*

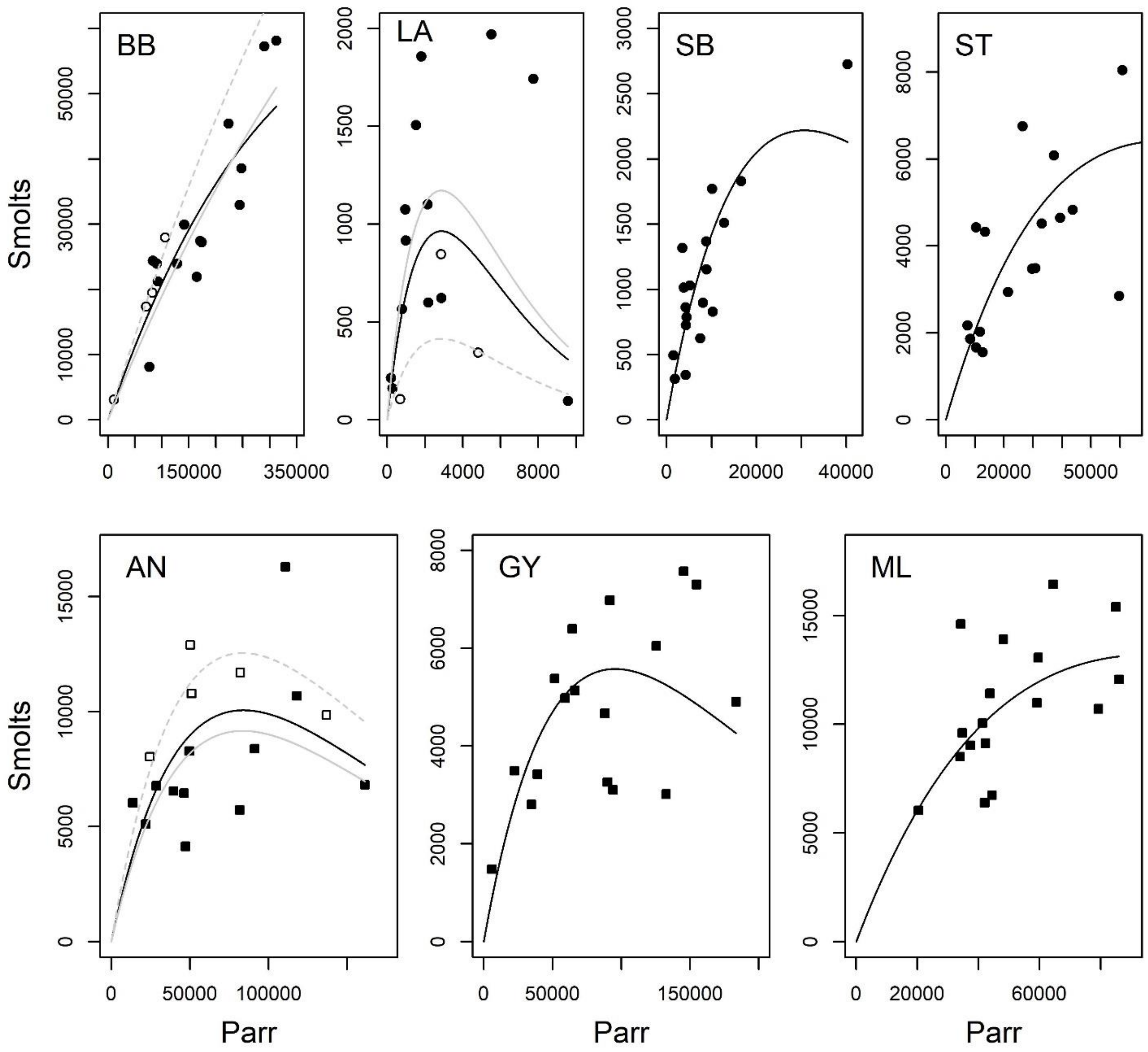


Figure 3G. *Parr to smolt stock-recruit in Big Beef (BB), Seabeck (SB), Little Anderson (LA), Stavis (ST), Germany (GY), Abernathy (AN) and Mill (ML) creeks. The black line represents the base Ricker model fit to all years. Filled symbols represent years before restoration, open circles represent years after restoration. Solid gray line represents the top restoration model before restoration, with the dashed line the fit after restoration.*

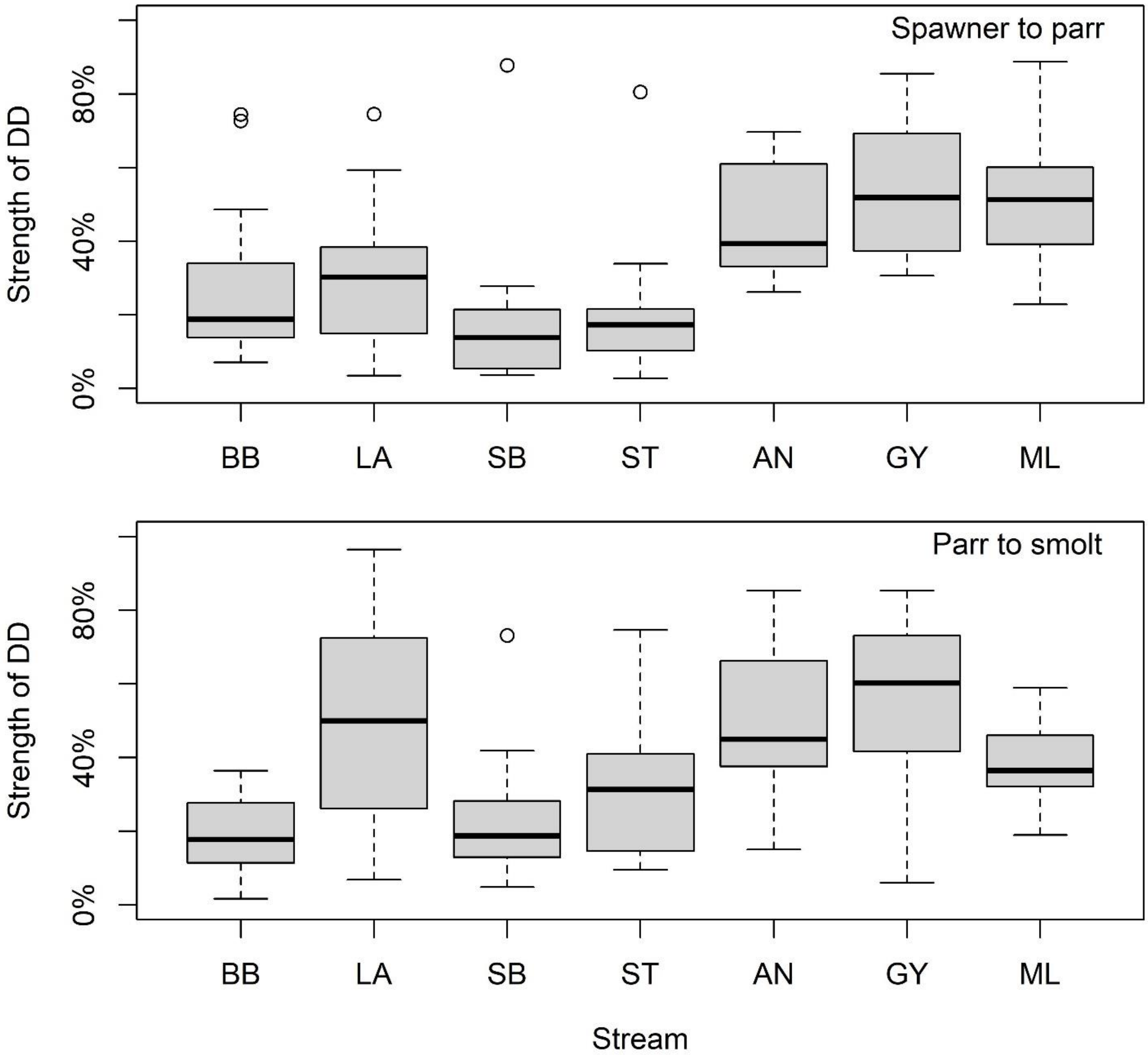


Figure 4G. *Strength of density dependence (according to Fig 1c), in the spawner to parr (top panel) and parr to smolt (bottom panel) life stages.*

In some streams, models which evaluated productivity before vs. after restoration performed the best (Tab. 2G). Assuming restoration altered productivity produced the top model for Big Beef spawner to parr, Big Beef parr to smolt, Little Anderson parr to smolt and Abernathy parr to smolt. However, in all of these cases the restoration model was statistically very similar to the base Ricker assuming no restoration effect (ΔAIC < 2, Tab. 2G). Surprisingly, productivity appeared lower in the post-restoration period in Big Beef for spawner to parr and Little Anderson for parr to smolt (Figs. 2G, 3G).

Productivity appeared to increase in the restoration period for both Big Beef and Abernathy parr to smolt, but interestingly the two creeks differed in the locations of the stock-recruit curve where post-restoration change was observed. In Big Beef Creek, the parr to smolt observations after restoration occurred on the linear portion of the curve near the origin characterized by weak density dependence and resulted in relatively small increases smolt abundnacce. In Abernathy Creek, after restoration observations occurred at or near the maximum recruit value (R_{max}), and the after restoration smolt production values were among the highest observed in the time series. Inclusion of the reference watershed predictor improved fits in Little Anderson Creek but not Big Beef or Abernathy creeks (Tab. 3G).

Table 3G. *Top three models for each life stage and stream in the restoration assessment. These models include residuals from baser Ricker model fit to the reference watershed in each complex. Within each stream and life stage, models with the lowest Akaike's Information Criterion (AIC) value have the most statistical support. Models with ΔAIC ≤ 2 are very statistically similar to one another.*

Stream	**Life stage**	**Model**	**Reference**	**AIC**	**ΔAIC**
Big Beef	Spawner to parr	restoration alters productivity	No	32.8	--
		restoration alters productivity	Yes	33.1	0.3
		base Ricker	No	33.7	0.9
	Parr to smolt	restoration alters productivity	No	6.7	--
		base Ricker	No	7.3	0.6
		restoration alters DD	No	7.4	0.7
Little Anderson	Spawner to parr	base Ricker	Yes	47.4	--
		base Ricker	No	48.8	1.4
		restoration alters DD	Yes	49.2	1.8
	Parr to smolt	restoration alter productivity	Yes	32.4	--
		restoration alters productivity & DD	Yes	33.1	0.7
		base Ricker	Yes	35.4	3.0

Abernathy	Spawner to parr	base Ricker	No	35.8	--
		base Ricker	Yes	36.5	0.7
		restoration alters productivity & DD	No	37.0	1.2
	parr to smolt	restoration alters productivity	No	15.1	--
		base Ricker	No	16.5	1.4
		Restoration alters productivity & DD	No	16.8	1.7

For most watersheds, the hypothetical restoration response curves generally showed greater separation (less overlap) from the base Ricker curves at the parr to smolt compared to spawner to parr life stages (Figures 5G, 6G). Furthermore, at both life stages, the 30% increase in Rmax tended to show greater separation from the base Ricker curve than the 30% increase in intrinsic productivity. However, Big Beef Creek was an exception to this pattern, as increased parr to smolt productivity curve showed greater separation from the base Ricker than the 30% increase in Rmax curve. This was notable because the observed Big Beef base Ricker showed weak density dependence (Fig 4G), in contrast to most other curves (Fig 5G, 6G). Among all hypothetical curves, the Little Anderson, Abernathy and Germany parr to smolt curves tended to show the most separation from the base Ricker, which also were watersheds with relatively strong density dependence (Fig 4G).

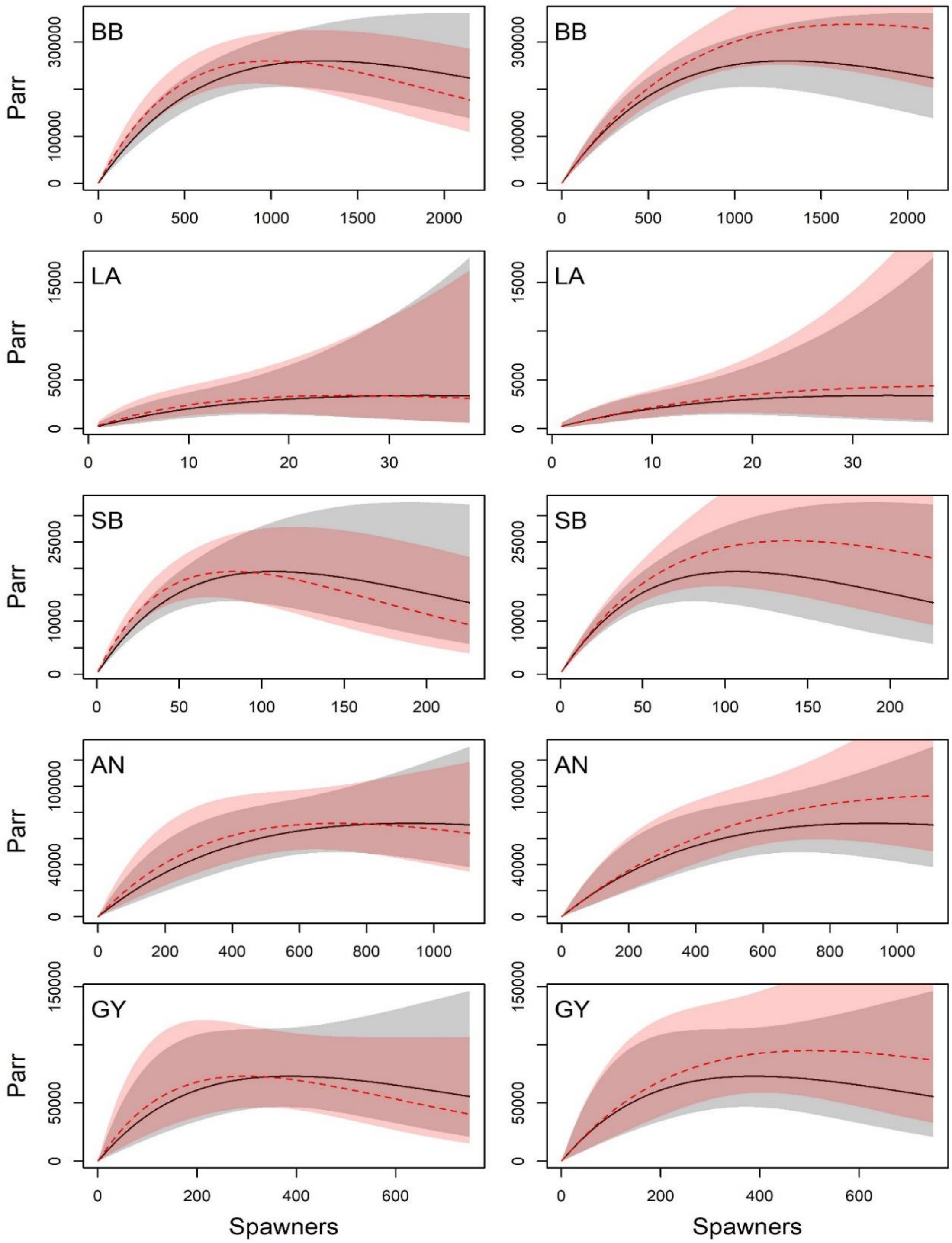


Figure 6G. *Hypothetical parr per spawner restoration stock-recruit curves in Big Beef (BB), Little Anderson (LA), Seabeck (SB), Abernathy (AN), and Germany (GY) creeks. The black solid line with gray 90% confidence bands represents the base Ricker fit from the before restoration period. The red dashed line with red 90% confidence bands represents a hypothetical 30% increase in intrinsic productivity (left column) or a 30% increase in the maximum number of recruits (right column), assuming the same standard error as the base Ricker pre-restoration fit.*

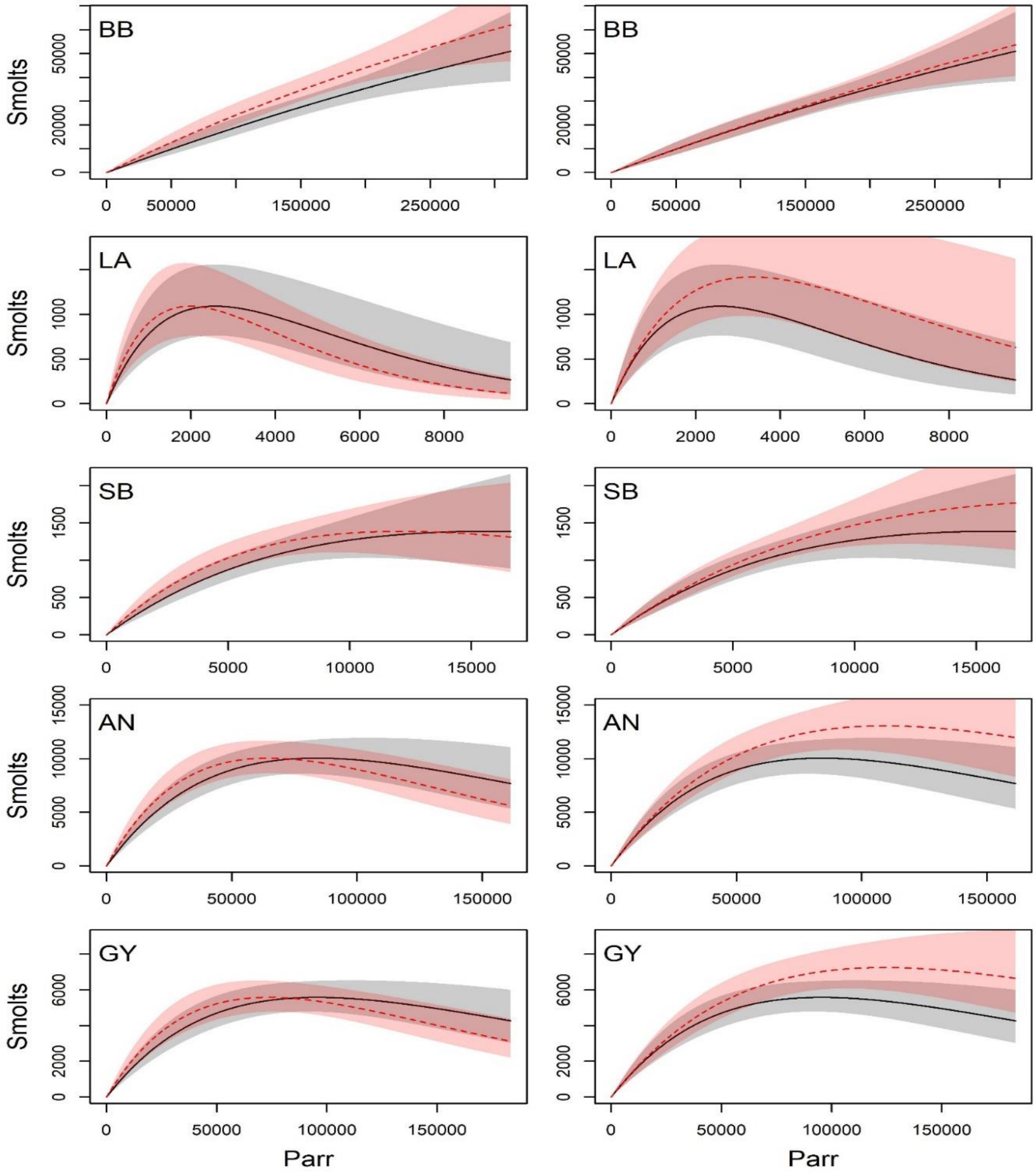


Figure 7G. *Hypothetical smolt per parr restoration stock-recruit curves in Big Beef (BB), Little Anderson (LA), Seabeck (SB), Abernathy (AN), and Germany (GY) creeks. The black solid line with gray 90% confidence bands represents the base Ricker fit from the before restoration period. The red dashed line with red 90% confidence bands represents a hypothetical 30% increase in intrinsic productivity (left column) or a 30% increase in the maximum number of recruits (right column), assuming the same standard error as the base Ricker pre-restoration fit.*

Our analysis focused on Coho salmon. However, results from the Asotin IMW suggest that the strength of density dependence effects in Steelhead in some systems may be difficult to assess. Abundance of adult Steelhead at the Asotin IMW had little apparent impact on emigration of juvenile and smolt Steelhead, despite low spawner abundance some years (Figs. 8G, 9G). This lack of relationship is likely due to a significant number of smolts being produced from resident Rainbow Trout adults. Therefore, strength of density dependence is a product of the combined abundance of anadromous and resident populations.

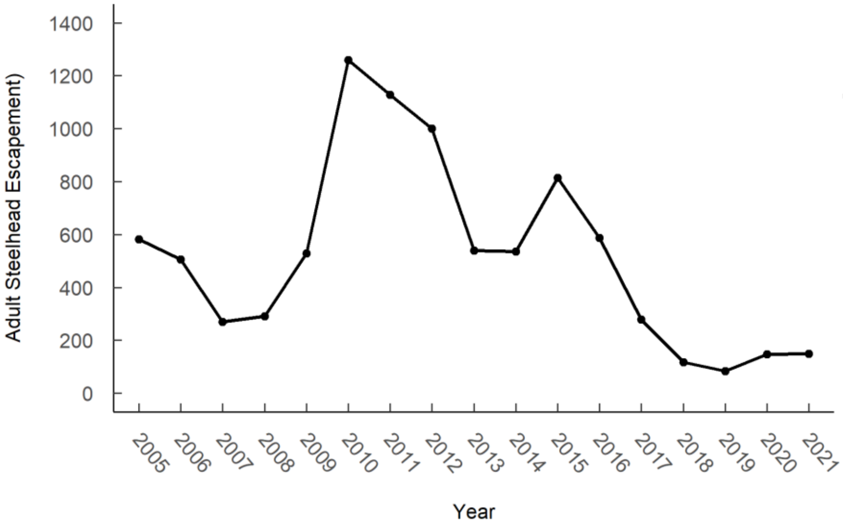


Figure 8G. *Adult steelhead escapement in Asotin Creek mainstem as determined by WDFW fish-in fish-out adult weir captures and PIT tagging: 2008-2021.*

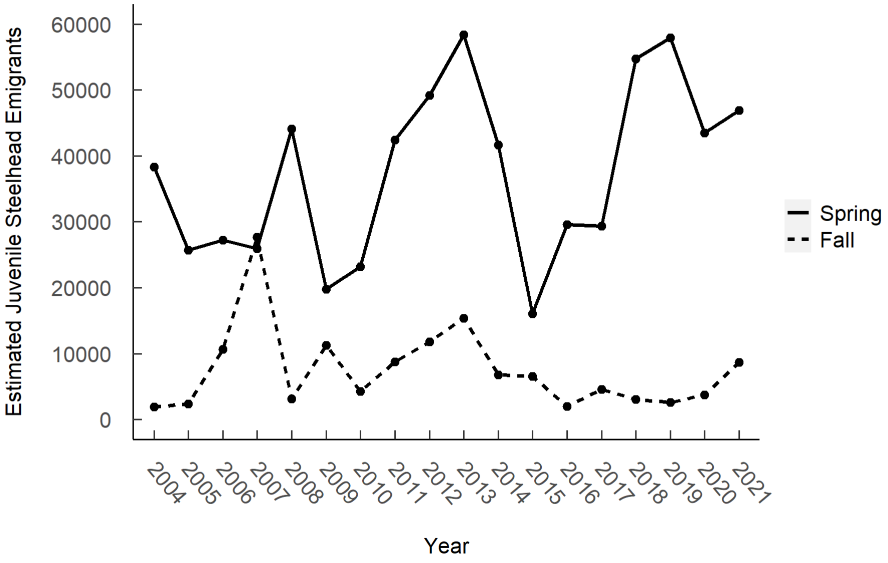


Figure 9G. *Juvenile (≥ 70 mm steelhead emigrants from Asotin Creek as determined by WDFW rotary screw trap captures, PIT tagging, and population estimates (Herr et al. 2021). Estimates include emigration from Asotin Creek.*

Discussion

Our evaluation of stock-recruit curves in the Hood Canal and Lower Columbia IMWs revealed that the strength of density dependence varied substantially variation across streams and through time. Furthermore, a combination of observed data and examination of hypothetical increases in productivity indicated that generating and detecting a fish response to restoration is most likely when density dependence is strong. Management strategies that ensure sufficient adults spawn to saturate available habitat will enhance the effectiveness of habitat restoration efforts.

We found a clear contrast in the strength of density dependence between the Hood Canal and Lower Columbia IMWs. In Hood Canal, we observed many years with relatively weak density dependence, and only a few years with strong density dependence. In Lower Columbia, most years had stronger density dependence than Hood Canal, and spawner values were typically in the range of the estimated Rmax.

Our empirical assessment of response to restoration demonstrated an ability to detect changes in productivity and Rmax despite relatively few observations in the “after restoration” period. In total, four of six possible stream-life stage tests yielded a top model exhibiting different stock-recruit relationships before vs. after restoration. Abernathy parr to smolt and Big Beef parr to smolt showed higher productivity after restoration than before it, though in both cases the restoration model was only marginally better than the base Ricker without a restoration effect ($\Delta AIC < 2$). Interestingly, Abernathy Creek exhibited higher productivity after restoration under strong density dependence whereas the increase in productivity at Big Beef Creek occurred under weak density dependence.

In two cases of our empirical restoration test (Big Beef spawner to parr, Little Anderson parr to smolt), the top model indicated lower productivity after restoration. We speculate that these results were due to the restricted spatial distribution of spawning fish observed in both creeks in recent years, as low water conditions combined with beaver activity concentrated spawning in lower reaches of both streams. Regardless, these results indicate that attributing changes in stock-recruit relationships to restoration will likely take A) more time to encompass a range of environmental conditions in the “after restoration” period and B) additional explanatory variables to account for patterns in productivity (e.g., spatial distribution). The reference stream improved model fits in some but not all cases. The use of reference streams our study design helps account for some sources of environmental noise (e.g., shared regional patterns of precipitation) but not all sources (e.g., beaver activity observed in treatment but not reference stream).

The hypothetical restoration curves (Figs. 6G, 7G) indicated that for most streams and life stages, we had a greater ability to detect a response to restoration when density dependence was strong. Little Anderson, Seabeck, Germany and Abernathy creeks all showed greater separation between the hypothetical and “before restoration” stock-recruit curves in the scenario that increased Rmax than the scenario that increased intrinsic productivity. Furthermore, in the increase Rmax scenario, the “before restoration” and hypothetical curves showed the greatest separation at high stock abundance (x-axis) values; abundances near Rmax and habitat capacity. Saturating the spawning grounds improves the chances of detecting a response to restoration actions that increase habitat capacity.

The exception to this pattern was Big Beef Creek parr to smolt example, where the hypothetical curve that increased intrinsic productivity showed greater separation from the “before restoration” curve than the increase in Rmax scenario (Fig 7G). In this case, the observed parr values were well below those needed to produce Rmax smolts, so the “before restoration” model had little information on capacity constraints under strong density dependence. Furthermore, it appears that that in Big Beef Creek, the strongest cases of density dependence tended to occur in the spawner to parr phase rather than the parr to smolt phase (Fig 4G). The spawner to parr hypothetical curve did show greater response to restoration in the increase Rmax scenario than the increase intrinsic productivity scenario, similar to results from the other creeks. Furthermore, Big Beef smolt production values for 3 years from the “before restoration” period in our analysis exceeded 90% of smolt abundance observations from 1978-2022 (including years prior to IMW study). Thus, the range in spawner abundance did include values required to maximize smolt production, but the failure of the parr to smolt models to inform smolt Rmax was because density dependence had already occurred before the parr stage.

Combined, these results suggest that high adult abundance improves the likelihood of observing a measurable response to habitat restoration in Coho Salmon. When spawner abundances are consistently low, exhibiting weak density dependence, it reduces the potential mechanisms or pathways by which restoration can benefit salmon. For example, creating more rearing space for territorial juvenile salmon through restoration is unlikely to help when abundances are too low to fully utilize habitat available prior to restoration. Implementing harvest management policies that ensure enough spawners to utilize available habitat would enhance the effectiveness of habitat restoration efforts.

Estimates of harvest rates support the stock-recruit patterns observed in our study streams. In the Lower Columbia IMW where density dependence was stronger, harvest rates averaged 14% (range 7 – 24%) from 2005 – 2021 (Pacific Fishery Management Council 2021 Review Report). In Hood Canal, where density dependence was weaker, harvest rates averaged 49% (range 24-71%) from 2003-2021 (BackFRAM model, M. Litz, personal communication). In Hood Canal, reducing harvest appears to be a more direct, immediate pathway to increasing adult abundance than habitat restoration, as the study streams appear to have greater juvenile rearing capacity than is typically utilized in most years. However, fisheries management involves complex, inter-jurisdictional governance, and harvest management objectives are set at a much larger spatial scale than IMW study sites. Furthermore, adult abundance is also constrained by marine survival, which has exhibited long term decline in Puget Sound (Zimmerman et al. 2015[b]).

Our results also emphasize important lessons for population monitoring at low abundances. Obtaining population scale abundance estimates at multiple life stages is essential because accounting for density dependence requires assessing a rate of productivity (juveniles per spawner) rather than abundance at a single life stage. A focus on juvenile life stages helps minimize the potential for observation error when adult abundance is very low. Redd surveys have variable observation probability and are especially problematic in systems with low spawner abundance (e.g., annual redd counts at Little Anderson Creek are often < 10). Juvenile life stages have higher abundance and population estimates using mark-recapture enable determination of precision. In other words, it is easier to count smolts and parr than adults because there are more of them.

The strength of density dependence in a watershed should influence restoration strategy. In systems with strong density dependence, restoration measures that increase the quantity of available habitat should be successful at increasing smolt production. Increasing pool area, enhancing connections to floodplain habitats, and removing barriers to migration are examples of restoration treatments that increase habitat availability. In systems with weak density dependence, implementing restoration treatments designed to increase habitat capacity are not likely to generate a positive fish response. Rather, the goal in systems like these should be the implementation of measures that can reduce the severity of density independent mortality factors and, thus, enhance intrinsic productivity. Measures that improve water quality or reduce mortality from predation are examples treatments that could enhance intrinsic productivity. Therefore, determining the strength of density dependence for a watershed is an important foundational element of developing an effective restoration strategy.

Key Findings

- Focus restoration efforts on watersheds that support enough adult salmon to benefit from an increase in habitat capacity. Many years the HC IMW watersheds do not have sufficient juvenile Coho Salmon to occupy available habitat. Increasing habitat quantity will likely only have modest effects on smolt abundance until escapement to these systems increases.
- In watersheds with weak density dependence restoration actions should focus on reducing the intensity of density-independent mortality factors.

- Determining juvenile capacity limits, and modifying restoration goals, accordingly, may be necessary to fully capture the benefits of habitat restoration.
- Integrating harvest and habitat actions in an “All-H” strategy remains a crucial goal for salmon recovery.

Appendix H: Correlations between habitat attributes and fish population metrics – Identification of limiting factors

Stream habitat restoration is usually preceded by efforts to identify the habitat conditions that limit the freshwater survival and productivity of salmon. The relatively modest fish response to restoration seen at many IMWs suggests that the factors controlling abundance and survival of fish populations may not be fully understood. The IMW studies provide a rare opportunity to directly assess relations between salmon population metrics (e.g., parr-smolt survival, smolt abundance) and commonly used habitat metrics (e.g., large wood density; pool frequency) over many years.

The analysis presented here is intended as an example of how these data might be used to investigate the relationships between habitat attributes and fish population performance. The habitat metrics we included in the analysis below represent a subset of the attributes that might be influencing fish production and survival. There would be considerable value in a comprehensive evaluation of the relationship between survival and smolt production and the potential factors influencing fish. These factors are not limited to habitat condition. As discussed above, salmon and steelhead production in some watersheds may be limited by the number of returning adult fish.

This analysis assessed relations between Coho Salmon smolts-per-parr (i.e., parr-smolt survival) and smolt abundance against four fish habitat metrics within each of the Hood Canal and Lower Columbia IMW streams from 2007 through 2022. We conducted this analysis using habitat data from sites on mainstem and large tributary reaches. Habitat metrics included instream very large wood density (i.e., LWD> 5 m long and > 0.3 m in diameter/100m), pool occurrence density (pct_pools), side channel occurrence density (pct_side), and median wetted stream width (wtwidth_p50).

As increasing wood, pools and floodplain habitats are common objectives of restoration efforts, we expected to find positive correlations between salmon survival and abundance and habitat metrics. Interestingly, about half of the correlations were negative, including some of the strongest correlations (Fig. 1H, 2H).

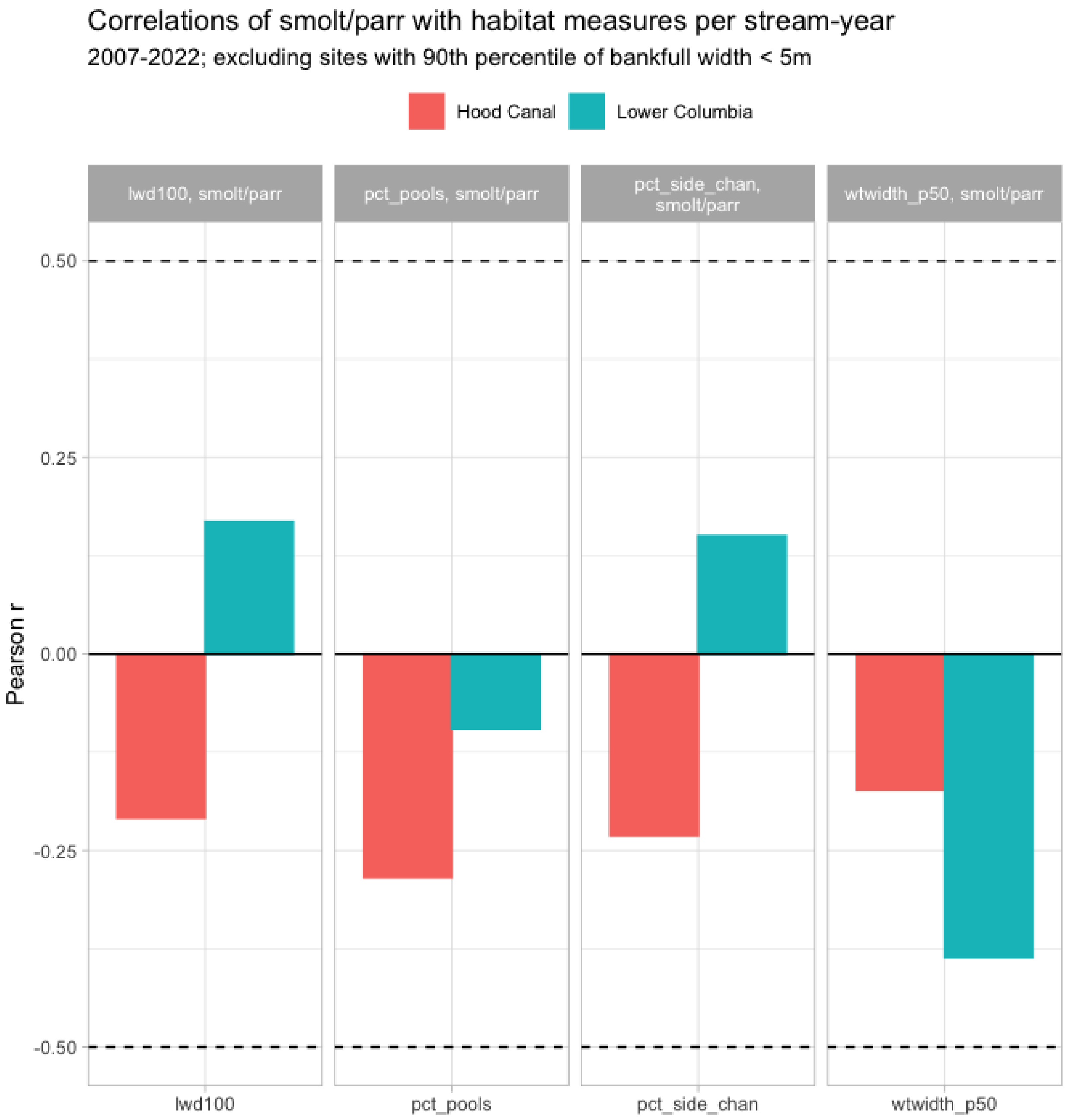


Figure 1H: *Correlation between habitat variables and parr-smolt survival for the Hood Canal and Lower Columbia IMWs. Data for all watersheds in each IMW were pooled for this analysis.*

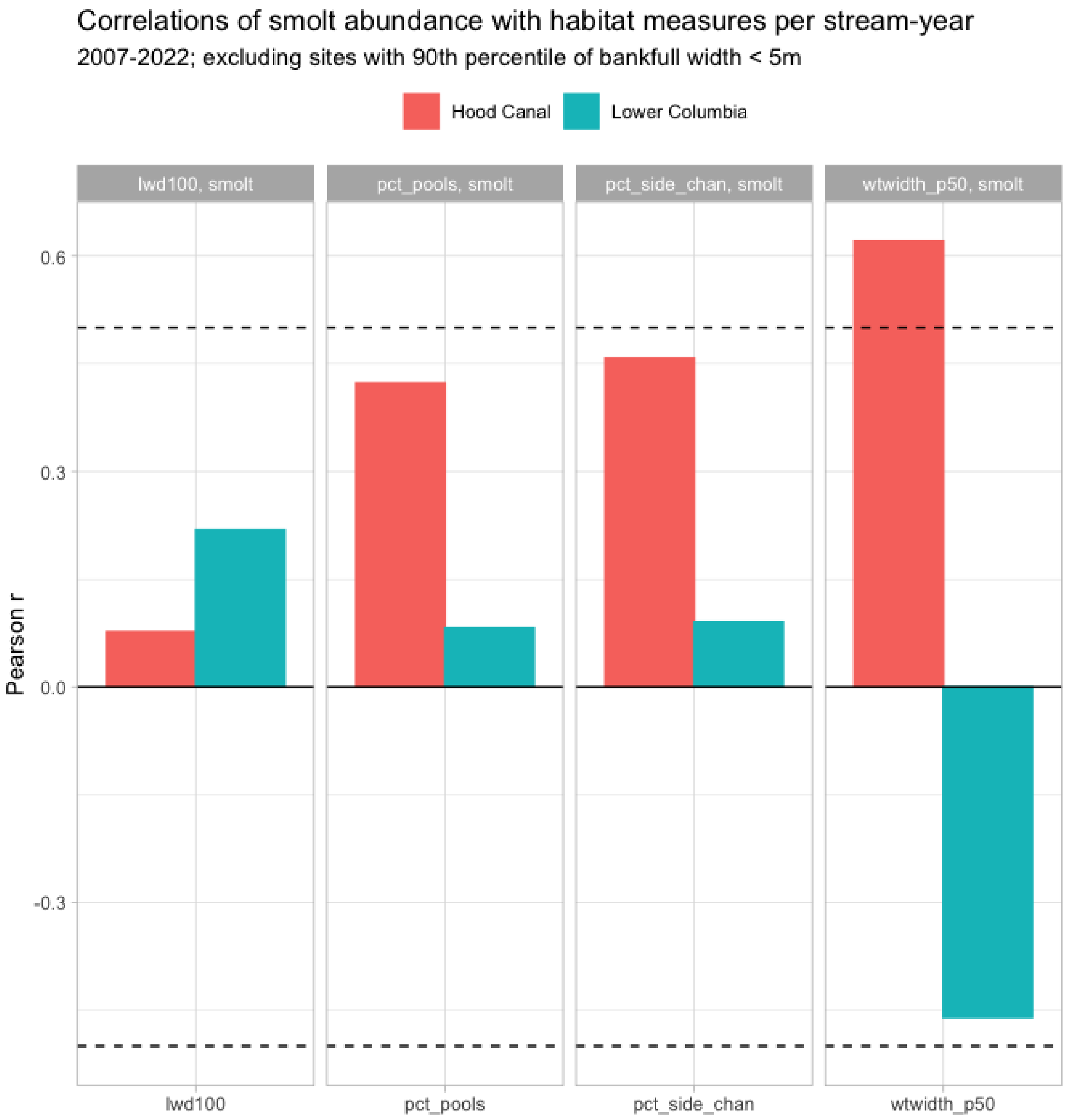
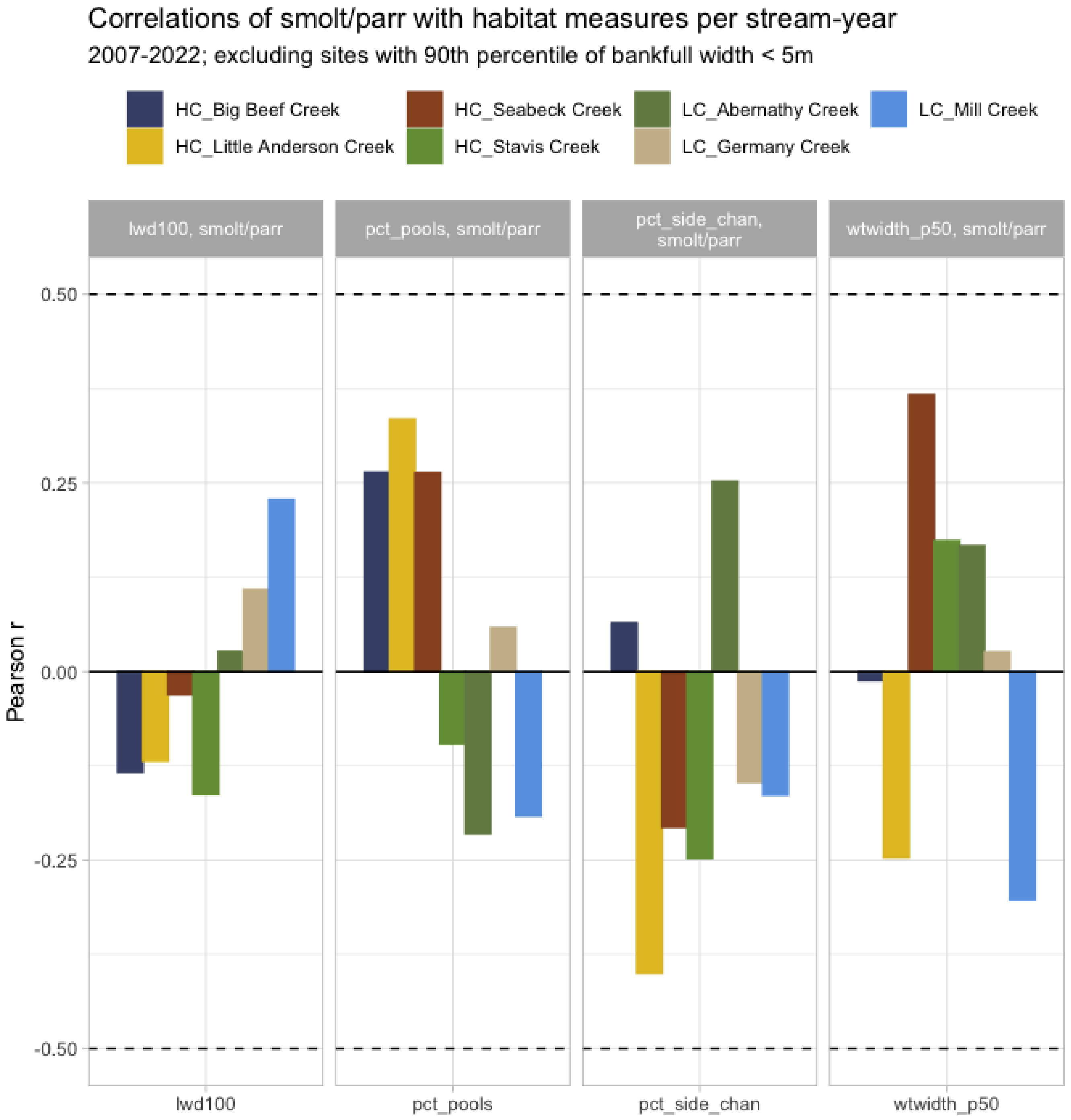


Figure 2H: *Correlation between habitat variables and smolt production for the Hood Canal and Lower Columbia IMWs. Data for all watersheds in each IMW were pooled for this analysis.*

There appears to be a great deal of variability in relationships between habitat and population variables for individual among watersheds (Figs. 3H, 4H). Relationships for individual watersheds show some relatively strong correlations between parr-smolt survival and abundance and habitat metrics. But there are also dramatic differences in fish-habitat relations among watersheds within IMW complexes, possibly because these rather simple correlations may not capture more complex, multivariate relations. However, the relationships are informative in that they suggest that +fish-habitat relations differ among watersheds.



Correlations of smolt/parr with habitat measures per stream-year

2007-2022; excluding sites with 90th percentile of bankfull width < 5m

Figure 3H: *Correlation between habitat variables and parr-smolt survival for individual watersheds in the Hood Canal and Lower Columbia IMWs.*

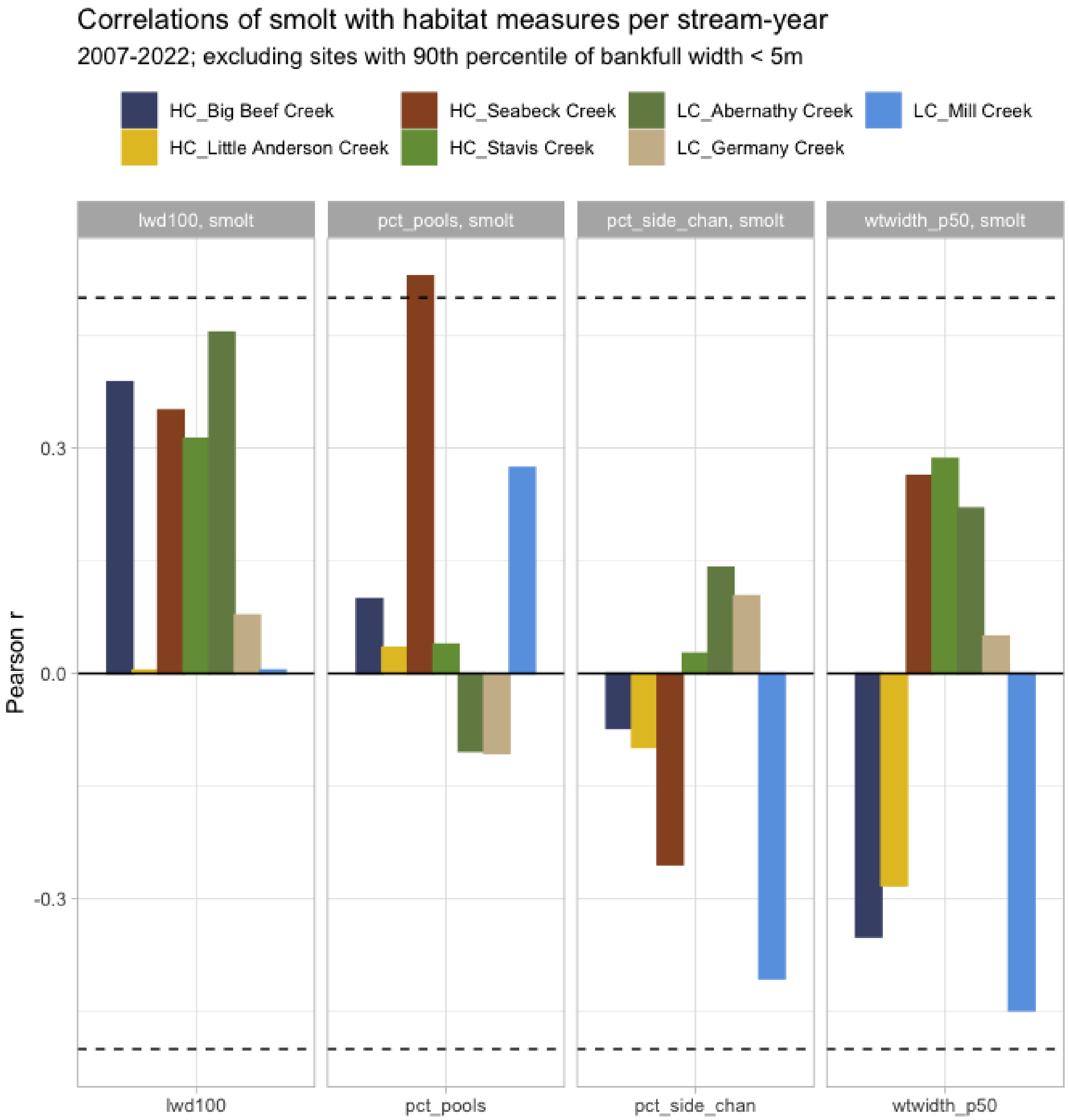


Figure 4H: *Correlation between habitat variables and smolt production for individual watersheds in the Hood Canal and Lower Columbia IMWs.*

Interpreting the correlations between habitat attributes and parr-smolt survival is greatly complicated by density dependent interactions. In the Lower Columbia IMW parr abundance due to high spawner abundance often exceeds habitat carrying capacity. In years where spawner abundance is high, parr abundance is usually high and habitat is more limiting. In these situations, we expect habitat metrics to correlate more closely with smolt abundance than with parr to smolt survival because habitat constraints provide an upper limit on smolt abundance, whereas survival rate will be density dependent, and hence more closely influenced by spawner levels. This may be less of an issue in the Hood Canal IMW, where parr abundance is frequently below habitat capacity due to low spawner abundance. Nonetheless, very little of the interannual variation in parr-to-smolt survival could be accounted for by a single habitat metric at either IMW.

The variation in relationships between instream habitat conditions and salmon parr-to-smolt survival and smolt abundance and suggests that habitat conditions that limit salmon freshwater survival and productivity can differ among contiguous watersheds (i.e., within an IMW) and among years within a watershed. For example, median wetted stream width is relatively strongly, positively correlated with parr-to-smolt survival in Seabeck and Stavis creeks. Much of the mainstem of these streams flows subsurface in most summers due to very large bedload deposits of gravel, especially in Seabeck Creek. However, in Little Anderson Creek median wetted stream width is relatively strongly, negatively correlated with parr-to-smolt survival.

This analysis was intended as a preliminary evaluation of the use of IMW data to help develop more effective protocols for identifying habitat features that are controlling salmon production. These results strongly indicate that limiting factors vary spatially and temporally. The rather weak, and sometimes counter-intuitive, relationships found between parr-smolt survival and smolt abundance with the simple habitat metrics we evaluated suggests that fish abundance is influenced by interactions among multiple habitat factors and this combination of factors change through the period of freshwater rearing and can differ among years. Despite the apparent complexity of this problem, the comprehensive data sets compiled over the last two decades at the IMWs may enable us to develop more effective tools for identifying limiting factors. Additional attention should be focused on this task in the coming years as matching restoration actions with the key elements constraining salmon smolt abundance is foundational to an effective restoration strategy.

Key Findings

- The weak and inconsistent relationships found between fish population metrics and single habitat metrics suggest that fish are likely governed by complex, interacting habitat conditions that vary spatially and temporally. This complexity, coupled with complications related to strength of density-dependence, can make it difficult to accurately identify the habitat conditions with the greatest influence on salmon and Steelhead.

- Further analysis of the IMW data, possibly augmented with comparable data sets collected by other monitoring programs, could be used to develop more effective techniques for conducting limiting factors assessments.

Appendix I: Factors to Consider in Planning Estuary Restoration

Within many coastal watersheds, juvenile Chinook salmon are well known for rearing in estuaries, leading to many estuary restoration efforts to benefit Chinook population recovery. While use of estuaries by juvenile Chinook salmon is well appreciated, several information gaps hamper effective science-based restoration and population recovery. To address these gaps, biologists and managers have generally proceeded in a geographically circumscribed framework, with the common refrain that "this is what Chinook do in our system."

Greene et al (2021) examined fish-habitat relationships in four representative tidal river deltas of Puget Sound: the Nooksack, Skagit, Snohomish, and Nisqually with the goal of developing general biological principles characterizing rearing conditions for natural-origin (NOr) juvenile Chinook Salmon that apply to a variety of estuaries, The selected systems vary in landscape features and outmigrant population attributes (e.g., proportion of natural-origin vs. hatchery-origin or HOr juveniles) and thus represent the diverse characteristics expected in estuarine systems inhabited by juvenile Chinook across a broad geographic range within and beyond Puget Sound.

Using long-term records from beach seine and fyke trapping, Greene et al (2021) addressed three main questions: 1) how does landscape structure affect juvenile Chinook salmon distribution and abundance in tidal deltas, 2) how common are habitat limitations (i.e., density dependence) in tidal deltas, and 3) under what conditions do fish experience growth variability and food limitation in tidal delta wetlands? The answer to these questions underlies whether estuary habitat restoration is likely to benefit Chinook salmon populations for a particular system, and thereby will contribute to recovery from listed status.

Overall, Greene et al (2021) found multiple lines of evidence for density dependence using stock recruit and bioenergetic modeling approaches. Specifically, finding estuary habitat capacity was often exceeded by juvenile Chinook cohorts in some estuaries and that hatchery origin fish can contribute to density dependence. Bioenergetic analyses found evidence that density dependent responses by fish can be expressed as reduced growth and prey selectivity. The study also found that landscape features within systems influence juvenile Chinook presence rates and density. In general, off channel habitats with higher landscape connectivity support higher fish abundance.

Because of the broad range of outmigration sizes and habitat areas in the four delta systems, the study was able identify an overarching consideration for planning estuary restoration. Fundamentally, managers should not expect a uniform response to habitat restoration in estuaries. Estuary systems with small juvenile Chinook outmigration populations relative to extant delta channel rearing area may show more muted responses to restoration than systems with high outmigration populations. Conversely, systems at capacity may nonetheless exhibit strong patchiness, potentially confounding a restoration response if not systematically sampled. Utilizing findings from this study, we provide a decision framework to help managers select appropriate estuary habitat strategies for any specific estuary system for Chinook Salmon (Fig. 1I). The study suggested three restoration strategies are possible in light of the current and desired future condition (DFC) of estuary habitat and juvenile Chinook salmon populations in a system.

- Strategy 1 - maintain current habitat conditions: This approach applies to systems where (a) the current juvenile Chinook salmon outmigration is within the range of its DFC, (b) the current outmigration does not exceed the indicators for density dependence derived from this study, and (c) the current estuary is well connected and diverse in terms of wetland and channel type complexity. Estuaries that fit this strategy would support high-quality habitats with Chinook salmon populations (NOr and HOr) at current (or DFC) levels where density dependence pressures within the estuary are weak.
- Strategy 2 - restore habitat connectivity and diversity: This strategy is appropriate for systems where (a) the current juvenile Chinook salmon (NOr and HOr) outmigration is within the range of its DFC, (b) the current outmigration does not exceed the indicators for density dependence derived from this study, but (c) the current estuary is not well connected and/or not diverse in terms of wetland and channel complexity. Estuaries that fit this strategy have reduced habitat extent but their Chinook salmon populations don't exhibit regular density dependence pressures within the estuary. Because the current (or DFC) population generally does not express density dependence, habitat restoration within these estuaries does not need to focus on restoring vast areas (i.e., capacity) but should work toward restoring connectivity and the diversity of wetland types and channel types within the estuary which will support resilience in the face of extrinsic pressures such as climate change.
- Strategy 3 - restore habitat capacity, connectivity and diversity: This approach is appropriate for systems where the current or DFC outmigration levels exceed the indicators for density dependence derived from this study. Estuaries that fit this strategy have reduced habitat extent and their Chinook salmon populations regularly exhibit density dependence within the estuary. Because of this, habitat restoration within these estuaries needs to focus on restoring large areas (i.e., capacity) as well as connectivity

> and diversity of wetland types and channel types within the estuary. Below we provide examples of this situation via the Skagit IMW and monitoring in the Snohomish, for which evidence exists for density dependence and habitat limitations.

More generally, the framework conveyed for estuary restoration (Fig. 1I) can be used to consider the potential benefits of restoration in other habitats. Consider for example, additions of large woody debris and barrier removal as ways to improve capacity in freshwater systems. If a system is poorly "seeded" with returning adults (e.g., due to low marine survival or high harvest), and therefore not meeting its DFC, these types of restoration might not have expected demographic benefits unless they also improve density-independent productivity (a concept discussed in the previous section).

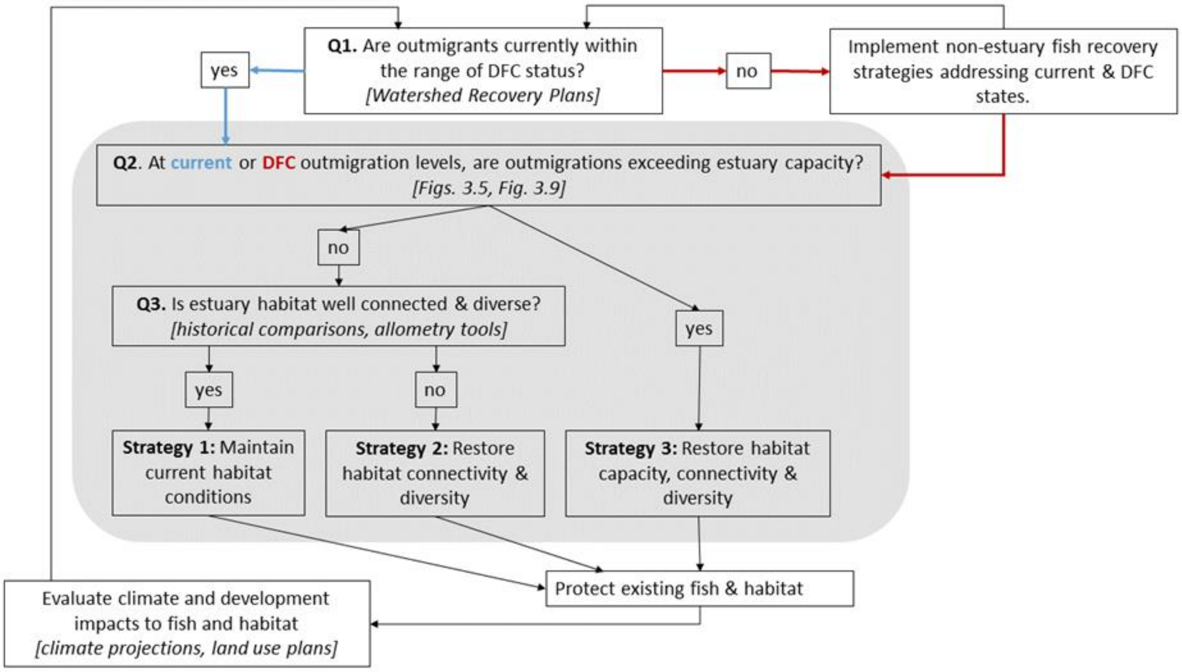
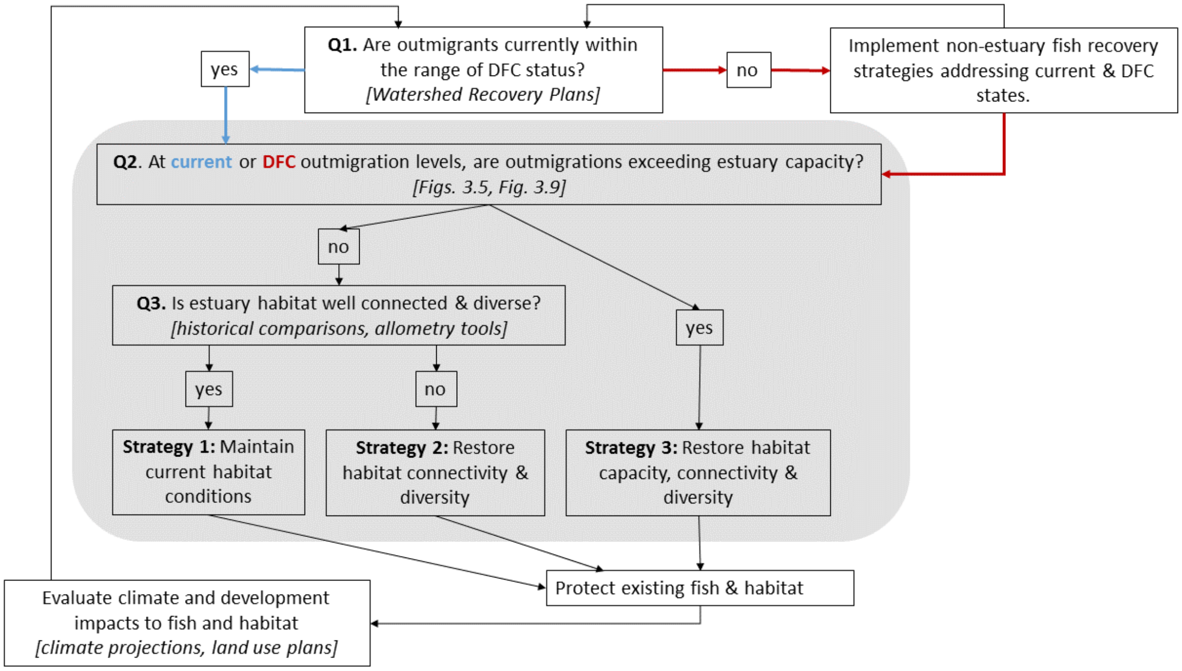


Figure 1I. *Decision diagram to evaluate what restoration strategy is appropriate for a specific estuary system for Puget Sound Chinook Salmon when populations are at current (blue arrows) or desired future conditions (DFC, red arrows), which can be addressed in parallel. The figure is a reproduction of Figure 3.11 from Greene et al (2021). The gray shaded area represents content developed within the scope of Greene et al (2021), and example diagnostic tools to answer questions are shown within brackets in italic. See Greene et al (2021) for more details.*

Key Findings

- Implement restoration that increases landscape connectivity, allowing juvenile Chinook Salmon to access areas of tidal marsh otherwise inaccessible.
- Emphasize restoration of blind channels, given their observed importance to natural origin fish.
- Develop a restoration portfolio of habitat types that provide various benefits for temperature and inputs of terrestrial, freshwater, and marine prey. A variety of wetland habitats contribute to growth and survival. Addressing restoration from a portfolio perspective may provide improved resilience to climate impacts such as sea level rise and temperature increases.
- Re-evaluate the concept of restoring estuary habitat capacity. Habitat restoration is often gauged from the perspective of increasing capacity, an important concept in estuaries where emigrating fish exceed habitat capacity. Many systems may only rarely experience these high levels of density except in the context of large, hatchery releases.
- Investigate in more detail the potential role of various aspects of hatchery releases (e.g., number released, individual size, timing, and location of releases) in affecting natural origin juveniles. Our analyses suggest that large hatchery releases may increase the likelihood for systems to exceed capacity and increase competition for preferred prey, but better documentation of potential causes is warranted.



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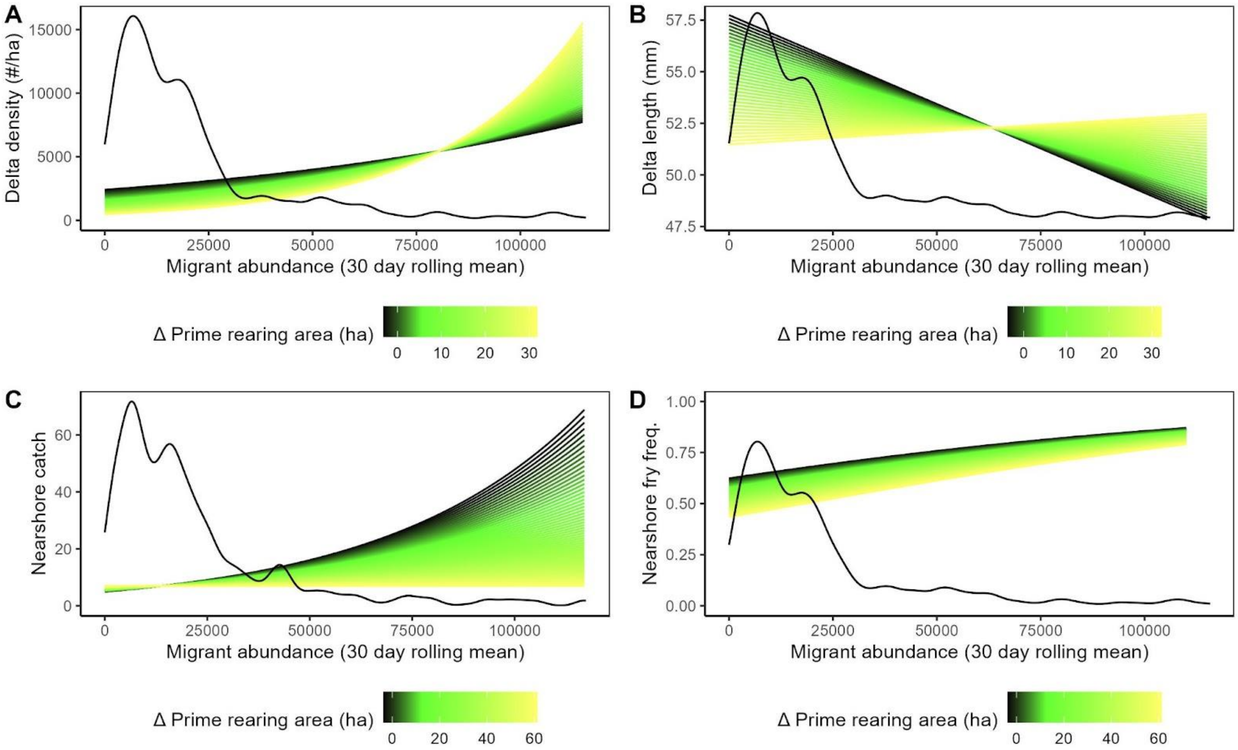

Figure 2I. *Colored lines: predictions from statistical models that examined the influence of habitat expansion (including from restoration) on juvenile salmon demographics. Models make predictions holding confounding factors such as time of year, water temperature, and spatial variation constant. The top panels demonstrate changes in populations characteristics within the tidal delta including reductions in density (A) and average body length (B). The bottom panels demonstrate demographic change of migrants captured in nearshore waters of Skagit Bay including declines in overflow abundance of Chinook (C) and the frequency of fry (≤ 45 mm) in the nearshore population (D). Black lines indicate the distribution of outmigrant abundance observations that informed the models. (Y axis for black lines not shown, but area under the line sums to one). Of note, migrant abundances were among the lower range for the overwhelming majority of observations, meaning predictions at the higher range reflect rare instances and less replication.*

Conclusions

The IMWs have documented that habitat restoration is contributing to salmon recovery. IMWs also are generating information that can help improve the effectiveness of habitat restoration efforts in Washington and suggest some new avenues for investigation that could further improve program effectiveness in the future.

The review of effectiveness of various wood placement projects provides new insights into how these wood projects can be better sited and designed. Wood projects need to be very intensive to produce a detectable habitat and fish responses. The review also identified the need to base restoration strategies on escapement levels as the relative strength of density dependence in a watershed or estuary provides an indication of the habitat restoration actions most likely to generate a positive fish response.

The Skagit IMW is providing a wealth of information on estuary restoration. As found at the freshwater IMWs, identification of priority estuary restoration actions should consider the strength of density-dependence. In estuaries that support high densities of juvenile salmon (like the Skagit) increasing the area of available habitat should be a priority. In contrast, in estuaries where abundance of juvenile fish is too low to fully occupy available habitat, restoration should focus on reducing the impact of density-independent mortality factors, like predation.

This review of IMW results to date provides strong evidence that fully characterizing habitat and fish response to restoration at the IMWs will require additional monitoring. The western Washington freshwater IMWs generated an estimate of the length of time required to detect a fish response to habitat restoration at the start of these projects. This estimate indicated that 10 years of post-treatment monitoring would be required to detect a 25% change in smolt production. This estimate may have been overly optimistic as the IMWs have found that habitat response to restoration treatments can take a long time to fully develop. Therefore, the 10 years required to assess response in smolt production would begin after habitat changes were fully developed. This lag is especially evident with wood projects. Placement of wood in the channel can have short-term effects on channel form. But the IMW results suggest that biological response to these types of changes tend to be relatively modest. Over time reaches treated with sufficient wood aggrade, accumulating additional wood and sediment, enabling the channel to interact more consistently with floodplains. Floodplain reconnection appears to have the potential to generate a much larger fish response than that associated with channel modification. At all four of the freshwater IMWs, reconnection of floodplains is just beginning to occur. Monitoring for multiple years after connection between channel and floodplain has been re-established will be required to determine the magnitude of the fish response to floodplain reconnection.

The IMW results indicate that identification of the factors controlling salmon and Steelhead production in a system can be very difficult. This understanding is necessary to implement effective restoration treatments. The evaluation of relationships between fish and habitat metrics included in this review was intended to determine if the IMW data could be used to help with this problem. The cursory assessment we conducted indicated that single habitat variables are not consistently related to fish population metrics. This finding suggests that factors controlling fish production are likely a combination of habitat attributes and these attributes vary both spatially and temporally. A more detailed investigation of this issue using the IMW data could provide a clearer understanding of the relationship between fish production and habitat condition.

An example of our incomplete understanding of the factors controlling salmon production is provided by comparing Coho Salmon smolt production across the ten watersheds in the western Washington freshwater IMWs. One watershed produces far more Coho Salmon smolts than the others (Fig. A). Big Beef Creek from 2005 through 2019 produced an average of about 850 smolts/km^2 of watershed area. No other IMW watershed produced more 280 smolts/km^2. This result is somewhat surprising, given that the density-dependence analysis done for this review indicates that Big Beef Creek habitat is not fully utilized by Coho Salmon, suggesting that the capacity to produce smolts is even higher. The cause of the high production capacity in Big Beef Creek is not known. But understanding why this system is so much more productive could enable the identification of watersheds that have high productive potential and provide information useful to developing restoration priorities.

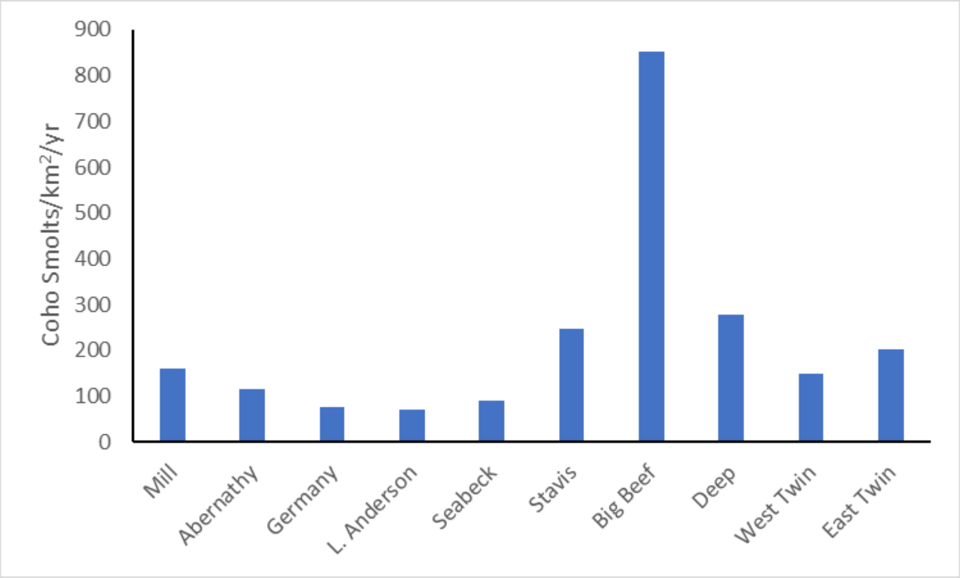

Figure A. *Annual Coho Salmon smolt production from the 10 watersheds included in the western Washington freshwater IMWs. Values represent averages from the years 2005 through 2019.*

References

Abbe, T. and A. Brooks. 2011. Geomorphic, engineering, and ecological considerations when using wood in river restoration. In: Stream Restoration in Dynamic Fluvial Systems: Scientific Approaches, Analyses, and Tools (Vol. 194, pp. 419–451). American Geophysical Union Washington, DC.

Anderson, J.H., K.L. Krueger, C. Kinsel, T. Quinn, W.J. Ehinger, and R.E. Bilby. 2019. Coho Salmon and Habitat Response to Restoration in a Small Stream. Transactions of the American Fisheries Society, 148: 1024-1038. https://doi.org/10.1002/tafs.10196

Anlauf, K.J., Jones, K.K., and Stein, C.H. 2009. The status and trend of physical habitat and rearing potential in coho bearing streams in the Oregon coastal coho evolutionary significant unit. Oregon Department of Fish and Wildlife, Salem, OR.

Bangen et al. in prep – Use of the Geomorphic unit delineation tool to quantify geomorphic change based on restoration with large woody debris.

Bennett, S., Pess, G., Bouwes, N., Roni, P., Bilby, R.E., Gallagher, S., Ruzycki, J., Buehrens, T., Krueger, K., Ehinger, W., Anderson, J., Jordan, C., Bowersox, B., and Greene, C. 2016. Progress and Challenges of Testing the Effectiveness of Stream Restoration in the Pacific Northwest Using Intensively Monitored Watersheds. Fisheries 41(2): 92-103.

Bennett, T.R., Roni, P., Denton, K., McHenry, M. and Moses, R., 2015. Nomads no more: early juvenile coho salmon migrants contribute to the adult return. Ecology of Freshwater Fish, 24(2), pp.264-275.

Bilby, R. E., W. J. Ehinger, C. Jordan, K. Krueger, M. McHenry, T. Quinn, G. Pess, D. Poon, D. Seiler, and G. Volkhardt. 2005. Evaluating watershed response to land management and restoration actions: intensively monitored watersheds (IMW) progress report. Prepared by the IMW Scientific Oversight Committee. Submitted to the Washington Salmon Recovery Funding Board.

Bilby, R., W. Ehinger, T. Quinn, G. Vokhardt, K. Krueger, D. Seiler, G. Pess, C. Jordan, M. McHenry, and D. Poon. 2005a. Study evaluates fish response to management actions. Western Forester 50:14–15.

Booth, D. B., R. A. Haugerud, and K. G. Trost. 2003. The geology of Puget Lowland rivers. Pages 14 – 45 in D. R. Montgomery, S. Bolton, D. B. Booth, and L. Wall, editors. Restoration of Puget Sound Rivers. University of Washington Press, Seattle, WA.

Booth, D.B. and C.R. Jackson. 1997. Urbanization of Aquatic Systems: Degradation Thresholds, Stormwater Detention, and the Limits of Mitigation. Journal of the American Water Resources Association 22:1-20.

Bouwes, N., Bennett, S., and Wheaton, J. 2016. Adapting Adaptive Management for Testing the Effectiveness of Stream Restoration: An Intensively Monitored Watershed Example. Fisheries 41(2): 84-91.

Bouwes, N., Moberg, J., Weber, N., Bouwes, B., Beasley, C., Bennett, S., Hill, A., Jordan, C., Miller, R., Nelle, P., Polino, M., Rentmeester, S., Semmens, B., Volk, C., Ward, M.B., Wathen, G., and White, J. 2011. Scientific protocol for salmonid habitat surveys within the Columbia Habitat Monitoring Program. Prepared by the Integrated Status and Effectiveness Monitoring Program and published by Terraqua, Inc., Wauconda, WA.

Brophy, L.S., Greene, C.M., Hare, V.C., Holycross, B., Lanier, A., Heady, W.N., O'Connor, K., Imaki, H., Haddad, T. and Dana, R., 2019. Insights into estuary habitat loss in the western United States using a new method for mapping maximum extent of tidal wetlands. PLoS One, 14(8), p.e0218558.

Camp, R.J. 2015. Short-term effectiveness of high density large woody debris, a cheap and cheerful restoration action, in Asotin Creek. Master's thesis. Utah State University, Logan, Utah.

Camp, R.J., and Wheaton, J.M. 2014. Streamlining field data collection with mobile apps. Eos, Transactions American Geophysical Union 95(49): 453-454.

Conner, M.M., Bennett, S.N., Saunders, W.C., and Bouwes, N. 2014. Comparison of Tributary Survival Estimates of Steelhead using Cormack–Jolly–Seber and Barker Models: Implications for Sampling Efforts and Designs. Transactions of the American Fisheries Society 144(1): 34-47.

Crawford, B., C. Drivdahl, S. Leider, C. Richmond, and S. Butkus. 2002. The Washington comprehensive monitoring strategy for watershed health and salmon recovery. Washington State Recreation and Conservation Office, Olympia, Washington.

Crozier L.G., M. McClure, T. Beechie, S. Bograd, D. Boughton, M. Carr, T. Cooney, J. Dunham, C. Greene, M. Haltuch, E. Hazen, D. Holzer, D. Huff and E. Willis-Norton. 2019. Climate vulnerability assessment for Pacific salmon and steelhead in the California Current Large Marine Ecosystem. PLoS ONE 14(7): e0217711.

Crozier, L. G., R. W. Zabel, and A. F. Hamlet. 2008. Predicting differential effects of climate change at the population level with life-cycle models of spring Chinook salmon. Global Change Biology 14:236-249.

Firman, Julie C., Steel, E. Ashley, Jensen, David W. , Burnett, Kelly M. , Christiansen, Kelly , Feist, Blake E., Larsen, David P. and Anlauf, Kara. 2011. Landscape Models of Adult

Coho Salmon Density Examined at Four Spatial Extents. Transactions of the American Fisheries Society 140: 2, 440 — 455.

Greene, C.M., E. Beamer, J. Chamberlin, G. Hood, M. Davis, K. Larsen, J. Anderson, R. Henderson, J. Hall, M. Pouley, T. Zackey, S. Hodgson, C. Ellings, and I. Woo. 2021. Landscape, density-dependent, and bioenergetic influences upon Chinook salmon in tidal delta habitats: Comparison of four Puget Sound estuaries. ESRP Report 13-1508.

Hall, J., Roni, P., Bennett, T., McMillan, J., Hanson, K., Moses, R., McHenry, M., Pess, G. and Ehinger, W., 2016. Life history diversity of steelhead in two coastal Washington watersheds. Transactions of the American Fisheries Society, 145(5), pp.990-1005.

Hall, J., M. McHenry, W. Ehinger, T. Bennett, K. Hanson, M. Liermann, and G. Pess. 2018. Strait of Juan de Fuca intensively monitoring watersheds 2017 synthesis report. Prepared for the Salmon Recovery Funding Board. 86 pages.

HDR Inc, and Cramer Fish Sciences. 2009. Abernathy and Germany Creeks Intensively Monitored Treatment Plan. Prepared for the Lower Columbia Fish Recovery Board, Longview, Washington.

Hood, WG, EE Grossman, and C Veldhuisen. 2016. Assessing Tidal Marsh Vulnerability to Sea-Level Rise in the Skagit Delta. Northwest Science 90(1):79-93. doi: http://dx.doi.org/10.3955/046.090.0107.

Independent Science Panel Report 2000-2: "Recommendations for Monitoring Salmonid Recovery in Washington State"

Kemp, P., D. Sear, A. Collins, P. Naden, and I. Jones. 2011. The impacts of fine sediment on riverine fish. Hydrological Processes, 25(11): 1800–1821.

Kramer et al. in prep – Estimating changes in juvenile steelhead capacity due to geomorphic changes forced by large wood restoration.

Krueger, K.L., K. Pierce, E. Pittman, K. Samson, R. Nauer, D. Price, T. Quinn. Intensively Monitored Watersheds: Habitat Monitoring Report 2012. Report to the Salmon Recovery Funding Board, Olympia, Washington.

Krueger. K.l., E. Ward, J. Anderson, T. Quinn, E. Pittman, W. Dezan, R. Bilby, W. Ehinger, G. Pess, M. McHenry, J. Lamperth, M. Litz. 2022. Temporal Variability, Trends, and Treatment Effects in the Western Washington Intensively Monitored Watersheds Report to the Salmon Recovery Funding Board Monitoring Panel, Olympia, Washington.

Kruger, K., et al. In Review. Trends, treatment effects, and temporal variability in Intensively Monitored Watersheds.   N. Amer. J. Fish. Mgmt.

Lamperth, J., M. Litz, A. Johnson, K.K. Krueger, W. Dezan, W. Ehinger, M. Zimmerman. 2021. Lower Columbia Intensively Monitored Watershed Study Annual Report for 2021. Report to the Salmon Recovery Funding Board Monitoring Panel, Olympia, Washington.

Lazorchak, J., D. Klemm, and D. Peck, Editors. 1998. Environmental Monitoring and Assessment Program-Surface Waters: Field Operations and Methods for Measuring the Ecological Condition of Wadeable Streams.

LCFRB. 2016. Lower Columbia IMW Treatment Plan Update. Lower Columbia Fish Recovery Board, Kelso, Washington. https://www.lcfrb.gen.wa.us/libraryimwcomplex

Loughin TM, Bennett SN, Bouwes N. 2021. Comparison of staircase and asymmetrical before–after, control–impact (aBACI) experimental designs to test the effectiveness of stream restoration at increasing juvenile steelhead density. Canadian Journal of Fisheries and Aquatic Sciences 78: 670-680. DOI: 10.1139/cjfas-2020-0096.

Martens, K.D. and Connolly, P.J. 2014. Juvenile anadromous salmonid production in Upper Columbia River side channels with different levels of hydrological connection. Transactions of the American Fisheries Society, 143(3), 757–767.

MDT (Monitoring Design for the Forestry Module of the Governor's Salmon Recovery Plan) 2002. Kate Benkert, Bob Bilby, William Ehinger, Peter Farnum, Doug Martin, Steve McConnell, Roger Peters, Tim Quinn, Mary Raines, Steve Ralph, Dave Schuett-Hames Northwest Indian Fisheries Commission. (https://www.dnr.wa.gov/publications/fp_cmer_gov_salmon_plan.pdf)MOC. 2002, The Washington Comprehensive Monitoring Strategy For Watershed Health and Salmon Recovery, Volume 2 of 3, December 2002

Morandi, B., H. Piégay, N. Lamouroux, and L. Vaudor. 2014. How is success or failure in river restoration projects evaluated? Feedback from French restoration projects. Journal of Environmental Management. 137. 178–188. 10.1016/j.jenvman.2014.02.010.

Pess, G. R., M. L. McHenry, M. C. Liermann, K. M. Hanson, and T. J. Beechie. 2022. How does over two decades of active wood reintroduction result in changes to stream channel features and aquatic habitat of a forested river system? Earth Surface Processes and Landforms 2022:1-13.

Pittman, N., and K. Krueger. 2012. Little Anderson Creek large woody debris enhancement monitoring report. Report to the Hood Canal Salmon Enhancement Group and Hood Canal Coordinating Council. WDFW Habitat Program, Olympia, WA.

Roni, P., G. Pess, T. Beechie, S. Morley. 2010. Estimating changes in coho salmon and steelhead abundance from watershed restoration: How much restoration is needed to measurably increase smolt production? North American Journal of Fisheries Management 30:1469-1484.

Roni, P., Hanson, K. and Beechie, T. 2008. Global review of the physical and biological effectiveness of stream rehabilitation techniques. North American Journal of Fisheries Management, 28(3), 856–890.

Roni, P., M. C. Liermann, C. Jordan, and E. A. Steel. 2005. Steps for designing a monitoring and evaluation program for aquatic restoration. Pages 13-34 in P. Roni, editor. Monitoring stream and watershed restoration. American Fisheries Society, Bethesda, Maryland.

Roper, B.B., J.L. Kershner, and R.C. Henderson. 2003. The value of using permanent sites when evaluating stream attributes at the reach scale. Journal of Freshwater Ecology 18(4): 585 – 592.

Steel, E.A., A. Muldoon, R.L. Flitcroft, J.C. Firman, K.J. Anlauf-Dunn, K.M. Burnett, and R.J. Danehy. 2017. Current landscapes and legacies of land-use past: understanding the distribution of juvenile coho salmon (Oncorhynchus kisutch) and their habitats along the Oregon Coast, USA. Can. J. Fish. Aquat. Sci. 74: 546–561. dx.doi.org/10.1139/cjfas-2015-0589.

Stevens, D.L., Jr., and A.R. Olsen. 2004. Spatially balanced sampling of natural resources. Journal of the American Statistical Association 99: 262-278.

Stillwater Sciences. 2008. Seabeck Creek channel and sediment assessment. Prepared for the Intensively Monitored Watersheds Project, Olympia, WA. 28p.

Sturza, M. T. 2017. Effectiveness of Salmon Carcass Analogs as a Form of Nutrient Enhancement for Juvenile Coho Salmon (Oncorhynchus kisutch) in Three Lower Columbia Watersheds. M. Sc. Thesis, Western Washington University, Bellingham, Washington http://cedar.wwu.edu/wwuet/597/.

Sutherland D. 2020. Transport Characteristics of Large Wood in Headwater Streams: Insights From a Restoration Field Study and Physical Modelling. Ph.D. dissertation, School of Geography and Environmental Science, University of Southampton.

United States Forest Service Olympic National Forest, Elwha Klallam Tribe, and Washington Department of Ecology 2002. Deep Creek, East Twin, West Twin Rivers Watershed Analysis. Olympic National Forest. Olympia, Washington.

Wall, C.E., Bouwes, N., Wheaton, J.M., Saunders, C., and Bennett, S. 2016. Net rate of energy intake predicts reach-level steelhead (Oncorhynchus mykiss) densities in diverse basins from a large monitoring program. Canadian Journal of Fisheries and Aquatic Sciences 73: 1081–1091.

Wheaton, J.M., Bennett, S.N., Bouwes, N., Maestas, J.D., and Shahverdian, S.M. 2019. Editors. Low-tech process-based restoration of riverscapes: design manual. Utah State University Restoration Consortium. Logan, UT. Available at: http://lowtechpbr.restoration.usu.edu/manual.

Wohl, E. and D.N. Scott. 2017. Wood and sediment storage and dynamics in river corridors. Earth Surface Processes and Landforms, 42(1): 5–23.

Zimmerman[a], M. S., K.L. Krueger, W. Ehinger, R.E. Bilby, J. Walter, and T. Quinn. 2015. Intensively Monitored Watersheds Program: Lower Columbia River Study Plan Update, 2015. Report to the Salmon Recovery Funding Board Monitoring Panel, Olympia, Washington.

Zimmerman[b], M. S., J. R. Irvine, M. O'Neill, J. H. Anderson, C. M. Greene, J. Weinheimer, M. Trudel, and K. Rawson . 2015. Spatial and temporal patterns in smolt survival of wild and hatchery coho salmon in the Salish Sea. Marine and Coastal Fisheries: Dynamics, Management, and Ecosystem Science 7:116-134.