Nearshore Restoration Associated with Large Dam Removal and Implications for Ecosystem Recovery and Conservation of Northeast Pacific Fish: Lessons Learned from the Elwha Dam Removal

by

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M.A., Moss Landing Marine Lab (San Francisco State University), 1987
B.Sc., San Francisco State University, 1983

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Supervisory Committee

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Abstract

This dissertation addresses the relationship between large-scale dam removal and the nearshore ecosystem function for fish. The work is based on almost a decade's worth of collaborative field work in the nearshore of the largest dam removal in the world recently completed on the Elwha River. The data analyzed span seven years prior to, during, and throughout the first year of each dam removal (January 2008 to November 2015). As of September 2015, approximately 2.6 million m^3 of sediment material increased the area of the Elwha delta to over 150 ha. Long term study of fish in the estuary reveals fish community response to dam removal, and indicates likely interactions in the nearshore between hatchery and wild fish, including chum salmon critical to watershed recovery. Continued hatchery releases may therefore further challenge chum salmon recovery, and this interaction should be considered when planning for future watershed recovery. Community analysis revealed that, while species richness and taxonomic diversity do not appear to have a significant response to dam removal, functional diversity in the nearshore does respond significantly to dam removal. Three main shifts occurred in the nearshore: large scale and rapid creation of estuary habitats; delivery of large amounts of sediment to the delta/estuary in a short period of time, and; a shift in original habitats from tidally influenced to non-tidally influenced habitats resulted in changes in estuary function. Changes in functional diversity occur disproportionately in the new sites, which have more unstable, and so less resilient, communities. Functional diversity in the original estuary sites appears to be more resilient than in the newly created sites due to the large-scale environmental disruption that, ironically, created the new sites. However, the functional diversity at the original sites may be defined in part by management activities, including hatcheries that could mute/mask/inhibit other community responses. Further, functional diversity at the newly formed nearshore areas is predicted to stabilize as the habitats are vegetated and mature. Principal components analysis of Elwha fish community over the course of this study reveals that the fish communities of the Elwha are predictably grouped, indicating that while a few new species are observed, dam removal has not resulted in observable disruptions in fish community assemblages. And finally, nearshore habitats are critical for many forage fish species, and an emerging topic for large-scale dam removals. Forage fish spawning response to dam removal appears to be complex and may be related to multiple factors including high interannual variability in physical habitat conditions, geographic factors and complex life histories of forage fish. Habitat suitability for forage fish spawning should increase as restored ecosystem processes and newly created habitats mature and stabilize, indicating that time may be an important factor in nearshore restoration for forage fish spawning. It is therefore important to implement long-term monitoring and incorporate nearshore ecosystem process and function for multiple life history stages of nearshore species, including forage fish, into large-scale dam removal restoration and management planning.

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Dedication

For Mary, Ben, Dave, Charlie, and Kendra for teaching me to hear the quiet language of the Elwha nearshore

Chapter 1 Introduction. Large-scale Dam Removals and Nearshore Ecological Restoration: Lessons Learned from the Elwha Dam Removals

In press Ecological Restoration

Author order and contributions: Shaffer, J. Anne (led all aspects of study and writing), Eric Higgs (supervised directed study, contributed to paper), Caroline Walls (contributed to writing of paper), Francis Juanes (committee chair, contributed to paper)

Abstract

Large dam removals are emerging as an important ecosystem restoration tool and they often have direct influence on the marine nearshore zone, but dam removal plans give little consideration to nearshore restoration. We provide an overview of the relationship between large-scale dam removals and nearshore restoration using the Elwha dam removal project, in Washington, US, as a basis. The following steps are essential for incorporating nearshore restoration planning into future dam removals: 1. Conceptual and technical modeling of nearshore physical and ecological processes at the drift cell scale to define nearshore priorities and geographic areas to be conserved/ restored; 2. Acquiring seasonal field data to inform models, including: water quality; sediment delivery volumes, timing, trajectory and composition; and basic fish community (abundance, size, species composition, and trophic components) data; 3. Mapping nearshore habitat areal extent and ecological function prior to, during, and after dam removal, including vegetation composition and invertebrate community composition; 4. Defining and addressing the implications of habitat barriers and fish management actions for nearshore ecosystem function prior to dam removal. Structures and hatchery practices that conflict with nearshore ecosystem function for wild species prior to, during, and after dam removal should be identified and eliminated; 5. Anticipating nearshore invasive species colonization as a result of dam removal;

and 6. Developing and implementing long-term adaptive management plans to ensure nearshore restoration goals are identified, and met. These steps must begin as early as possible in the planning process.

Restoration Recap

- Worldwide it is estimated that there are 40,000-47,000 large-scale dams Many have had significant impacts to watershed and marine ecosystems. Large dams built in the last century are now deteriorating, and dam removal is increasing as a restoration tool. The Elwha dam removal project, on the Olympic Peninsula of Washington state, is the largest dam removal project to date.
- Nearshore habitats provide flood protection, water quality, and critical habitat for fisheries. However, most dam removal plans do not substantially address nearshore restoration (Table 1). Through restoration of the Elwha River nearshore environment, we developed important recommendations for future dam removals (Table 2).
- Planning should adequately include the nearshore ecosystem at all stages. Defining physical and biological linkages between nearshore ecosystems, drift cells, and ecological function is critical in meeting restoration goals of dam removal.
- Adaptive management of nearshore restoration and conservation must be early, ongoing, and integral to dam removal.

Introduction

Nearshore Ecosystems: What they are; How they are Formed; and Why they are Important

As large-scale dam removals increase in frequency, the need to understand the best practices for nearshore restoration grows. The nearshore environment provides a critical connection between marine ecosystems and the riparian watershed. The nearshore environment and habitats, hereafter called ‘nearshore’, are defined as extending from the area of tidal influence in lower rivers, and including riparian zones, offshore to a depth of 30 meters below Mean Low Low Water (MLLW) (Shaffer et al. 2008). The nearshore encompasses a critical set of ecosystems connecting freshwater and marine corridors. Formed and maintained by complex hydrodynamic and sediment processes (Schwartz 1973, Pilkey and Cooper 2014), the nearshore can be highly variable ecologically. Examples of the nearshore include: mangroves, shallow coral reefs, estuaries, salt marshes, rocky intertidal, un-vegetated and vegetated tide flats, kelp beds, and rocky reefs (Bertness et al. 2014). Additionally, drift cells are a key feature that define the nearshore. An idealized drift cell consists of three components: a site that serves as a sediment source and origin (usually an erosional bluff); a zone of transport where sediment may be temporarily deposited alongshore; and a terminus area of deposition and transport (Jacobson and Schwartz 1981).

The nearshore provides ecosystem services of flood protection, water quality, and critical ecosystem function. In North America, iconic cod and salmon, including Atlantic salmon (*Salmo salar*), Chinook (*Oncorhynchus tshawytscha*), coho (*Oncorhynchus kisutch*), steelhead (*Oncorhynchus mykiss*), cutthroat (*Oncorhynchus clarkii*), chum (*Oncorhynchus keta*), pink (*Oncorhynchus gorbuscha*), and sockeye (*Oncorhynchus nerka*) salmon, all depend on the nearshore for the life history stages of migration, resting, rearing, and feeding. Forage fish, which support global fisheries valued at $11.3 billion, depend on the nearshore for the same life history phases, as well as spawning (Reeves et al. 1989, Fresh 2006, Penttila 2007, Simenstad et al. 2011, Shaffer et al. 2012, Martin 2014, Pikitch et al. 2014). The nearshore has also been documented as a limiting factor for survival of juvenile anadromous salmon as they transition to adult and offshore habitats (Greene and Beechie 2004).

The nearshore is economically valuable, as well. According to Wilson & Liu (2008) the world's total economic value of coastal marine systems is estimated to be US $22 trillion. Global nearshore ecosystem services have yet to be calculated. Regionally, nearshore ecological services for lower British Columbia, Canada are estimated to be $30-60 billion a year (Molnar et al. 2012). Along the northwest coast of the United States, Washington state coastlines provide ecosystem services of $985 million to $4.4 billion per year (Flores et al. 2013, Flores and Batker 2014). These values will likely increase in the future concomitant with climate change.

Human development has concentrated along northeast Pacific shorelines for more than 13,000 years (Gustafson 2012). With non-Tribal settlement in the region, shorelines continue to be filled and armored, lower rivers channelized and diked, and large docks and piers built overwater. Non-point and point source storm water from upland development is conveyed to the shoreline. Cumulatively, such development has resulted in a severe loss of nearshore habitat and a number of impacts to marine ecosystem function globally (Levin and Lubchenco 2008, Dugan et al. 2011, Pilkey and Cooper 2014). Disruption of nearshore hydrodynamics and related sediment processes is a central nearshore impact (Bottom et al. 2005, Rice 2006, Dugan et al. 2008). Hobson et al. (2001) documented that dramatic shifts in upland management can affect nearshore production.

Large-Scale Dams and the Nearshore

Large-scale dams (>15 m in height) are well documented to have significant impacts to land margin form and functional processes by blocking fish passage and by altering river flows and sediment delivery to the nearshore. Dams located hundreds of miles inland may have significant ecosystem scale impacts on the coast. Drinkwater & Frank (1994) provide an overview of the major types of impacts of in-river dams to marine fisheries of the Black Sea, San Francisco, and Hudson Bays. The delta of the Ebro River, the largest river in Spain, has decreased in area, and its salt wedge has increased, due to in-river dams that have disrupted sediment and hydrodynamic processes (Jimenez and Sanchez-Arcilla 1993). Holmquist et al. (1998) state that high dams have an impact to shrimp and non-native species colonization (WCD 2000). In the United States, sediment delivery to the Columbia River littoral system has been decreased by a factor of three and is now a fraction of pre-dam rates (Gelfenbaum et al. 1999). Slagel & Griggs (2008) have estimated that sand volume contribution to beaches in California has been reduced from dam impoundment by up to 50% since 1885. Bennett (2005) cites dams as a significant negative factor to federally listed smelt species in San Francisco Bay. Nobriga et al. (2005) revealed that dams reduced sediment delivery to the nearshore by approximately 50%.

Habitat impacts are not the only nearshore factors associated with large-scale dams. Salmon hatcheries have become prominent management features over the last 100 years to increase fish production that has been decimated by habitat degradation and overharvest (Waples 1991, Lichatowich and Lichatowich 2001). Fish hatcheries are a management tool often associated with large-scale dams and dam removal (Ward et al. 2008). However, research has shown that hatcheries actually impede watershed restoration by displacing wild fish stocks and diluting genetic rigor (Lackey 2000, Weber and Fausch 2003, Kaeriyama and Edpalina 2004, Naish et al. 2007). In the northeast Pacific, the release of hatchery juvenile Chinook and coho salmon into lower rivers have been documented to negatively affect wild pink and chum salmon populations (Johnson 1973, Cardwell and Fresh 1979), which is one of the reasons hatcheries are now being questioned as a true restoration tool (Gregory et al. 2002). The relationship between hatchery practices and nearshore function is still not fully understood.

Restoration of the Nearshore

In the last 20 years there have been increased efforts to restore degraded aquatic ecosystems, including the nearshore (Borja et al. 2010, McGraw and Thom 2011). In 2011 alone, in the United States, $316 million was allocated through the federal NOAA Restoration Office for ecosystem restoration (McGraw and Thom 2011), and the US Army Corps of Engineers is slated to allocate $337 million to aquatic ecosystem restoration over the next biennium (USACE 2014). The majority of this restoration funding is allocated to the nearshore.

Restoration of the nearshore marine environment may range from independent, small-scale riparian plantings, shoreline vegetation and sediment enhancements, to large-scale, full ecosystem restoration events. Small and medium scale projects are often relatively straight forward, and show clear improvements relative to unrestored areas (Toft et al. 2013). While these small marine restoration projects may result in an increase in acres of marine habitat, or an increase in the abundance of an individual species, many projects do not consider the underlying causes of degradation. If the causal mechanisms are not understood, the ‘restoration’ will provide little recovery to species and functions that would be present in an intact system, and so fail to achieve full ecosystem restoration (Powers and Boyer 2014). Without true ecosystem restoration, ecosystem services may not be restored, and the intended restoration will ultimately fail. It is therefore critical to appropriately scope nearshore restoration actions.

Ecosystem Based Management (EBM) is an emerging tool in conserving and protecting the world's vanishing coastal resources (Levin and Lubchenco 2008), including the nearshore (Browman et al. 2004, Barbier et al. 2008). To date, EBM tools have not focused on functional linkages between nearshore ecosystems and watershed species management actions. Hatcheries have transitioned from a top EBM restoration tool to a controversial management issue for ecosystem restoration. Evidence suggests that interactions between wild and hatchery fishes may disrupt residence time and increase competition and predation on wild stocks (Levin and Williams 2002, Webber 2003, Naish et al. 2007). The implications of hatcheries for the nearshore, and the role that hatchery management plays in the ecological function of a restoring estuary and the nearshore, have been inadequately researched and are thus poorly understood. Further, the interactions between hatcheries, dam removals, and nearshore ecosystem restorations are likely central to dam removal restoration success, but are not currently considered in dam removal planning efforts (Table 1).

There are many compelling reasons nearshore restoration should be considered in the restoration planning and/or monitoring phases of dam removal. Among them are: the loss of nearshore habitats worldwide; the long-term impacts of dams to the nearshore; the potential for nearshore ecosystem shifts from dam removals; and the potential for significant ecosystem-scale restoration opportunities associated with dam removals. The Elwha dam removal project provides our first opportunity to focus on the restoration response of nearshore ecosystems to dam removals, and to inform planning processes for future restoration projects. Table 2 provides an overview of the limiting factors of nearshore restoration that were illuminated during the Elwha dam removal. Dam removals are increasing in frequency. Our objective in this paper is to provide an overview of the relationship between large-scale dam removals and nearshore restoration, and to give specific guidance for future restoration actions. The Elwha dam removal project provides the basis for our recommendations.

Elwha Nearshore Restoration

Located on the north Olympic Peninsula of Washington State, United States (Figure 1), the Elwha nearshore is severely sediment starved and ecologically impaired due to a number of anthropogenic impacts, including two large hydroelectric dams. Glines Canyon Dam (64 m tall) and Elwha Dam (33 m tall) were installed in the Elwha River at the turn of the previous century. The two dams were 21 km and 8 km from the nearshore, respectively (Figure 2). Major impacts to the Elwha nearshore ecosystem directly related to the dam removals include: ongoing shoreline armoring, lower river alterations, and in-river dams (Shaffer et al. 2008). As a result, the Elwha bluff and spit beaches are steep, with coarsened substrate, and more variable grain size than comparable intact drift cells (Parks et al. 2013, Parks 2015). Furthermore, dikes and shoreline armoring remain after dam removal, resulting in only a partial restoration in the Elwha nearshore.

Ecologically, the impacts are significant. Forage fish spawning in the Elwha nearshore is significantly lower than in comparative drift cells (Weifferling 2014). The lower Elwha river hydrodynamics are disrupted from straightening of the river, due to lack of sediment and lower river alterations, including dikes (Shaffer et al. 2008, 2009). Fish use in the Elwha estuary is also disrupted (Shaffer et al. 2009). While eelgrass bed distribution along the Elwha drift cell is not significantly different than comparative areas across the drift cell (Norris et al. 2007), kelp bed distribution has expanded significantly across the drift cell since the armoring of Elwha feeder bluffs during installation of the industrial waterline and dams (Barry 2013). Finally, the distribution, size, and density of large woody debris (LWD) of the Elwha nearshore is significantly lower than on unaltered shorelines due to anthropogenic pressures (Rich et al. 2014).

Long-term monitoring has revealed that the Elwha nearshore, while impaired, is ecologically complex, diverse, and important ecologically for fish. Fish use of Elwha nearshore habitats is highly variable, seasonal, and driven by species life history (Shaffer et al. 2008, 2009, 2012). Numerous juvenile fish species using the Elwha nearshore are listed under the federal Endangered Species Act (ESA) as threatened or endangered, including Chinook and coho salmon that originate from as far away as the Columbia and Klamath River systems (Shaffer et al. 2012, Quinn et al. 2013a&b). Thus, nearshore restoration is important at an ecosystem level, as well as at regional, and larger scales. Pre-dam removal monitoring also indicates that hatchery practices, which result in upwards of 3 million salmon smolts released into the Elwha nearshore during peak salmon outmigration, can seasonally overwhelm fish abundance in the estuary, shift fish species composition and abundance in the Elwha estuary, and eclipse seasonal wild outmigrating fish (Shaffer et al. 2009, Quinn et al. 2013a&b).

Twenty-five years after being legislated, the Elwha dam removal project began in September 2011 and concluded in September 2014. Approximately 20 million cubic meters (mcm) of sediment stored behind the dams are now being released into the watershed. Of this, approximately 10 mcm of silt, sand, and gravel material will be delivered to the nearshore (Gelfenbaum et al. 2015, Warrick et al. 2015, Randle et al. 2015) within five years of dam removal (U.S. DoI 1996, Shaffer et al. 2008). Extensive watershed restoration planning and monitoring work defined nearshore baseline conditions and monitored dam removal response (Duda et al. 2008, 2011, Warrick et al. 2015, see special edition of Geomorphology 2015). But little scoping, planning, and/or implementation of nearshore restoration projects was achieved prior to, or during, the Elwha dam removals. There was, to our knowledge, no funding for nearshore restoration relative to that for watershed restoration. Further, no adaptive management actions were in place to identify or address nearshore ecological issues identified prior to, or during, dam removals. A few studies did recommend restoration of the nearshore habitats (Shaffer et al. 2009, Rich et al. 2014, Weifferling 2014), but these were unfortunately late in the dam removal timeline, and largely independent of the planning and funding framework. Therefore, few of the recommendations were incorporated into the formal dam removal process (Table 2).

In the Elwha, exhaustive project planning was done prior to dam removals to minimize sediment impacts to in-river fish migration. These included 'fish windows,' during which time dam removal was halted with the intent of minimizing sediment loads during fish use of the river. Planning, however, did not consider sediment delivery timing to the nearshore. As a result, the Elwha dam removal project could be a large scale disturbance event to the nearshore fish habitat, which is seasonally highly functioning (Shaffer et al. 2009). And while detrital input from rivers is a significant source for detrital organic carbon for marine basins of the Salish Sea (El-Sabaawi et al. 2010), the short and dramatic nature of this sediment delivery may overwhelm the Elwha nearshore system, and force an ecosystem shift to an alternative state of equilibrium (Levin and

Lubchenco 2008). It is therefore critical to, as accurately as possible, anticipate dam removal impacts specifically for nearshore function, and in particular for fish use of the nearshore.

The Elwha dam removals were intended to result in restoration of the watershed ecosystem and the rebuilding of anadromous fish runs of the Elwha River (U.S. DoI 1996). However, at the beginning of the project virtually nothing was known about how fish, including the many target species that have critical nearshore life history phases, would respond to the episodic and large volumes of sediment released into the nearshore. Much attention and decades of planning were dedicated to defining and prioritizing watershed habitat restoration projects in the Elwha River for a number of these salmon species (Ward et al. 2008, Quinn et al. 2013a). However, planning prior to dam removals did not identify or prioritize detailed nearshore restoration actions for these and other important species.

Based on the paucity of information on nearshore restoration aspects of large-scale dam removals, and our career-spanning experience in the nearshore of the Elwha dam removal project, we provide the following recommendations. These are the critical nearshore planning, management, and monitoring elements to consider in nearshore restoration planning through future large-scale dam removals.

Recommendations for Incorporating Nearshore Restoration into Large-Scale Dam Removals

Link Nearshore Physical Processes and Ecosystem Restoration.

Dam removals are intended to restore ecological function, largely through the restoration of physical ecosystem processes, including the nearshore. These physical processes therefore should be defined and monitored at both the watershed and drift cell scale, and then evaluated and monitored for ecological function. This will require integrating key nearshore ecological, in particular fish use, elements into physical monitoring.

As stated by Parks et al (2013), seasonal and inter-annual timing of sediment delivery to the intertidal along the entire drift cell and habitat, and direct linkage of this delivery to community changes within the nearshore, are critical to define for accurate understanding and restoration of the nearshore. This includes defining seasonal timing, volume, grain size and intertidal distribution of sediment delivery, as well as nearshore habitat change associated with sediment delivery across the drift cell. This involves mapping habitat changes (not just sediment volumes). In the Elwha nearshore in 2013, two years after dam removal began, 65% of total retained sediment still remained in the watershed, and less than 12.5% of the 20 mcm of total estimated sediment that could potentially be released to the watershed had reached the nearshore. Some areas of shoreline aggraded only a few centimeters, while others grew by tens of meters (Gelfenbaum et al. 2015). However, when mapped for habitat coverage, these sediment volumes translate to upwards of 35 hectares (85 acres) of new lower river and estuary (Shaffer et al 2017).

It is also important to define, through pre-dam removal monitoring, nearshore basic water quality. Water quality parameters, including turbidity, temperature, pH, dissolved oxygen, and salinity, are critical components to understanding both physical and nearshore responses to large-scale dam removal. These data must be able to accurately reflect both seasonal and inter-annual changes in nearshore water quality, in both the original nearshore and newly created nearshore habitats- not just pre-dam removal sites. Concomitant data in comparative areas are critical to define dam removal from natural nearshore variability. East et al. (2015), Foley et al. (2015), and

Draut and Ritchie (2015) documented that, as the river mouth of the Elwha extended, lower river habitat shifted from estuarine to non-tidally influenced lower river. This information is critical to understanding changes in fish use of the newly restoring nearshore.

Define Nearshore Habitat Associated with Dam Removals, and the Restoration Priorities

Nearshore ecosystem functions are linked across the drift cell**,** and species that use the watershed have critical nearshore life history phases. It is therefore critical to, in stepwise fashion, define the ecological condition, the ecological linkages with dam removal, and the subsequent nearshore conservation and restoration priorities of each land form within the entire drift cell, relative to dam removal. Nearshore habitats within the dam removal drift cell that are identified as intact and functioning properly should be a top priority for protection during and after dam removals.

Habitats that are defined as degraded should be prioritized and restored well prior to dam removal, and protected after dam removal. This includes identifying and resolving important additional nearshore disrupting features within the dam removal drift cell. Nearshore habitat restoration from dam removals can be disrupted by dikes and shoreline armoring remaining in the nearshore during and after dam removal (Parks 2015). These features should therefore be clearly identified and incorporated as important components of large-scale dam removal restoration. Through long term fish use monitoring in the Elwha, we observed that remaining dikes in the lower river appear to actually be preventing habitat restoration in the lower Elwha river by disrupting water flow and fish access to areas that could otherwise be critical refuges during high sediment flows (Shaffer et al. 2009, 2017, Table 2).

Define the Key Ecological Processes of Nearshore Restoration Associated with Large-Scale Dam Removal

Monitoring long-term fish use of the nearshore is critical to understanding fish use response to dam removals. Through long-term beach seining of the Elwha nearshore, we found these newly created nearshore estuary areas are accessible and used by fishes almost immediately, including by species targeted for restoration, such as juvenile Chinook salmon, surf smelt (*Hypomesus pretiosus*), and gravid eulachon (*Thaleichthys pacificus*) (Shaffer et al 2017). It is extremely important to thoroughly define the nearshore ecological aspects of dam removal restoration goals (for example, nearshore life history phases of salmon species, or key forage fish that they depend on), as well as the ecosystem restoration actions to protect and restore priority nearshore ecological processes that will achieve these goals. The following are a few specific elements to define.

First, it is important to define nearshore fish community response to dam removal. Defining fish community composition, individual fish species abundance, and distribution within dam removal and comparative drift cells- using standard protocols before**,** during, and after dam removal phases- are important to provide critical information for planning the nearshore restoration aspects of dam removals. Ecological metrics for fish, including functional diversity and species richness, can provide important insight into additional restoration actions in the nearshore associated with dam removal. This should include all species important to the ecosystem, not just the commercially and recreationally important species.

Second, nearshore restoration, specifically for forage fish, should be identified**.** Beach spawning fishes have very specific sediment and habitat requirements for spawning, which make them excellent metrics to define nearshore restoration. For example, surf smelt spawning habitat along the Elwha beaches has been documented to be just a fraction of what is available along comparative drift cells, due to sediment starvation (Parks et al. 2013, Weifferling 2014). Further, eulachon, which are river spawning smelt, were once common in the Elwha, but are now documented to be in the Elwha River in low numbers, likely due to insufficient spawning habitat (Shaffer et al. 2007). Approximately half of the estimated 10 mcm of sediment that will be released to the Elwha nearshore is of a size appropriate for surf smelt, eulachon, and sand lance spawning (East et al. 2015, Gelfenbaum et al. 2015, Warrick et al. 2015). Anticipating trajectory, timing, and duration of delivery of appropriate grain size along the drift cell prior to dam removals could have greatly increased the effectiveness of our restoration planning and monitoring. Conversely, it is important to define the lack of an expected response to a restoration. For example, despite the abundant appropriate grain size material being delivered to the Elwha nearshore, sand lance, which spawn intertidally in winter along the comparative drift cell, have not yet begun spawning again along the Elwha shoreline (Weifferling 2014, Shaffer, Coastal Watershed Institute, unpub. data). Delivery of the appropriate sediment is therefore not the only important consideration for dam removal restoration for this forage fish species. Nearshore restoration specifically for salmon species affected by dam removal is also an important planning focal point. All anadromous salmon have a nearshore life history phase which should be included extensively in dam removal restoration planning. In the Elwha, surprisingly, no project scale pre-dam removal planning or resources were allocated to identify, prioritize, and/or implement habitat restoration actions to restore the Elwha estuary for outmigrating salmon smolts. Therefore, the Elwha estuary continues to be constrained by a series of flood-control dikes, which appear to be disrupting nearshore restoration processes in the estuary (Shaffer et al. 2008, 2009, Figures 5A-C).

Third, nearshore restoration and relationships with fish management practices are important aspects to include in dam removal considerations and planning. Interactions of hatchery and wild fish are well documented in other systems (Johnson 1973, Cardwell and Fresh 1979, Kaeriyama and Edpalina 2004). The role dam removal and the associated fish management practices will have on specific nearshore life history habitat functions, and how these relate to the larger ecosystem restoration, are therefore important to define. Hatchery release practices should be analyzed prior to dam removals, specifically to understand if and when released fish are recruiting to the nearshore, and how these introductions will interact with wild fish use of the nearshore during critical habitat restoration phases. Hatchery release dates, species, and number of fish released relative to nearshore habitat use will define the interaction of hatchery releases to wild fish utilizing the estuary and nearshore, and allow managers to understand how management activities may translate to nearshore restoration response. If overlooked, fish management practices intended to promote ecosystem restoration could instead hamper restoration. In the Elwha, there are significant potential interspecies interactions during chum salmon outmigration with hatchery releases of juvenile Chinook and coho salmon, which are known to have negative interactions with juvenile chum. This concern was the focus of initial study and hatchery recommendations to delay hatchery releases until after chum outmigration (Peters 1996). Unfortunately, these recommendations were not adhered to by state hatchery managers. On average over 3 million fish, including almost 2 million juvenile Chinook salmon and 380,000 coho salmon are released annually to the Elwha lower river during peak chum salmon outmigration months (Quinn et al. 2013a&b). These fish are observed in the estuary in very high numbers (Shaffer et al. 2009). Given the large numbers of fish in a small estuary, there are likely interactions with wild fish. Hatchery release practices should therefore be reviewed and revised specifically for species interactions and community effects in the nearshore prior to dam removals.

Finally, it is important to anticipate the potential and prioritize management for non-native/invasive species. Invasive species are well known to be able to monopolize newly created estuary habitat, to the exclusion of native species, with long-lasting and negative impacts (Powers and Boyer 2014). Because there is a paucity of effort on the nearshore, invasive plant species, such as scotch broom (*Cytisus scoparius*), have already been observed in the newly forming Elwha nearshore and they are only now being addressed. Future dam removals should anticipate the establishment of non-native vegetation and fish species to, if possible, prevent establishment and plan to act more proactively.

Develop Conceptual and Technical Models of Nearshore Physical and Ecological Processes

Conceptual and quantitative models are powerful and necessary tools to accurately integrate these elements to define the nearshore species, including specific life histories, and linkages to ecosystem processes that are the most impacted by dams. Models are an excellent way to define the highest nearshore restoration potential associated with dam removal. The models should encompass, at a minimum, the entire dam removal area and comparative drift cells, and they should focus at an ecosystem (not individual species) scale. The models should include all the dominant physical and ecological aspects of the drift cell and watershed that drive nearshore ecosystem function and interact with dam removal. They must also include, if any, a thorough analysis of the interaction of fish management practices in the watershed on nearshore function. Properly scoped, the models will be a powerful tool to define priority areas of restoration and geographic areas of the nearshore that have key information and action gaps. The scope of the nearshore conceptual model must include the highly seasonal and inter-annual variability of nearshore ecosystem function, as evidenced by long-term, seasonal pre-dam removal monitoring of both the dam removal nearshore and comparative drift cells.

Conclusions

In conclusion, planning for ecosystem restoration of nearshore habitats is a critical component to large-scale dam removals. As evidenced by the Elwha dam removal project, future large-scale dam removal planning should comprehensively include the nearshore ecosystem, at a drift cell scale, as a priority before and during dam removal, through conceptual and quantitative modeling and field assessment of the physical and ecological nearshore of both the dam removal and comparative nearshore. Impediments to nearshore ecosystem processes, including habitat impairments and fish management tools, must be identified and critically reviewed for negative nearshore ecosystem restoration interactions. Given variability in nearshore systems, these steps should begin years prior to dam removals. Finally, as illustrated by the Elwha dam removal project, scoping large-scale dam removals can take decades. Science moves much more quickly than management. But managers must have the will to update plans to incorporate new information as it becomes available, in order to ensure the best restoration outcome. Therefore, adaptive management should be an integral part of the restoration process for nearshore environments during dam removal planning and implementation. Early indications are that large-scale dam removals, including the Elwha dam removal project, appear to have many immediate and positive responses (O'Connor et al. 2015). However, without a prior, comprehensive, and long-term nearshore restoration plan, watershed restoration will be incomplete.

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Table 1.1 Large Dam Removal Projects environmental planning documents.

Y=Included; N=Not included; M=Mentioned

Dam Removal Project	**Nearshore impacts of dam removal identified**	**Nearshore restoration associated with dam removal scoped and additional actions, if any, prioritized**	**Citation**
United States			
Elwha EIS (US)	Y	M (mentioned, but not included in detailed planning	U.S.DoI 1996; Ward et al. 2008;
Matilija Dam EIS	Y	N	USCoE 2010
Klamath Dam Removal EIS and Reports	Y	N	US Departments of the Interior and Commerce 2012
San Clemente	Y	N	California Department of Water Resource 2102
Marmot Dam	N	N	FERC 2008
Searsville Dam	N	N	USFWS & NMFS 2012
France			International Rivers 2015
St Etienne du Vigan	N	N	
Kemansquillec (leguer River)	N	N	
Spain			International Rivers 2015
Robledo	N	N	

Table 1.2 Nearshore restoration planning considerations to address key nearshore limiting factors of the Elwha drift cell relative to dam removal.

Nearshore linkage/Limiting factor action	**Suggested planning actions appropriate to restore limiting factor associated with dam removals**	**What was done**	**Restoration planning gaps**	**Dam Removal Documents Referenced In Action and Gaps**
Identify nearshore relationship to watershed restoration project	Detailed review of nearshore implications of project both physical and ecological	Comprehensive call to action by community including nearshore technical and education workshop. Some project habitat review relative to sediment delivery to offshore areas and estimation of ecosystem response	Workshop restoration recommendations not incorporated into project. No analysis relative to life histories of species key to watershed ecosystem restoration (salmon estuary phase, forage fish spawning, etc)	U.S. DoI 1996; Triangle and Associates 2004; Todd et al. 2006; Stolnack and Naiman 2005; Ward et al. 2008
Identify ecosystem function of nearshore, nearshore limiting factors and links to restoration to drift cell associated with large-scale dam removal	Develop conceptual model to identify and prioritize nearshore limiting factors and relationship to dam removal. Identify data gaps	Conceptual model developed. Key nearshore limiting factors of the drift cell identified: Sediment starvation from shoreline armoring and in-river dams, lower river alterations. Data gaps on general ecosystem function and physical processes in the nearshore identified. Some restoration issues identified through	No nearshore restoration specific planning in project. Elwha Nearshore Consortium (ENC) work began late in the dam removal timeline (2006) and was external to the formal planning processes	Shaffer et al. 2008; McDonald and Harris 2013

Nearshore linkage/Limiting factor action	Suggested planning actions appropriate to restore limiting factor associated with dam removals	What was done	Restoration planning gaps	Dam Removal Documents Referenced In Action and Gaps
		conceptual modeling by independent body (ENC)		
Address priority data gaps to inform additional restoration planning	Key data gaps for physical and ecological processes and ecosystem services addressed and restoration information gaps addressed	General broad data gaps and questions on Elwha drift cell physical and ecological processes addressed. Sediment monitoring in lower river, delta, and offshore initiated. Ecological baseline information within the drift cell collected.	Much of the physical process monitoring and modeling work informative but not designed to address specific nearshore restoration planning questions (sediment trajectory and fate specific to shoreline and lower river alterations).	Norris et al. 2007; Parks et al. 2013, Shaffer et al. 2009, 2012; Quinn et al. 2013a&b; Flores et al. 2014; Rich et al. 2014; Weifferling 2014; Gelfenbaum and others 2015 special edition Geomorphology. Parks 2015
Use conceptual model and data to defining restoration projects linked to dam removal that address key nearshore restoration needs. Sediment starvation due to shoreline armoring, in-river dams resulting in loss of estuary habitat	Sediment modeling to define sediment trajectory and fate, specific to shoreline actions to optimize sediment delivery. Removal of shoreline armoring, protection of existing nearshore habitats. Dike alternatives to promote hydrologic	Extensive nearshore sediment modeling and baseline physical and ecological monitoring Relative contribution of river and bluff contribution to nearshore defined, and roll of armoring on sediment limitation	Sediment modeling to date has not accounted for seasonal ecological function, or defined sediment trajectory or delivery to beaches along the drift cell. No restoration recommendations can therefore be generated	Parks et al. 2013, Shaffer et al. 2009, 2012; Rich et al. 2014; Weifferling 2014;

Nearshore linkage/Limiting factor action	Suggested planning actions appropriate to restore limiting factor associated with dam removals	What was done	Restoration planning gaps	Dam Removal Documents Referenced In Action and Gaps
	connectivity to estuary. Fish management actions to assure no impacting interactions.	identified. Data are important for beach spawning fishes in lower river and shoreline. A few specific recommendations for restoring estuary hydrodynamic processes.	from sediment monitoring for these ecosystem functions General restoration needs and issues identified not included in dam removal planning. Not prioritized.	
Post dam removal assessment of nearshore restoration and next steps	Dike of lower river continues to block fish access to remaining habitat and disruption of nearshore hydrodynamics; shoreline armoring remains along feeder bluffs and industrial waterline. No restoration actions; additional armoring has been added to shoreline since nearshore planning began.	Modifications scoped for flood protection and fish passage	Only modifications for flood protection implemented on west levee. Dike was raised and widened, and additional armoring placed along dike and shoreline. No fish passage provided in dikes	Corum 2009
Dam removal and post dam removal fish management practices in watershed confounding nearshore ecosystem use	Delay hatchery release until chum migration over (June)	None	None	Peters et al. 1996

Figure 1.1 Elwha drift cell.

Landforms (top panel), watershed (bottom left) and geographic location North Olympic Peninsula, Washington State, USA. Map by Dave Parks, DNR.

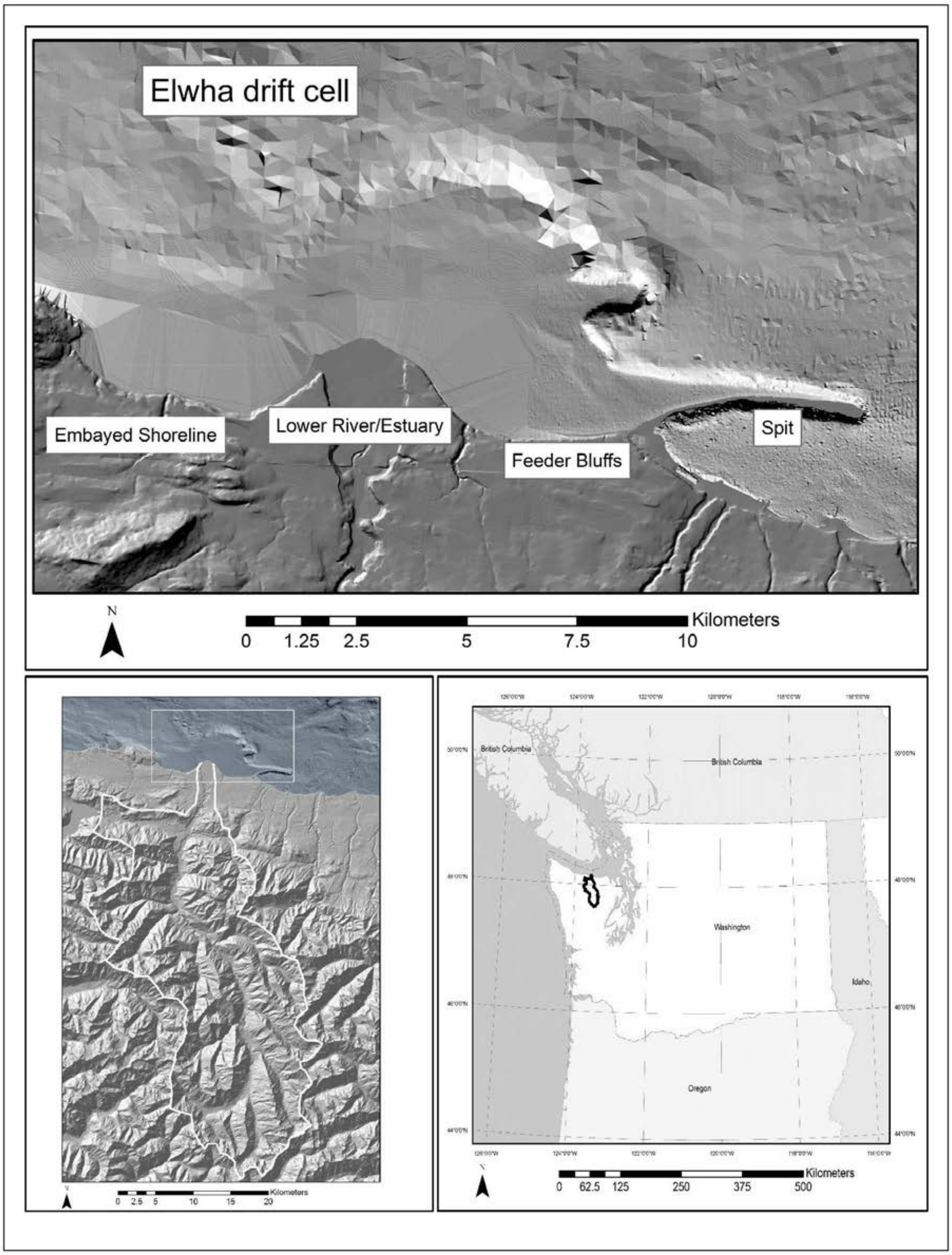

Figure 1.2 Elwha River Dams.

Both dams were installed in the river at the turn of the previous century. After over a quarter of a century of planning, dam removal began in September 2011 and was completed 31 August 2014.

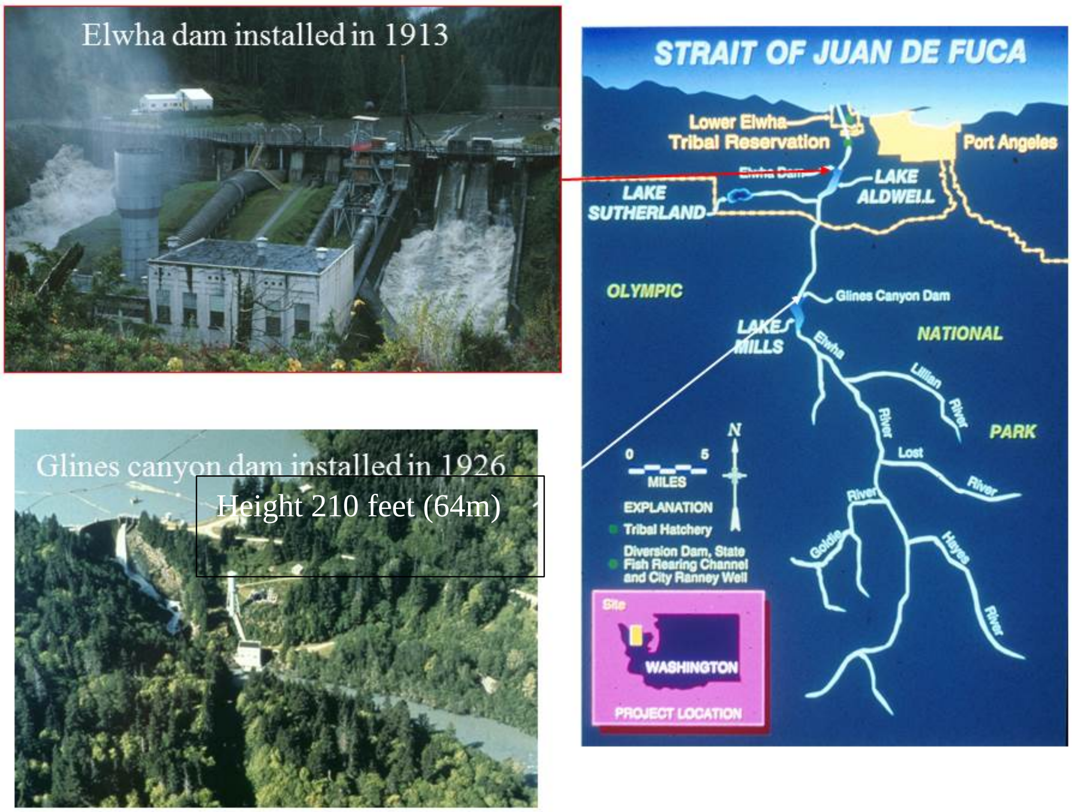

Figure 1.3 Embayed shoreline of Elwha drift cell prior to and during dam removal.

Dam removal began in September 2011 and concluded in September 2014. Substrate suitability for forage fish spawning increased dramatically in the lower river and embayed shoreline regions of the Elwha nearshore during the dam removal process, and persists now that dam removal is complete. Photo credit: Anne Shaffer.

Nearshore sampling Freshwater Bay
Summer 2007

Nearshore sampling Freshwater Bay
Summer 2013

Figure 1. 4 Elwha estuary & lower river before and after dam removals.

A. Estuary in August 2010 (photo credit: John Gussman); B. Estuary in April 2014 (photo credit: Tom Roorda). Mapping estimates indicate that the Elwha nearshore estuary and lower river habitat has grown by approximately 80 acres (Shaffer et al. unpublished data).

Figure 1.5 Outstanding nearshore restoration needs of the Elwha.

A: Elwha feeder bluffs; B. Ediz Hook, spit formation that forms the terminus of the Elwha drift. Historic photo credit (left): Dean Reed (Nippon, retired). Photo credit (right): Anne Shaffer

A1. Elwha feeder bluffs 1929 when first armored

A2. Elwha feeder bluffs 2010

B2. Base of Ediz Hook 2014

B1.Base of Ediz Hook approx. 1930’s

Chapter 2 Nearshore fish community responses to large scale dam removal: implications for watershed restoration and fish management

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Author order and contributions: Shaffer, Anne (developed and led all aspects of study and paper), Francis Juanes (Committee chair), Thomas P. Quinn (study collaborator), Dave Parks (aerial mapping of estuary and lower river), Tara McBride field coordination), Jamie Michel (assisted in field work, coordinated field work), Cayla Naumann (assisted with R analysis), Morgan Hocking (statistical advising), Chris Byrnes (field sampling permitting and technical assistance).

Abstract

The nearshore is a critical zone for northeast Pacific Ocean fish communities, including ecologically and culturally important salmon species. The largest dam removal in the world was recently completed on the Elwha River, with the goal of restoring fisheries and ecosystems to the watershed. The nearshore Elwha fish community was monitored monthly from January 2008 to November 2015 before, during, and after dam removal. As of September 2015, approximately 2.6 million m^3 of sediment material had increased the area of the Elwha to over 150 ha. Newly formed nearshore habitats were quickly colonized by fish communities during the dam removal period but the communities were similar in total species richness and Shannon diversity before and after dam removal, and were similar to a nearby reference site (Salt Creek estuary). Select fish species, including ESA-listed Pacific salmon and trout *Oncorhynchus* spp., and eulachon *Thaleichthys pacificus*, and non-native, American shad (*Alosa sapidissima*), appeared quickly in

these new habitats. Hatchery releases of Chinook, *O. tshawytscha,* coho, *O. kisutch,* and steelhead, *O. mykiss* (over 3 million total fish annually to the lower river), dominated the Elwha estuary catch from April through August of each year before, during, and after dam removal. Chum salmon catch rate, size, and duration of estuary occupancy declined during and after dam removal. Overall catches of chum salmon fry prior to, during, and after dam removal were significantly negatively correlated with Chinook salmon catches but significantly, and positively, correlated with coho salmon. When assessed at the Elwha estuary separately, chum abundance was significantly positively correlated with Chinook, coho, and steelhead abundance. These patterns indicate overlap, and likely interaction between these respective groups of hatchery and wild fish. Continued hatchery releases may therefore further challenge chum salmon recovery and should be considered when planning for watershed recovery.

Introduction

The nearshore of the North Pacific Ocean is critical habitat for numerous species of Pacific salmon (*Oncorhynchus* spp.) and forage fish as they grow, rest, and migrate between spawning and rearing areas (Healey 1982; Simenstad 1982; Thorpe 1994; Quinn, 2005). Many populations of these species, including Chinook (*O. tshawytscha*), coho (*O. kisutch*), and chum salmon (*O. keta*), steelhead (*O. mykiss*), and forage fish including surf smelt, *Hypomesus pretiosus*, eulachon, *Thaleichthys pacificus*, and sand lance, *Ammodytes hexapterus*, are in steep decline across parts of the northeast Pacific (NOAA 2010, 2015, 2016). To reverse these population trends, the United States has spent billions of dollars restoring fish habitat along the Pacific coast over the last decade, including approximately US$30 million a year through the Washington State Salmon Recovery Office (Washington State RCO 2013). Hatcheries are also a complex element of salmon management that can complicate watershed recovery efforts, though little work has been done assessing hatchery impacts to nearshore ecosystems (see Naish et al. 2008 for an overview).

Located on the north Olympic Peninsula, in Washington State, the Elwha River dam removal project is the largest dam removal project completed to date in the United States with the specific, federally mandated intent of restoring native fisheries and ecosystems of the Elwha River watershed (DoI 2005) (Figure 1). The estimated project cost is US$325 million (Olympic National Park 2015). The Elwha River system has populations of all salmonid species native to the region but they were greatly diminished by the dam installations (Pess et al. 2008; Ward et al. 2008).

Chum and pink salmon are important components of northeast Pacific watershed ecosystems as drivers of nutrient cycling. While both species are the most abundant salmon in many watersheds, chum salmon are much larger, do not have an alternating year life cycle (Quinn

2005), and so are especially important from the standpoint of nutrient cycling. The biomass of returning chum salmon predicted the extent of marine nutrient subsidy to species of mosses, herbs, shrubs, trees and insects in riparian areas of coastal British Columbia (Hocking and Reimchen 2009). Further work has also shown that marine nutrients derived from chum and pink salmon transform riparian plant community structure and diversity (Hocking and Reynolds 2011; Hurteau et al. 2016). Adult chum and pink salmon can also provide an important cross-boundary nutrient source to coastal streams, including the production of juvenile coho salmon (Nelson and Reynolds 2014).

Prior to dam installations early in the 20th century, chum salmon were the second most abundant salmon species in the Elwha River (Ward et al. 2008) but before dam removal began in 2011 they had declined to ca. 1% of historic levels (ca. 200 vs. 18000 in the past; Ward et al. 2008). Juvenile chum salmon migrate downstream in their first year of life after at most a short period of residence in the stream, and occupy estuarine waters for several weeks or more (Healey 1982; Simenstad et al. 1982; Salo 1991). In contrast, pink salmon tend to make little use of estuaries and move quickly offshore (Quinn 2005). Due to their important role in supporting ecosystem function, the high potential for their population recovery in the relatively pristine watershed, and strong dependence on the Elwha nearshore, chum salmon are important for the Elwha recovery project.

There are two hatcheries on the lower Elwha River within 3 km of the estuary that, combined, annually released over three million juvenile Chinook and coho salmon and steelhead during the period when juvenile chum salmon are present (Shaffer et al. 2009; Quinn et al. 2013, 2014).

Peters (1996) did not observe any predation by hatchery-produced salmonids on chum salmon in the Elwha River system but recommended that releases be delayed to avoid overlap with chum salmon. Therefore, such possible interactions merit further investigation.

After over two decades of planning, Elwha River dam removals began in September 2011, and were completed by September 2014. The nearshore fish community's response to this sediment delivery to the nearshore lower river and estuary has not been quantified. Our study documents the changes in nearshore habitat due to Elwha Dam removal and the subsequent response of the nearshore fish community, with a focus on juvenile chum salmon. Comparing periods before, during, and one year after dam removal, we investigated whether changes in fish use of the Elwha nearshore, as defined by basic ecological metrics of fish abundance, species composition, diversity, and richness, occurred. We also assessed whether juvenile chum salmon utilization of the estuary changed, and considered what interactions, if any, may have occurred between chum and other salmon species observed in the Elwha estuary. Finally, we assessed the relationship between hatchery practices in the Elwha system and the fish community of the Elwha nearshore. In total this study provides first insights into how nearshore fish communities respond during and in the early years after a large-scale dam removal that involves large sediment delivery to the estuary. This will provide important information for future large-scale dam removals and can guide Elwha nearshore restoration and fisheries management.

Methods

To provide a context for the extent of ecological change in the Elwha River estuary, we mapped the area of the shoreline, delta, and lower river before, during, and after dam removal. A time-series of lower river channel and shoreline positions were digitized from geo-referenced digital ortho-photograph mosaics (WDNR 2011; Randle et al. 2015) for the pre-dam removal (1936-2011), dam removal (2011-2014), and post dam removal periods (2014-2015) using ARC-GIS 10 (ESRI 2010). Control baselines were established in the lower river at the approximate upper limit of tidal influence and on the east and west limits of the active delta. The areal extent (ha) of the delta was then systematically measured over time by digitizing a series of line and polygon shape files in ARC-GIS in relation to the established baselines. Root Mean Square Error (RMSE) for mapped line and polygon positions was on the order of 1-2 m.

We quantified the nearshore Elwha fish community using standardized beach seining techniques (PSWQA 1996) every month from January 2008 to November 2015 using a modified ‘Before, After, Control, Impact (BACI)’ design (Smith et al. 1993). Pre, during, and post dam removal sampling were the “before vs during vs. after” comparison. Sampling in the nearshore of the Elwha River and a nearby, unaffected stream (Salt Creek) were the ‘control vs impact’ component. It should be noted that there are a number of differences between the two rivers of this study. The basin area of the Elwha River is 824 km^2 whereas Salt Creek is smaller (121 km^2) and the Elwha River system is also steeper and glacially-fed whereas Salt Creek is a lower gradient, rain-dominated watershed (Smith 1999; McHenry et al. 2004). Furthermore, Salt Creek has no hatchery in the watershed. Notwithstanding these differences, the Salt Creek nearshore is proximate and thus subject to similar climate influences, is similarly accessible to marine and euryhaline fish species, and has many of the same freshwater fish species. Salt Creek therefore provides a useful comparison to assess variation (rather than a true ‘control’) with respect to the nearshore community.

Two locations were sampled each at the Elwha River and at Salt Creek estuaries each month (Figure 1) on a single day each month during neap tide and daylight hours. Due to unavoidable constraints, the Salt Creek estuary was not sampled during March, April, July-Sept of 2008, and neither site was sampled from July 2009 through January 2010. Two additional sample locations were added along the newly formed Elwha estuary after the large amount of sediment delivered along the Elwha River mouth caused it to grow dramatically, beginning in March 2013. The original sample locations were labeled Elwha 'original estuary sites,' and the new sample locations, Elwha 'new estuary sites' (Figure 1). All fish captured were identified and up to 25 of each were measured to the nearest mm (total length for all non-salmonids, and both total and fork length for salmonids), and then all were released alive on site. All collections were conducted according to guidelines set out by the Canadian Council for Animal Care and protocols approved by the University of Victoria Animal Care Committee, and with permits from the Washington Department of Fish and Wildlife, and NOAA-Fisheries.

For analysis, data were divided into two rivers (Elwha River and Salt Creek), three sample locations (Elwha original, Elwha new, and Salt Creek, each with two seining sites), and three dam removal phases: pre-dam removal (January 2008 – 31 July 2011), dam removal (August 2011-30 August 2014), and post dam removal (Sept 2014- 1 Nov 2015. Four response variables were tested in this analysis: 1) community species richness (number of species collected), 2) community diversity (Shannon-Weiner index), 3) chum salmon abundance, and; 4) chum salmon body size.

Elements of the pre-dam removal fish use data have been published as baseline data by the co-authors, and are provided in their entirety for use in this study to define fish use response to dam removal (Shaffer et al. 2009, 2012; Quinn et al. 2013, 2014). Data were nested by sample location and month, and therefore length, abundance, and richness data were analyzed using generalized linear mixed effect models with a Poisson distribution using the package lme4 in R (R core team 2013, Bates et al. 2015). Abundance data were highly skewed and thus were log transformed to improve model performance. A Gaussian distribution was used for species diversity data. The dependent variables (species richness, diversity, juvenile chum salmon abundance, and body size) were related to the predictive variables (month, location, other salmon species and size, and dam removal phase during the December to June period when chum salmon migrate) through this analysis. Candidate models with different fixed effects were competed through model dredging and averaging of top models with ΔAIC < 4 was performed using the package MuMIn in R (Wagenmakers and Farrell 2004; Bolker et al. 2009; Barton 2012). The random effects were month and sample location for community analysis, and sample location for chum salmon analysis. To better define dam removal effect on chum salmon, additional models were run for chum abundance and length for (December - March) and late (April - June) periods for the Elwha River data. The random effect for this set of models was ‘month’. Table 1 provides a summary of questions addressed by the models, and results of full models are provided in Appendix 3.

We obtained hatchery data from the resource management information system of the Regional Mark Processing Center (RMPC) a subsidiary of the Pacific States Marine Fisheries Commission: http://www.rmpc.org/ and detected a positive correlation between hatchery releases of Chinook salmon, coho salmon, and steelhead trout with our catches of these species for the months of release over the seven years of the study (R^2=0.63 $p<0.05$). We used catches of these three species in our seining data and modeled the relationship between chum abundance and to Chinook, steelhead, and coho salmon catches as an indicator of hatchery influence. The numbers of fish released were not used because the timing of releases varies so much with respect to our sampling that they seemed less representative than our catches.

One of the hatcheries also released, in five of the seven years of our study, chum salmon fry. The chum salmon releases were small and opportunistic, based largely on the interception of spawning adults for brood stock (Patrick Crain, Olympic National Park, pers. comm., Appendix A 3). These releases did not correlate with our monthly catches (R^2=0.29; $p>0.50$; n=5) and were always < 1% of the total number of hatchery fish released. They were also likely a very small fraction of the total number of chum salmon, though there was no enumeration of the wild population. Consequently, we did not consider the chum hatchery releases in any more quantitative detail.

Results

Habitat mapping

Over the 80 years prior to dam removal the lower Elwha River and estuary were dynamic, reflecting ongoing disruption of hydrodynamic processes through lower river diking and sediment starvation from in river dams (Figure 2, Appendix A1). Overall the lower river and estuary ranged from 115 to 122 ha (mean = 119.3) before dam removal began. The area remained similar in 2011 (115.4 ha) and 2013 (116.8 ha) but increased to 142.8 ha in 2014 and

157.7 ha in 2015. The wetted area of the delta also increased to approximately 3 times the pre-dam removal size, from < 4 ha in 1956 to > 15 ha in 2015. The length of the main river channel varied greatly, initially doubling, and then returning to pre-dam removal lengths over the course of four years of dam and post dam removal (Appendix A1).

The largest change in aerial extent of the estuary occurred during 2013-2014, after the second year of the dam removal phase. By the end of the first year of post dam removal, scale and rate of changes in the Elwha delta and shoreline appeared to be decreasing (Table 3, Appendix A1). The sediment and associated wetted area appear to be shifting east with prevailing marine wave energy rather than merely growing. The western shore of the delta expanded during the first months of dam removal but then contracted (Appendix A1).

Fish use of the Elwha nearshore

Species richness ranged from 1-13 over the seasons and years at the Elwha River and Salt Creek locations. The Elwha River was dominated seasonally by Chinook salmon, coho salmon, sculpins (primarily *Leptocottus armatus,* and *Oligocottus snyderi*), and surf smelt, whereas Salt Creek was dominated seasonally by three spine stickleback (*Gasterosteus aculeatus*), shiner perch (*Cymatogaster aggregata*), sculpins, and coho and chum salmon (Table 2, 3). Both species richness and species diversity varied with dam removal phase and location. Species richness was only significantly different during the dam removal phase, when it was higher at the Elwha River than Salt Creek, but not after dam removal. Species diversity was significantly different after dam removal [Table 4, $p<0.001$; $t > 2.0$; Figure 3 and 4, Appendix A4], and significantly higher at the Elwha River than Salt Creek [Table 4, $p<0.001$; $t > 2.0$; Figure 3 and 4, Appendix A4]. Diversity was also affected by the interaction of the two factors (Table 4, $p<0.001$; $t > 2.0$; Figure 3 and 4, Appendix A4). Species diversity and richness indices were not significantly different between original and new estuary locations within the Elwha estuary during the dam removal and post dam removal phases (Figure 3 and 4, Appendix A4).

In general, the species percent composition stayed constant at both rivers over the entire dam removal project. However, there were a few changes in species of fish observed in the Elwha River estuary that were not observed at the comparative site, nor detected by the community analysis. Three species, bull trout (*Salvelinus confluentus*), eulachon, and redside shiner (*Richardsonius balteatus*) were observed consistently in the Elwha west estuary, but not at Salt Creek, within weeks of dam removal initiating, through dam removal, and post dam removal (Table 2 and 3). Eulachon were observed during winter months, primarily in the new habitat and most were gravid, or spent. Bull trout were observed in all months except early fall, and in new and original sampling locations of the Elwha. In addition, a non-native species, American shad (*Alosa sapidissima*) was observed for the first time in the Elwha nearshore during the second year of dam removal (2013) through the first year of post dam removal. Prior to dam removal this species was only observed at Salt Creek. Finally, adult chum salmon were observed in the original Elwha River estuary for the first time in November 2015, and were spawning there in 2016 (Shaffer, personal observations).

Juvenile salmon were the dominant component of the lower Elwha River and estuary community (but not Salt Creek) from January through August in all years. Salmon species percent composition of the Elwha catches reflected both hatchery release species and proportions throughout this study. Chinook and coho salmon abundance in the Elwha estuary decreased during dam removals and increased after dam removals concluded (Table 2, 3) but the results were influenced by hatchery releases during all three phases of the project. For all years, juvenile Chinook was the dominant salmon species in the Elwha nearshore and annually ranged from 20-90% of the salmon present, followed by coho salmon (4-60% of all juvenile salmon in the Elwha nearshore annually). Juvenile Chinook, coho, and steelhead proportions mirrored those of annual hatchery releases in the system (Appendix A3). In contrast, juvenile coho and chum were the only salmon observed consistently at Salt Creek over the course of the study.

Percent abundance of both juvenile Chinook and chum salmon dropped in the Elwha original sites during dam removal. Chinook salmon catches, however, increased at the Elwha new sites after dam removal. In contrast, Elwha coho salmon percent composition changed little during dam removal, at 16% or less of all salmon in new site catches. The relative contribution of juvenile chum salmon to overall percent composition of fish species stayed fairly constant, and low relative to the mean percent composition of other salmon species over the study period at both new and original sites of the Elwha River and Salt Creek estuary sites (Table 2, 3).

All juvenile chum salmon in this study were caught from December through June. During this period, month was the strongest predictor for chum abundance, with maximum catches in March. In addition, other species of salmon, site, dam removal, and the interactions of site and dam removal project phase had significant effects in February-June ($p<0.001$, Figure 5A and B, Table 4). Prior to, during, and after dam removal, chum salmon appeared in the Elwha nearshore by

March, two months earlier than at Salt Creek. During dam removal, chum salmon were first observed at the Elwha during the same months as pre-dam removal, but fish were present in the Elwha estuary for a shorter time period. During and after dam removal, juvenile chum were not observed in either the Elwha original or new locations after March (Figure 5A).

Juvenile chum salmon abundance was significantly related to dam removal phase, and the interaction of dam removal and site, as well as other species of salmon. Overall, juvenile chum catches in both estuaries were significantly, negatively correlated to Chinook catches, and significantly positively correlated with coho before, during, and after dam removal ($p<0.001$; Table 4, Appendix A4). Assessing Elwha estuary alone, chum abundance was significantly, and positively correlated to Chinook, coho, and steelhead, and was also significantly lower at the Elwha after dam removal ($p<0.001$, Figure 6, Table 5 Appendix 4). In addition, catches from April through June (‘late season’) were significantly lower during and after dam removal than before dam removal ($p<0.001$ and $p<0.005$, respectively).

Juvenile chum salmon size was related to several factors. Prior to dam removals the Elwha River chum salmon were larger (and arrived earlier) in the nearshore than were those at Salt Creek ($p<0.007$, Figure 7b, Table 4). During dam removals, Elwha chum salmon were smaller than those at Salt Creek ($p=0.014$) but after dam removal, the Elwha River chum salmon were once again larger than those at Salt Creek ($p<0.001$).

The two hatcheries released a total of 1.7 to 3.5 million Chinook, coho, and steelhead smolts annually over the course of this study. Most hatchery releases of Chinook, coho, and steelhead from 2008-2015 began in March and extended through June, and so overlapped with chum salmon migration (December through June; Appendix A2). When compared by month, average length of Chinook and coho salmon and steelhead were at least 50% larger than chum salmon for most of these releases. Assessing over the migration period, the Elwha River estuary chum salmon were significantly larger from April through June than earlier in the season (December through March). Chum salmon were therefore smaller than before dam removal, due in large part to their early exit from the estuary.

Discussion

This work provides a number of important insights into the nearshore ecological response to large scale dam removals, including changes in the habitat extent, fish species use, interaction between species, and effects of processes (i.e., hatchery releases) distinct from the dam removal. Prior to dam removals the Elwha estuary was virtually non-existent. Though sediment deposition from dam removals increased the delta shorelines and estuary to approximately 150 ha, the estuary is still very small for the size of the river, and so all the more important for the function it provides to the nearshore of this region. A large proportion of the aerial extent of the new estuary and lower river habitat at the Elwha River mouth and shoreline was created within the first 15 months of dam removal, and was immediately used by fish along the delta and shoreline. Fish community metrics (species richness and diversity) of the new areas were not significantly different than those of the original areas, indicating that the Elwha new and original nearshore is functioning similarly for fish across the lower river and delta before, during, and a year after dam removal.

We are still early in the estuary restoration process. Ultimately the habitat stresses to the fish community of the Elwha delta due to large sediment loads from dam removal should be temporary, and river conditions for migrating salmon, including chum, should stabilize as the sediment delivery from dam removal decreases. The newly formed lower river and estuary habitat should continue to transition/stabilize into a ‘normal’ system, the vegetative communities should mature, and so provide additional habitat and prey resources for additional species as well as juvenile chum refuge, feeding, and transition to salt water, and possibly spawning habitat for adults. In the long term the estuary will likely evolve to include detrital-based fauna, possibly increasing harpacticoid copepods that are important prey for juvenile salmon, including chum salmon (Sibert et al. 1977; Sibert 1979; Healey 1979).

The similar and variable fish species richness and diversity values during dam removal, and the first year of post dam removal phases at the Elwha River and Salt Creek nearshore sites are consistent with earlier studies that documented high seasonal and interannual variability in the nearshore fish community in the Elwha prior to dam removal (Shaffer et al. 2012) and in other areas (Weitkamp et al. 2014). These results indicate that, as of one year after dam removal was completed, the juvenile fish community species diversity and richness of the Elwha estuary was resilient to the high volumes of sediment and hydrodynamic changes in the lower river and estuary. Month of the year was the dominant factor affecting which, how many, and the proportion of fish species utilizing the Elwha River and Salt Creek estuaries, consistent with other studies suggesting that seasonal variability is the dominant factor determining nearshore fish community structure in northeast Pacific systems (Miller et al. 1980, Fresh 2006, Shaffer et al. 2008, 2012). Specifically, the seaward migrations of salmonid fishes show a very strong seasonal component, linked to the basic life history of the species (Quinn 2005), and this was a dominant signal in the data.

The addition and persistence of new species, including bull trout, redside shiner, and eulachon to the lower Elwha River and estuary at the beginning of dam removal, and the first observation of adult spawning chum in the original estuary site one year after dam removal ended, were consistent with the physical changes documented by Draut and Ritchie (2015), East et al. (2015), and Foley et al. (2015). Specifically, the Elwha River mouth and tidally influenced areas have shifted north by over 100 m, and the original estuary area was, at the end of 2015, no longer tidally influenced. Thus, as the river mouth pushed north, new estuary areas were formed, and areas that were originally estuary are now freshwater and just at the head of tide. The increase in species richness and diversity during and after dam removal at Elwha reflects this increase in complexity of nearshore habitats created from sediment delivered after dam removal.

This increase in size and complexity of the lower river and additional estuary and freshwater habitats were reflected in changes in the Elwha fish community, which in turn have implications for recovery. Eulachon are a particularly important addition to this habitat. A US federally listed forage fish, eulachon spawn in natal rivers at the head of tide (Fisheries NOAA 2015), and are a priority for northeast Pacific restoration. Eulachon were documented in the Elwha River prior to dam removal (Shaffer et al. 2008) but were not observed in the estuary or lower river side channels prior to dam removal. Similarly, the presence of spawning chum salmon in the newly transformed lower river side channels (directly observed in the fall of 2016) indicates this area may be providing an important new function for restoring salmon spawning reaches in the lower river.

The fish community composition of the Elwha lower river and estuary appears to be defined by factors in addition to dam removal, including hatcheries. When compared proportionally, salmon abundance in the Elwha estuary mirrored salmon percent compositions released annually from the hatchery over the course of this study, irrespective of dam removals. For example, Chinook, coho, and steelhead were the dominant species released from the hatcheries and the dominant salmon in our catches, and seasonally dominated the fish community.

Our sampling also revealed interesting timing differences in juvenile salmon use of the nearshore. Prior to dam removal, Elwha River chum salmon arrived in the estuary approximately two months before they did in Salt Creek, and were the same size or slightly larger than Salt Creek chum salmon. Pacific salmon populations, including chum, often differ in the timing of adult return migration and spawning but the juveniles tend to migrate to sea at similar times in a given area (Tallman and Healey 1991). As described earlier, the Elwha River system is much larger and in many ways different than the Salt Creek basin so different adult timing would not be unexpected. However, the timing of juvenile migration would be expected to be similar, given the spatial proximity of the two systems and similar abundance of nearshore resources for them as forage. The difference in timing may reflect the effects of the hatchery releases of other salmon species on the Elwha River chum salmon population, resulting in a selection for early timing of chum outmigration to avoid or minimize interactions with the other species. In addition, the high sediment loads during dam removal shifted water quality regime in the river

(East et al. 2015; Foley et al. 2015), perhaps contributing to earlier and more rapid exit from the Elwha estuary and river system during dam removal.

It is also important to note that chum salmon size was related to dam removal phase. During dam removal, chum fry left the Elwha estuary sooner than other dam removals stages, and at a smaller size overall, but chum salmon in the Elwha estuary at any given month were not significantly smaller than in the same months during other phases of dam removal. One year after dam removal completed, the post dam removal size of juvenile chum salmon present in the Elwha appears to be increasing, suggesting that dam removal effects on chum size and abundance may be temporary.

The dominance of hatchery fish in the Elwha estuary fish community is likely attributed to the small size of the Elwha estuary relative to the river, the large numbers released from hatcheries relative to the wild populations, and the proximity of hatcheries to the estuary. Such preponderance of hatchery-origin salmonids is not unlike some other northeast Pacific estuaries, though many others are dominated by or exclusively occupied by wild populations (Weitkamp et al. 2014). Further, our results indicate that this dominance appears to be affecting fish interactions in the Elwha estuary and lower river. Chinook, steelhead, and coho abundance in the Elwha estuary and lower river were largely defined by hatchery releases, and juvenile chum abundance was significantly and positively correlated to Chinook, steelhead, and coho abundance. The two months when juvenile chum salmon abundance was not significantly related to Chinook salmon abundance (April and May) were the months of and after the hatchery released chum fry, providing a pulse of chum to the estuary and masking, or possibly temporarily reducing changes in chum salmon abundance due to interactions. Collectively these observations indicate that hatcheries are playing an interactive role in fish use of the Elwha nearshore.

Collectively, the lower abundance and smaller size of Elwha estuary chum salmon relative to both the Salt Creek chum salmon and pre-dam removal phase Elwha estuary fish, and the earlier exit from the Elwha estuary during dam removal were likely all due in part to physical environmental stress, including likely trophic disruptions in the ecosystem.

Harpacticoid copepods are the principal food of chum salmon during the first critical weeks of estuarine life. Harpacticoids, in turn, depend on heterotrophic food sources, and primarily the bacterial flora associated with organic detritus. In general, estuaries receive pulsed inputs of detritus from several sources including vegetation from landward and downstream transport from the upland areas of the watershed. Chum residence in estuaries is thus related to a detritus-based, benthic derived food web (Sibert et al. 1977; Sibert 1979). Given the extremely small size and high energy nature of adjacent Elwha shoreline areas prior to and during dam removal, the detrital food web of the Elwha estuary was likely defined by the Elwha River. East et al. (2015), Foley et al. (2015) and others documented dramatic shifts in estuary water quality and configuration due to river sediment loads associated with dam removal. These shifts likely affected the harpacticoid/detrital systems in the estuary and lower river, and may also have temporarily decreased food resources, resulting in a shorter chum residence in the estuary (Healey 1979).

Modeling results also indicated that the timing and numbers of chum salmon in the Elwha estuary during dam removal were correlated with juvenile Chinook, steelhead, and coho abundance, all of which were driven by the large hatchery releases. Chinook salmon dominated the releases numerically, and occurred at the peak of the chum salmon migration. The interactions between juvenile chum and Chinook salmon might include competition for food (Cordell et al. 2011) and predation. Duffy et al. (2010) reported that Chinook salmon preyed on fish up to 50% of their length. This is within the size ranges of Chinook smolts and chum fry we observed in the estuary but at the extreme ends of the distributions (i.e., large Chinook and small chum salmon). This could explain the significant negative relationship between the two species over both study sites. The coho salmon and steelhead are larger at release and so also potential predators on chum salmon (especially coho salmon: e.g., Parker 1971; Fresh and Schroder 1987) but tend to move through estuaries more rapidly than do chum and Chinook salmon. This could account for the significant positive relationship between chum and Chinook, coho, and steelhead at the Elwha estuary alone. Unfortunately our sampling was not intense enough to fully detail the species interactions. When considered together, the mixed negative and positive relationships indicate that these species are overlapping despite management recommendations that hatchery actions be modified to prevent interaction with chum salmon. Overall, our work indicates that the nature of ecological interactions between chum, Chinook, coho, and steelhead is complicated, and that here and in other restoration projects, the mix of species and the proportions of wild and hatchery origin populations may affect the behavior and ecology of the species involved.

The beneficial expansion of estuary and lower river habitat for juvenile chum salmon and other fishes discussed above could be offsetting the temporary detrimental effects of high sediment loads during the dam removal phases, further complicating the detection of causal connections between habitat alteration and fish population responses. However, hatchery releases will continue to affect the fish community of the Elwha estuary and lower river. More detailed study is therefore important to define ecosystem functions of the evolving estuary and interspecies interactions with hatchery management practices.

In summary, the fish communities of Elwha delta, shoreline, estuary and lower river were resilient, supporting a variety of fish species through the dam removal phase of the Elwha restoration project. Fish began using the newly formed estuary and lower river habitats as soon as the habitats became available, resulting in a somewhat higher species richness and diversity in the Elwha nearshore. This included non-native species, indicating that ‘pioneering’ by invasive species may be a concern. Chum salmon showed evidence of effects during the dam removal phase but this appeared to be temporary. There appears to be significant correlation between chum and other species of salmon in the nearshore, and in the Elwha estuary that may indicate interactions. Juvenile Pacific salmon dominated the fish community of the Elwha delta in the spring, and hatchery-produced fish were a large component of these populations. Consequently, behavioral and ecological interactions between wild and hatchery-origin cohorts of these species in the still-small estuary may influence the performance of species of concern such as the wild chum salmon that are important for watershed recovery.

Large scale dam removals are becoming an important tool for ecosystem recovery. This work provides conclusive evidence of nearshore fish community resilience, and rapid restoration associated with dam removal. To achieve full ecosystem recovery, it is important to integrate and prioritize the nearshore and estuary life histories of fish communities, and species interactions, in long term dam removal planning and adaptive management. It is also important to consider in detail and properly address hatchery management actions relative to nearshore ecosystem function.

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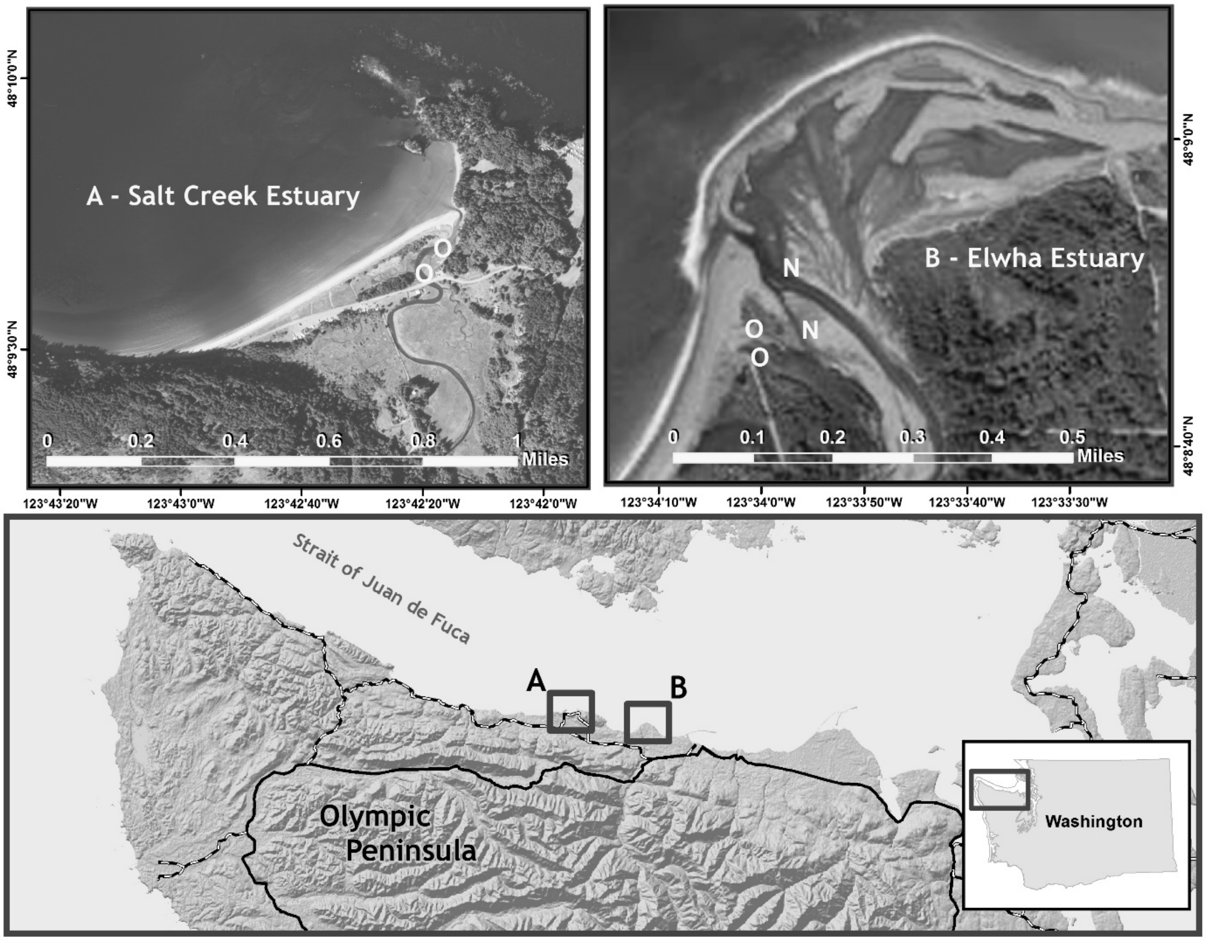
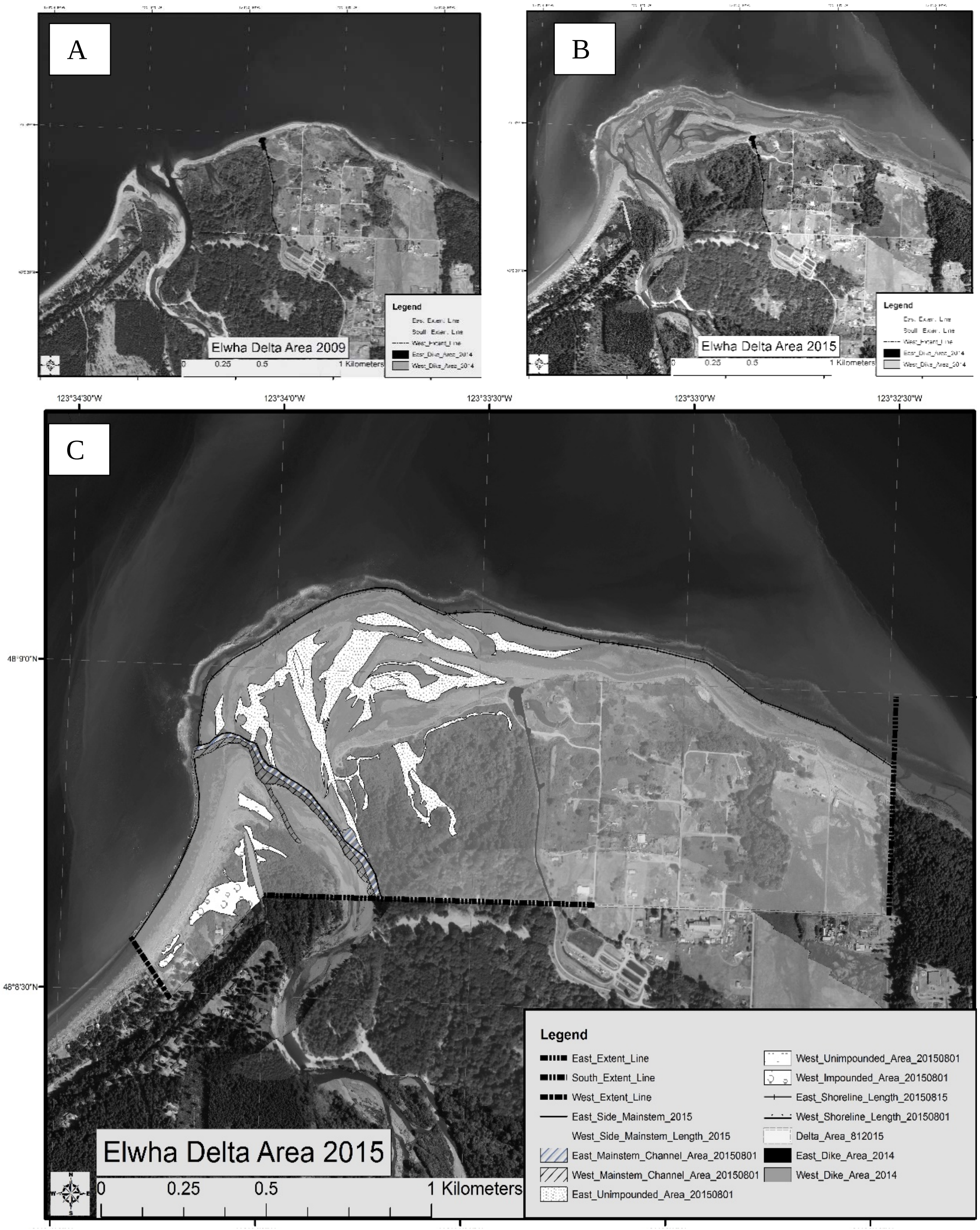


Figure 2.1 Elwha River and Salt Creek study sample sites.

Map by Terry Johnson, WDFW. O=original sites sampled 2008-present; N=New sites created from delivery of dam removal sediment and sampled from 2013-present.

Figure 2.2 Sediment distribution and example of mapping of aerial extent of the Elwha River delta, shoreline and lower river, and wetted area coverages 1956-2015.

A. 2009; B. 2015. C. Summary extent of classes mapped in Appendix.



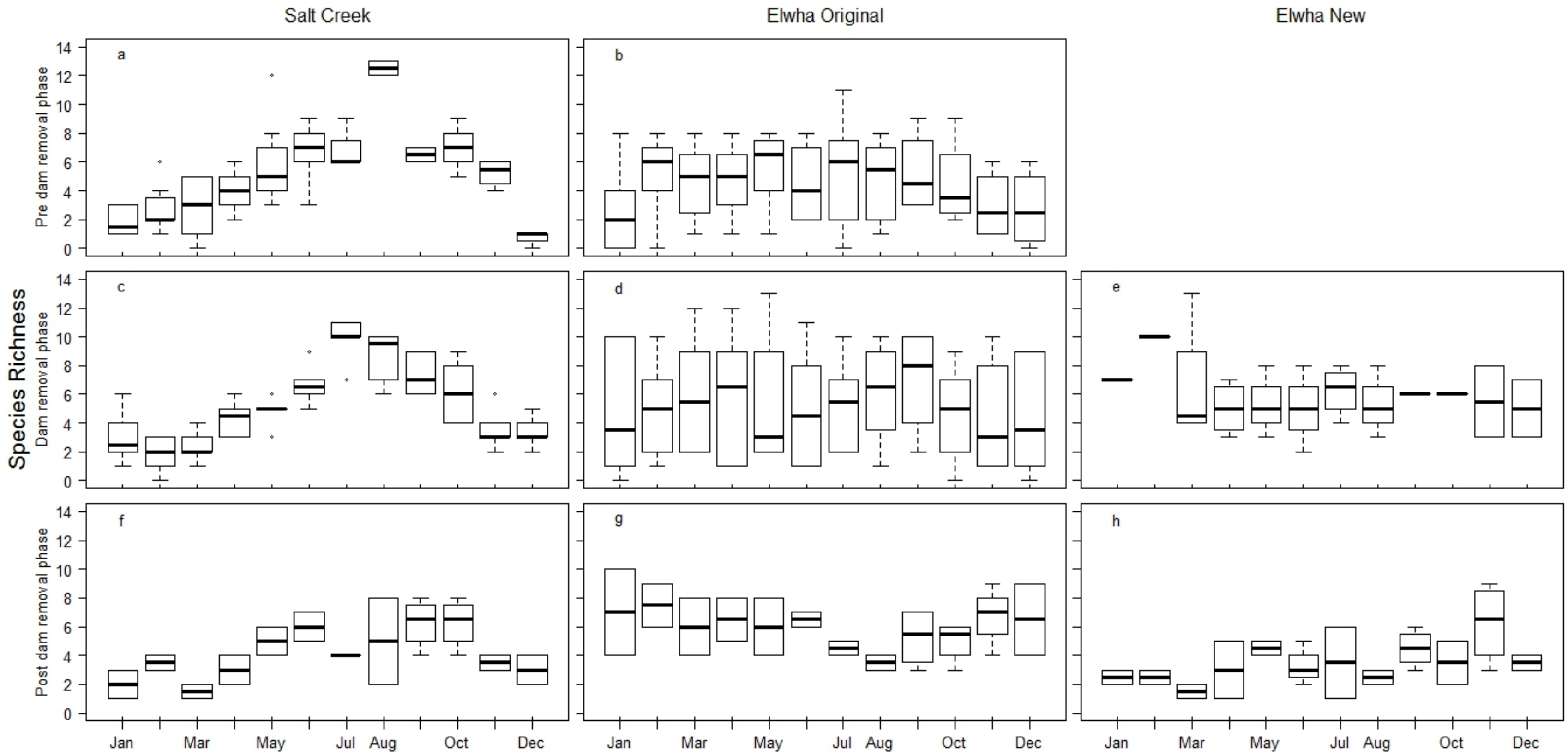


Figure 2.3 Median, first and third quartiles, min and max values and outliers of species richness of the Elwha River and Salt Creek nearshore fish communities.

Pre (2008-2011), during (2011-2014), and one year post Elwha dam removal (2015). Elwha sampling sites include the original sites prior to dam removal and new sites created by sediment delivery during dam removal.

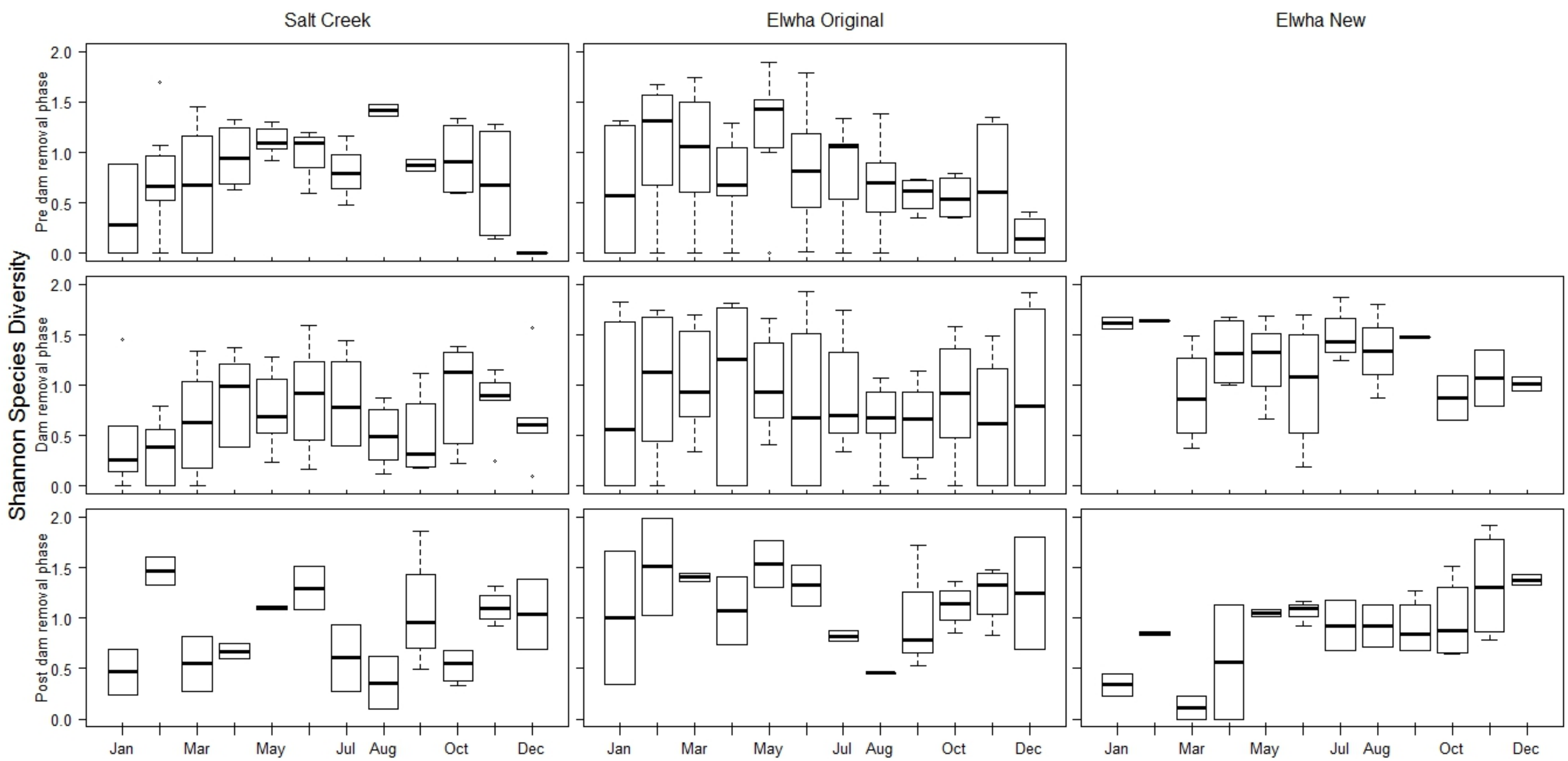


Figure 2.4 Shannon index of species diversity of the Elwha River and Salt Creek nearshore fish communities. Median, first and third quartiles, min and max values and outliers for

Pre (2008-2011), during (2011-2014), and one year post Elwha dam removal (2015). Elwha sampling sites include the original sites prior to dam removal and new sites created by sediment delivery during dam removal.

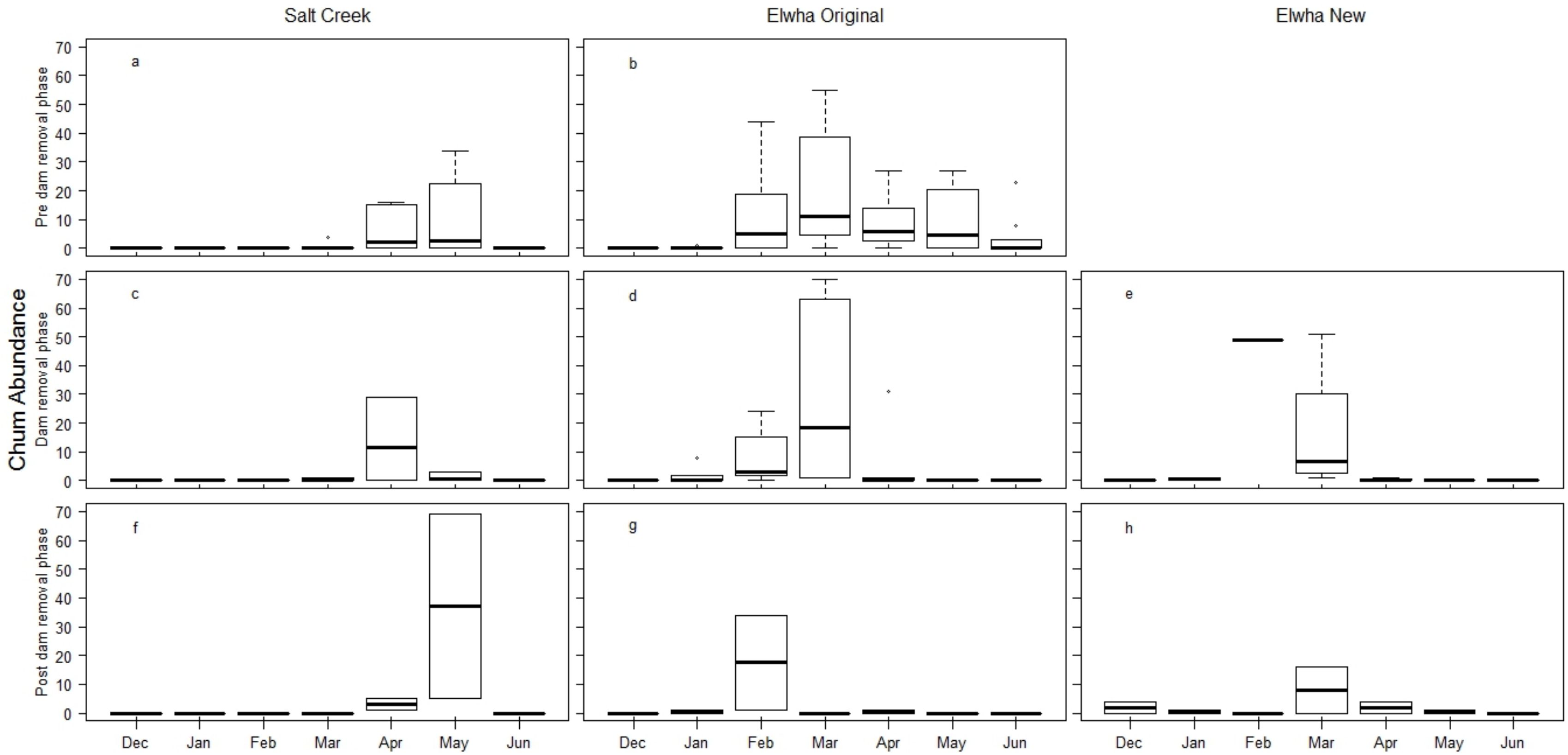


Figure 2.5a Median, first and third quartiles, min and max values and outliers of number of juvenile chum salmon per site and date (catch) from December to July in the Elwha River and Salt Creek nearshore.

Pre-dam removal (2008-2011), dam removal (2011-2014) and post dam removal (2015) phases. Elwha sampling sites include the original sites prior to dam removal and new sites created by sediment delivery during dam removal.

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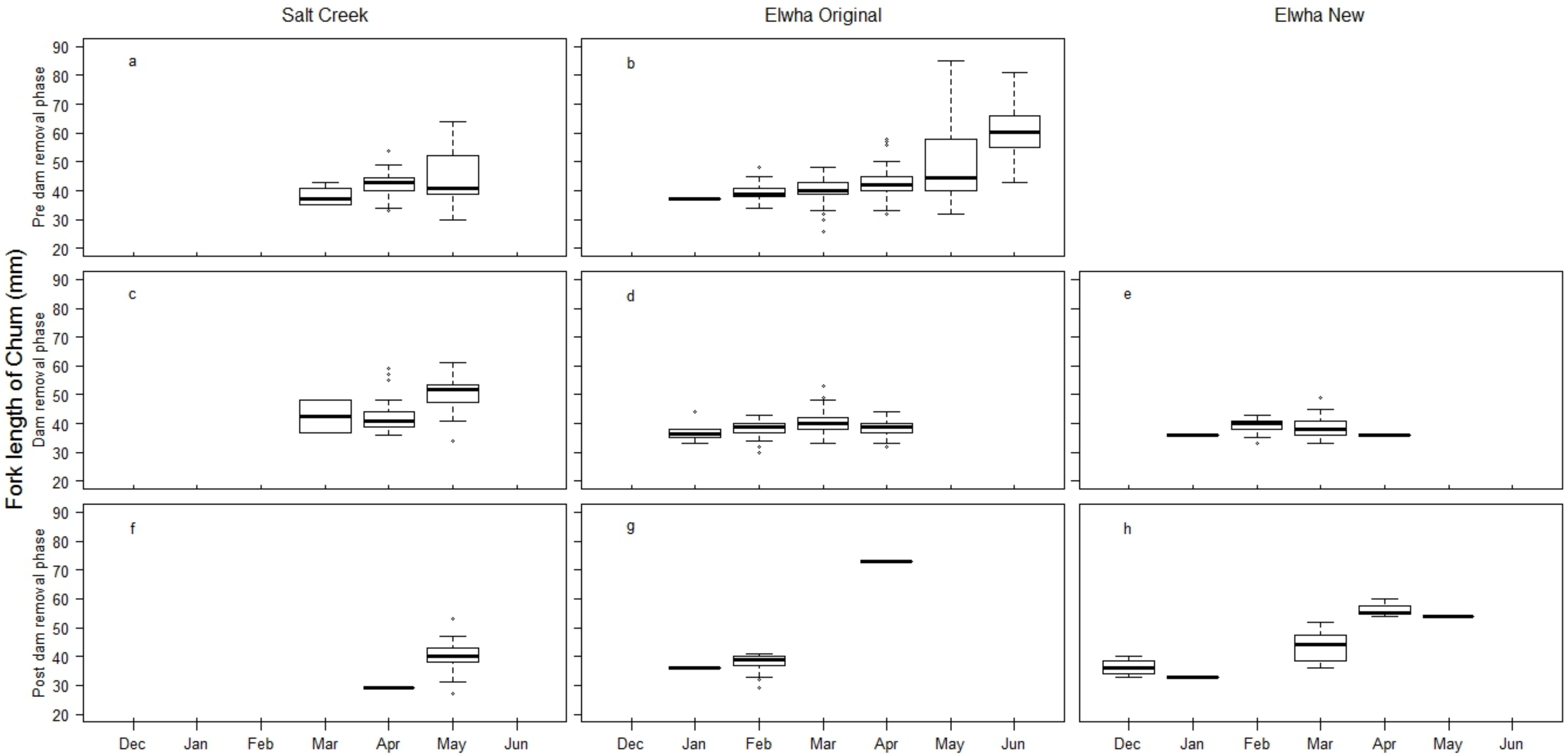


Figure 2.5b Median, first and third quartiles, min and max values and outliers of juvenile chum salmon length from December to July in the Elwha River and Salt Creek nearshore. Pre-dam removal (2008-2011), dam removal (2011-2014) and post dam removal (2015) phases. Elwha sampling sites include the original sites prior to dam removal and new sites created by sediment delivery during dam removal.

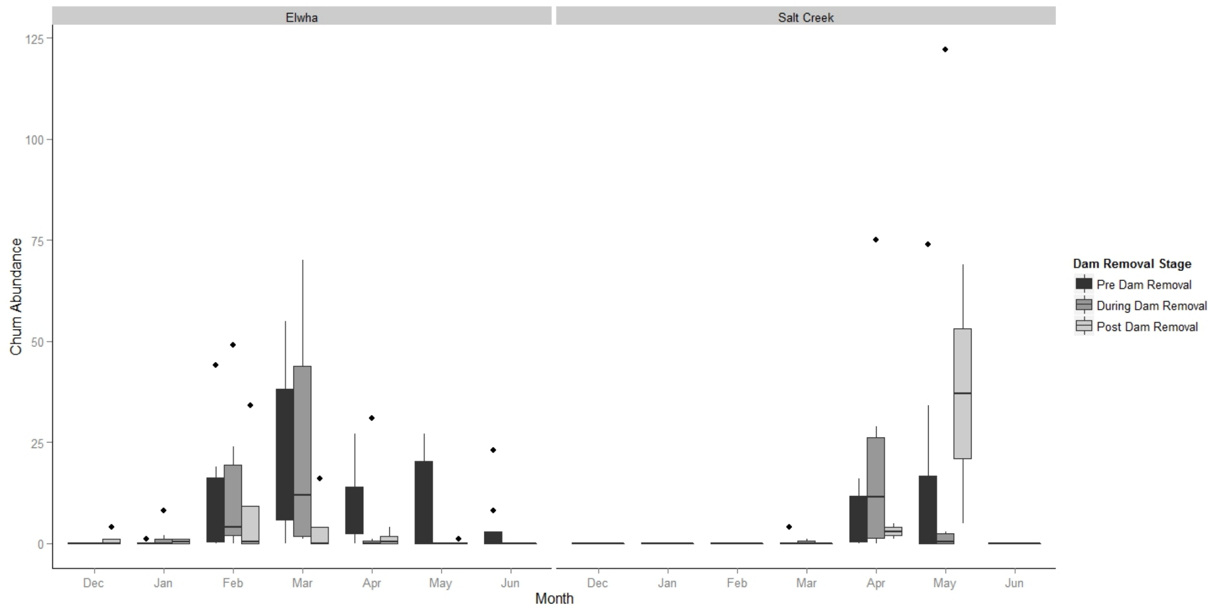


Figure 2.6 Juvenile chum salmon abundance by month.

Elwha River (left side) and Salt Creek (right side) nearshore areas before, during and post Elwha dam removal. Bold lines are median values; top and bottom of squares are first and third quartiles. Horizontal lines are the minimum and maximum values if no outliers are displayed. On boxes with outliers whiskers represent 1.5 times the interquartile range-or approximately 2 standard deviations

Table 2.1 Mixed effects models used for data analysis

Hypothesis	Model Parameters	Response Variable	Random effect
Fish community species richness is related to dam removal, site, site*dam removal interactions	Dam removal phase, site, interaction of site*dam removal phase	Species richness	Sample location, Month
Fish community species diversity is related to dam removal, site, site* dam removal interactions	Dam removal phase, site, interaction of site*dam removal phase	Species diversity	Sample location, Month
Juvenile chum salmon abundance is related to dam removal, site, site* dam removal interactions, and other species	Dam removal phase, site, interaction of site*dam removal phase, Chinook, coho, and steelhead abundance	Chum abundance (both sites)	Sample location
Juvenile chum abundance is related to dam removal, early/late outmigration season, other species, and dam removal* season interactions	Dam removal phase, other salmon species, and chum outmigration season (defined as early (December through March) and late (April thru June), interaction of dam removal phase*season.	Chum abundance Elwha only	Month
Juvenile chum salmon length is related to dam removal, site, interaction of dam removal*site	Dam removal phase, site, interaction of site*dam removal phase	Chum length (both sites)	Sample location

Table 2.1 Mixed effects models used for data analysis, contd.

Hypothesis	Model Parameters	Response Variable	Random effect
Juvenile chum salmon length at the Elwha is related to dam removal, site, and interaction of dam removal* outmigration (early/late) season	Dam removal phase, other salmon species, and chum outmigration season (defined as early (December through March) and late (April through June), interaction of dam removal phase*season.	Chum length Elwha only	Month

Table 2.2 Total abundance and percent juvenile fish species composition Elwha River estuary 2008-2015.

Red line indicates dam removal. Black line indicates the end of dam removal. Italics and bold are new species to appear after dam removal.

Elwha

	Original estuary								**New estuary**		
Year	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2013**	**2014**	**2015**
Total Fish	**5300**	**2192**	**19527**	**4647**	**3157**	**2668**	**11957**	**4384**	**1712**	**3008**	**1385**
Chinook salmon *Oncorhynchus tshawytscha*	36%	30%	71%	8%	5%	3%	2%	13%	6%	26%	24%
Coho salmon *O. kisutch*	6%	14%	6%	10%	16%	6%	2%	7%	4%	7%	1%
Chum salmon *O. keta*	2%	7%	1%	1%	4%	1%	1%	1%	3%	2%	2%
Cutthroat trout. *clarkii*	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Steelhead trout *O.mykiss*	0%	0%	0%	0%	1%	0%	0%	1%	0%	0%	0%
Unid trout *Oncorhynchus spp*	1%	0%	0%	0%	1%	0%	0%	0%	0%	0%	0%
Bull trout *Salvelinus confluentus*	0%	0%	0%	0%	0%	0%	0%	1%	0%	0%	0%
Surf smelt (juv&adult) *Hypomesus pretiosus*	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
3-Spine stickleback *Gasterosteus aculeatus*	39%	39%	5%	23%	47%	74%	91%	70%	65%	3%	3%
Starry flounder *Platichthys stellatus*	3%	1%	0%	1%	1%	0%	0%	0%	6%	4%	19%
Staghorn sculpin *Leptocottus armatus*	9%	8%	2%	5%	6%	2%	0%	0%	6%	43%	27%
Prickly sculpin *Cottus asper*	*1%*	*0%*	*0%*	*3%*	*11%*	*9%*	*1%*	*2%*	*9%*	*3%*	*20%*
Redside shiner *Richardsonius balteatus*	*0%*	*0%*	*0%*	*0%*	*3%*	*1%*	*2%*	*2%*	*0%*	*0%*	*0%*
Eulachon *Thaleichthys pacificus*	*0%*	*0%*	*0%*	*0%*	*0%*	*0%*	*0%*	*0%*	*0%*	*0%*	*10%*

Table 2.3 Percent dominant fish species sampled in the Salt Creek estuary 2008-2015.

2008 was not sampled March-June, July-Sept.

	2008	2009	2010	2011	2012	2013	2014	2015
Total fish	**2256**	**2018**	**4678**	**7523**	**12655**	**11173**	**8019**	**2879**
Chinook salmon *O. tshawytscha*	0%	0%	0%	0%	0%	0%	0%	0%
Coho salmon *O. kisutch*	0%	35%	7%	5%	20%	5%	2%	1%
Chum salmon *O. keta*	4%	2%	1%	0%	1%	0%	1%	3%
Cutthroat trout *O. clarkii*	0%	1%	0%	0%	0%	0%	0%	0%
Starry flounder *P. stellatus*	2%	1%	2%	0%	0%	0%	1%	0%
3-Spine stickleback *G. aculeatus*	0%	10%	4%	0%	0%	3%	3%	27%
Shiner perch *C. aggregata*	66%	29%	63%	72%	65%	72%	73%	42%
Staghorn sculpin *L. armatus*	25%	21%	16%	12%	8%	15%	17%	24%
Surf smelt *H. pretiosus*	0%	0%	0%	8%	0%	0%	0%	0%

Table 2.4 Top mixed-effects models that predict Elwha nearshore fish community species richness, community diversity, chum salmon abundance, and chum salmon body size.

Models are ranked using AIC. Top contributing models (Δ AIC<4) for each analysis (by italic) are listed. Δ AIC= change in AIC score from top model, Wi = AIC model weight. The models are ordered by decreasing weight. Site = Elwha/Salt Creek, DRS=Dam Removal Stage; SL=Sample location (Original/New). Season = chum outmigration period (early = Dec through March, late = April through June). Random effects for noted as 1|effect and are, for community indices through= month, and sample location. Random effect for chum abundance = sample location. Random effect for chum length and abundance, Elwha only, = month. Interactive terms are cojoined with ':' Coefficients, Standard Errors, and P-values are listed in Appendix 4.

Model	Δ(AIC)	Wi	Best model better than this model by factor of
Species richness			
DR, (1| SL), (1| Month)	0.00	0.64	1.00
DRS, Site, (1 | SL), (1| Month)	2.00	0.24	2.71
DRS, Site, Site:DRS, (1 | SL), (1| Month)	3.20	0.13	4.95
Species diversity			
DRS, site, Site:DRS, (1 | SL), (1 | Month)	0.00	0.46	1.00
DRS, (1 | SL), (1 | Month)	0.50	0.36	1.28
Site, DRS, (1 | SL), (1 | Month)	1.60	0.21	2.22
Site, (1 | SL), (1 | Month)	2.48	0.13	3.45
DRS, Site, Site:DRS, (1 | SL)	4.50	0.05	9.47
Chum abundance both sites, individual interactive species			
Chinook, Coho, Steelhead, Month, DRS,Site, Site:DRS, (1|SL)	0.00	0.37	1.00
Chum abundance Elwha only			
Chinook, Coho, DRS, Season, Steelhead, DRS:Season, 1|Month	0.00	0.85	0.99
Coho, DRS, Season, Steelhead, DRS:Season, 1|Month	3.90	0.12	6.99
Chum fork length (both sites)			
Month, DRS, Site, Site:DRS, (1 | SL)	0.00	0.83	1.01
Month, DRS, Site, Site:DRS, Site:Month, (1 | SL)	3.17	0.17	4.94
Chum fork length Elwha only			
Season, DRS, (1 | Month)	0.00	0.58	1.00
Season, SL, DRS, (1 | Month)	0.78	0.39	1.48

Table 2.5 Poisson regression model estimated average chum abundances.

Upper and lower 95% CIs by site and dam removal phase. Month was excluded from the model to get averages across all months. 95% CIs were computed using the mcprofile package in R (Gerhard 2014).

					Percent change/difference from		
Dam removal phase	Site	Chum abundance (average number of fish per sample)	95%CI		Previous dam removal phase	Pre-dam removal phase	Control site
			Lower	Upper			
Pre dam removal	Elwha	9.86	8.48	11.41			338%
Dam removal	Elwha	5.53	4.83	6.30	-44%	-44%	126%
Post dam removal	Elwha	2.11	1.62	2.70	-62%	-79%	36%
Pre dam removal	Salt Creek	2.91	2.39	3.53			
Dam removal	Salt Creek	4.39	3.61	5.31	51%	51%	
Post dam removal	Salt Creek	5.84	4.52	7.43	33%	101%	

Chapter 3 Changes in nearshore functional diversity associated with large-scale dam removals.

Abstract
Functional diversity is an important ecological component for understanding nearshore systems. In this study, functional diversity indices of functional evenness, richness, dispersion, divergence, and Rao's quadratic entropy were determined relative to other fish community studies and to a large- scale dam removal project. Our work indicates that while species richness and taxonomic diversity do not appear to have a significant response to dam removal, functional diversity in the nearshore does respond significantly to dam removals. I attribute these changes to three main shifts in the nearshore: large-scale and rapid creation of estuary habitats; delivery of large amounts of sediment to the delta/estuary in a short period of time, and; a shift in original habitats from tidally influenced to non-tidally influenced habitats. The functional response was different between original and new sites created from the restoration action. Changes in functional diversity occur disproportionately in the new sites, which are also more unstable both physically and ecologically, and so less resilient functional communities. Functional diversity in the original estuary sites appears to be more resilient than in the newly created sites due to the large scale environmental disruption that, ironically, created the new sites. However, the functional diversity at the original sites may be defined in part by management activities, including hatcheries that could mute/mask/inhibit other community responses. Further, functional diversity at the newly formed nearshore areas is predicted to stabilize as the habitats are vegetated and mature. Principal components analysis of Elwha fish community over the course of this study reveals that the fish communities of the Elwha are predictably grouped, indicating that dam removal has not resulted in observable disruptions in fish community assemblages.

Introduction
Community assemblage is a key dimension for understanding how an ecosystem works. Community richness, evenness, and diversity help to understand the structure of marine communities, and as well as how marine communities respond to disrupted ecosystem processes. Functional, or trait based, community composition has been found to be a more informative tool

for community composition and changes than species community diversity indices (Botta-Dukat et al. 2005; Petchey and Gaston 2005). For example, functional diversity, defined by Mouillot et al. (2007) as ‘the value and range of functional traits of the organisms in a given ecosystem’ is a key factor for ecosystem processes and ecological interactions, particularly for coastal fish communities. Defining the functional assemblages of fish communities is therefore becoming an important tool to understanding nearshore ecosystem structure and challenges (Mouillot et al. 2007) as well as the resilience of nearshore ecosystems. Functional diversity encompasses numerous indices that describe various aspects of functional trait space (Bourdon 2016).

There are a number of functional diversity traits that are used to quantify biodiversity, ecosystem functioning and environmental constraints. There are no set guidelines for the number of traits to use for assessing a community. Rather, traits selected to assess functional diversity should be limited to those traits that are important and accurately reflect the system (Petchey and Gaston 2005). Functional trait space is often multidimensional because usually more than one trait is required to effectively describe species. Functional diversity is defined as the distribution of species in a functional space whose axes represent functional features. Functional richness represents the amount of functional space occupied by a species assemblage. Functional dispersion is a multidimensional functional diversity matrix (Laliberte et al. 2014). Functional evenness corresponds to how regularly species abundances are distributed in the functional space. Functional divergence defines how far species abundances are from the center of the functional space (Mouchet et al. 2010). Rao’s quadratic entropy (Q) is a distance matrix that defines the pairwise distances between species weighted by the relative abundance. Rao’s Q takes into account abundances where functional richness cannot, thereby preventing overestimation of the influence of uncommon species (Bourdon 2016). Table 1..

Choosing the most appropriate functional metrics depends on the question being asked, the number of species involved, and the type of data collected (Mouchet et al. 2010). Functional divergence (here called ‘functional diversity’), functional dispersion, richness, evenness, and Rao’s Q have been found to be useful for aquatic communities (Moullot et al. 2006, Guillemot et al. 2011, Villeger et al. 2012, Bourdon 2016), and so are the focus of this paper.

Functional redundancy, defined as the number of taxonomically distant species that exhibit similar ecological functions, is another important ecological parameter. Functional redundancy is the difference between species diversity and functional diversity (Guillemot et al. 2010, Kang et al. 2015). Systems that have high functional redundancy have a higher degree of stability and are more resilient to ecosystem disruptions. (Pillar et al 2013, Kang et al 2015). However, the removal of a function may be of higher impact than in a system with low functional redundancy.

In this Chapter I explore the functional diversity of fish communities of two estuaries on the north Olympic Peninsula, Strait of Juan de Fuca, with an emphasis on the functional metrics of the Elwha River estuary and the role of large-scale dam removal in changing functional diversity compared to a nearby estuary that did not experience large scale dam removals (see Chapter 1). I detail the trait-based functional diversity, defined as Rao's Q, and functional redundancy, and so functional stability of the Elwha estuary fish assemblage before, during, and one year after large-scale dam removals.

Specifically I will address the following questions:

1. What are the functional parameters of the central Strait of Juan de Fuca nearshore estuarine fish communities?
2. How do these functional parameters of the Elwha estuary respond to large-scale dam removal?
3. Are the functional elements of the Elwha estuary more resilient after dam removals than before or during dam removal?

Methods

Functional divergence, functional richness, and Rao's estimate of quadratic entropy are the most informative functional diversity metrics defining the functional structure of the nearshore fish community central to this study (Botta-Zukat 2005, Mouchet et al., 2010). Field data collection followed methods detailed in Chapter 2. In short, fish use of the Elwha and a comparative estuary of the Salt Creek system were assessed thru monthly beach seining at established sites in the Elwha and comparative sites. The beach seine was a standard Puget Sound protocol dimensions. Sampling was conducted once a month, on the neap tide, during daylight hours at designated sampling locations. All sites were sampled within 8 hours. Sampling time period was broken into three periods: pre-dam removal (2008-2011), dam removal (2011-2014) and post dam removal (2014-2015). For each sample, all fish were identified to the lowest taxa possible and up to 25 fish for each species and life history stage (adult, juvenile, post larval) were measured. In March 2013, two additional sites, named Elwha ‘new’, were added to the sampling plan. These were located in new estuary areas created as a result of dam removal.

I selected a subset of functional traits that: 1. Best encompass the widest selection of fish guilds observed in the Elwha delta and comparative sites, and; 2. Allows for comparison with published work in other systems. The four traits selected for analysis were body size, body type, feeding strategy, and vertical distribution (Table 1). Abundance data for each species, by month and site, were converted to functional trait values by multiplying with literature based trait values (Table 2), and then all sample dates with a minimum of four species (required for analysis) were analyzed for functional metrics of functional richness, evenness, divergence, dispersion, Rao’s Q, and functional redundancy for the three dam removal phases using the FD package in R (Laliberté and Legendre 2010; Debastiani and Pillar 2012. Laliberte et al 2014). I calculated a one-way ANOVA on functional dispersion values, followed by Tukey’s tests for significance among sites and dam removal stages using the Mass program in R Data (Venables and Ripley 2002). All data were standardized as part of the analysis. Fish community dendrograms were generated for all fish with more than five observations over the course of the study (Laliberté and Legendre 2010’ Oksanen et al 2013, Oksanen 2015) for the Elwha original and new sites to graphically illustrate changes in the Elwha fish community groupings associated with dam removal.

Results

A total of 39 species and life history stages were collected over the course of the study (see Table 2 in Chapter 2 for complete species list). Functional richness and evenness and functional diversity and divergence were similar for most sites. Functional richness, evenness, and Rao’s entropy differed with both site and dam removal (Fig 1, 2). Functional diversity mirrored Rao’s Q, and was significantly lower at the Elwha original sites relative to the new sites during all phases of dam removal ($p<0.05$; Figure 4, 5, Appendix A1&2). Functional diversity at the Elwha original site did not differ significantly across the three dam removal phases ($p>0.50$; Figure 4,5, Appendix A2). Functional diversity was not significantly different between the Elwha original and Salt Creek sites during any dam removal phase except for Elwha original post dam removal, which was significantly different from Salt Creek pre dam removal ($p>0.50$ and p,0.02; Figure 5, Appendix 2).

The newly formed Elwha estuary sites had significantly higher functional diversity relative to the Elwha original sites both during and after dam removal ($p<0.05$; Figure 5, Appendix A2). The functional diversity of the Elwha new sites was also significantly different than Salt Creek, the comparative site, but only during the dam removal phase of the study (Figure 5, Appendix A2). Overall, the Elwha new sites had the highest functional diversity of all sites for both dam and post dam removal phases (Figure 5; Appendix A2)

Functional redundancy was highest at the Elwha original sites for all phases of dam removal and significantly higher than the Elwha new sites and the comparison sites ($p<0.05$; Figure 6, Appendix A3). Functional redundancy was significantly higher at the Elwha original sites during the dam removal phase compared to pre and post removal phases. In contrast, Elwha new sites were significantly lower than both Elwha original sites (for all dam removal phases, $p<0.05$; Figure 6, Appendix A3). Functional redundancy at Salt Creek was not significantly different than at the Elwha new sites ($p>0.50$, Appendix A3).

Cluster analysis plots revealed that the fish community of the Elwha over the course of the study grouped into approximately 7 general clusters (Figures 7, 8). Smelts (Osmerid), salmon and trout (Salmonidae), sculpins (Cottidae), perch (Embiotocidae and Cyprinidae), and flatfish (primarily Pleuronectidae) grouped together at both the original and new sites, with little association. Interestingly, chum salmon (*Oncorhynchus, keta*) were functionally the most closely related to the three-spine stickleback (*Gasterosteus aculeatus*) and surf smelt (*Hypomesus pretiosus*), and had a distant association with other salmon. In general, associations were tighter at the Elwha original than at the Elwha new sites, likely due to fewer years of data at the Elwha new sites.

Discussion

Results of this work indicate that, overall the functional metrics of functional richness and evenness are low, divergence is high, and Rao's Q is similar for the central Strait of Juan de Fuca estuary fish community relative to other functional/trait-based fish community studies (Baptista et al. 2015, Bourdon 2016). Further, this work reveals several important functional features of the Elwha estuary that appear related to dam removals. Despite the large scale delivery of over 10 mcm of sediment to a small and degraded estuary during and after dam removal, the functional diversity of the original Elwha estuary sites did not change relative to dam removal, or the comparative site.

The lack of functional response in the original Elwha estuary contrasts with findings of Baptista et al. (2015), who observed a functional trait response to estuary hydrologic changes. Possibly the Elwha estuary was already in such a state of degradation that additional disruption has not had an effect on the estuary community. Alternatively, other external forces on the Elwha estuary fish community, including the ongoing hatchery releases continue defining the functional metrics of the site throughout the dam removal phases (see additional discussion in chapter 2). If so, the large environmental changes due to dam removal do not play an important role in shaping the environmental community of the Elwha original estuary relative to these additional factors. This functional 'stability' was also reflected in the significantly higher redundancy of the original Elwha estuary, relative to both the new Elwha sites and the Salt creek comparative area during and after dam removal. Therefore the Elwha original estuary sites, while having lower functional diversity, appear to be more stable and less susceptible to disruption from environmental change. To date there has been no detailed analysis on the relationship between continued large-scale hatchery releases and estuary resilience. This is outside the scope of this study, but worthy of future work.

In contrast, the new Elwha sites, which first formed little over a year after dam removal began, had significantly higher functional diversity relative to both the Elwha original and comparative Salt Creek sites. This higher functional diversity is consistent with species diversity changes as detailed in Chapter 2. One potential explanation for this difference is that as soon as the new sites were available they were being used, or 'pioneered' not only by species found in the original sites, but by new species not observed in the estuary prior to dam removals. This includes non-native shad (*Alosa sapidissima*).

Three major shifts in physical habitat are at the center for these changes in the ‘new’ sites relative to the original Elwha and Salt Creek comparative sites.

1. The expansion of the Elwha nearshore thru the creation of both new lower river side channels and estuary habitat formed in a severely constrained and small estuary (chapter x this study;
2. High sediment loads delivered to the estuary (Warrick et al. 2015), and; 3. Shifts in habitat from estuarine to freshwater (East et al. 2015, Foley et al. 2015).

Combined, the extremely fast and large-scale changes to the estuary and lower river resulted in both higher functional diversity thru the introduction of new, functionally distinct species to the system that also resulted in a disparate, and significantly lower redundancy in the still establishing new Elwha delta habitats relative to the original habitats. This lower redundancy, indicates a less resilient and more unstable community in the new regions of the Elwha estuary. Thus, while new sites have a higher functional diversity they may be more susceptible to disruption, including colonization by pioneering native species (e.g., eulachon , *Thaleichthys pacificus*, and non-native species (e.g., shad). Shad have a warm water anadromous life history. As climate change advances, shad may be a future concern for the watershed (as they are in the nearby Columbia River, see Hasselman et al. 2012). With the advent and establishment of new nearshore spawning habitats in the Elwha nearshore, including along lower river and side channel habitats, eulachon may re-establish in this watershed. As the sites and communities stabilize, the functional stability of the system should re-establish to a higher functional diversity and redundancy. As the sites stabilize I predict these sites to become more stable, and so more resilient.

Finally, the community dendrograms revealed that fish in the Elwha original and new estuary sites grouped fairly logically, with the exception of chum salmon, which were associated more closely with forage fish than other salmon. This is the first time such a functional association with a salmon and a group of forage fish has been noted in an estuary, and points to a new functional role of chum salmon as a forage species. Chum historically were the second largest run in the Elwha system, and are an important part of the Elwha ecosystem restoration (see Chapter 2).

Table 3.1 Definitions of functional traits used in this analysis

Metric	Definition	Citation
Functional richness	Represents the amount of functional space occupied by a species assemblage	Laliberte et al. 2014
Functional dispersion	A multidimensional functional diversity matrix	Laliberte et al. 2014
Functional evenness	Corresponds to how regularly species abundances are distributed in the functional space.	Mouchet et al. 2010
Functional divergence	Defines how far species abundances are from the center of the functional space	Mouchet et al. 2010
Rao's quadratic entropy (Q)	A distance matrix that defines the pairwise distances between species weighted by the relative abundance. Rao's Q takes into account abundances where functional richness cannot, thereby preventing overestimation of the influence of uncommon species	Bourdon 2016
Functional redundancy	The difference between species diversity and functional diversity. High redundancy indicates high stability and more resilience to ecosystem disruptions.	Guillemot et al. 2010, Kang et al. 2015

Table 3. 2. Four trait categories used.
For additional details see Baptista et al. (2015).

Size	Small (<70mm)	1
	Medium (70-150mm)	2
	Large (151-400mm)	3
	Very large (>400mm)	4
Body transverse shape	<0.5 (flat horizontally e.g. flatfish)	1

	0.5-1	2
	1-2	3
	>2 (flat vertically e.g. perch/salmon)	4
Feeding guild	Omnivorous	1
	Planktivorous	2
	Piscivorous	3
	Zoobenthivorous	4
	Detritivorous	5
Vertical distribution	Benthic	1
	Pelagic	2
	Demersal	3

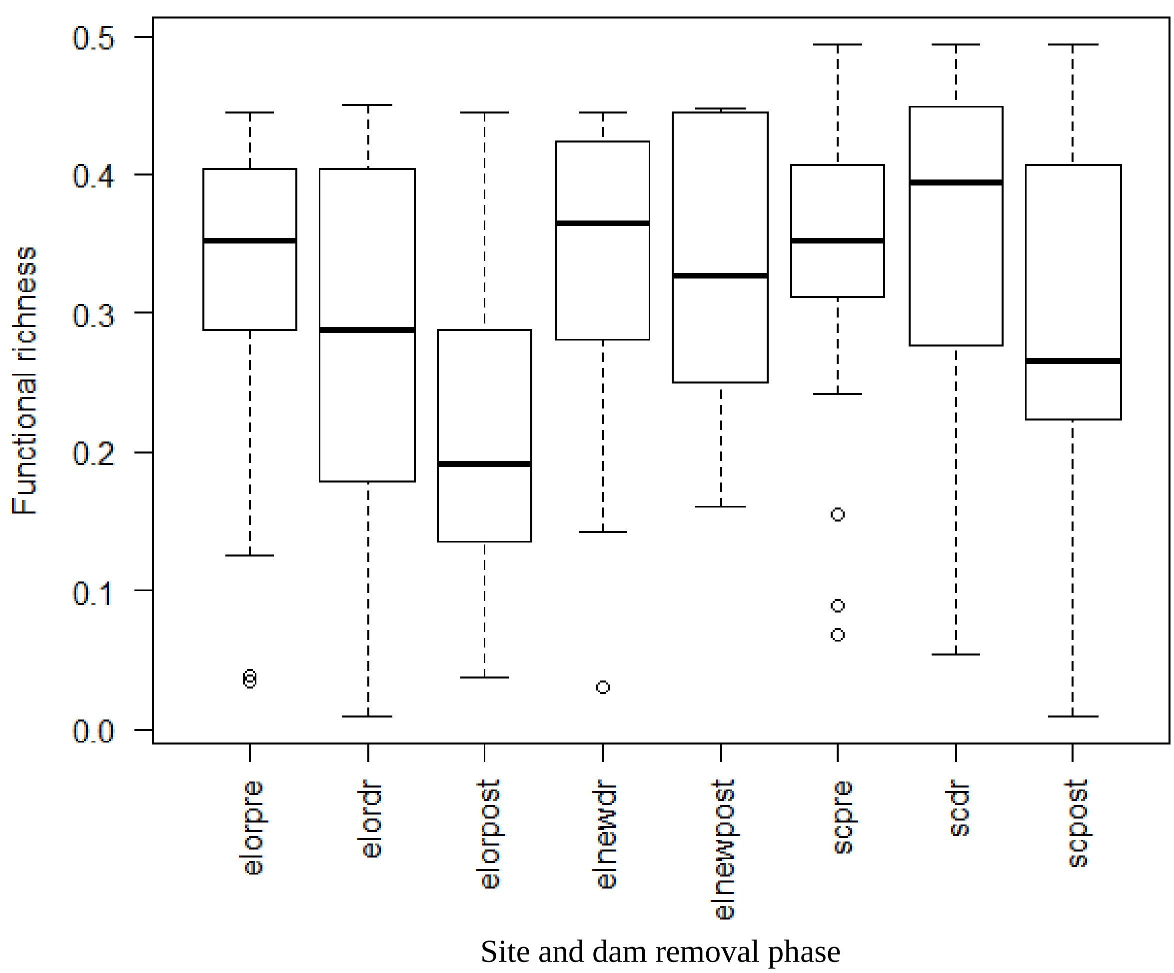
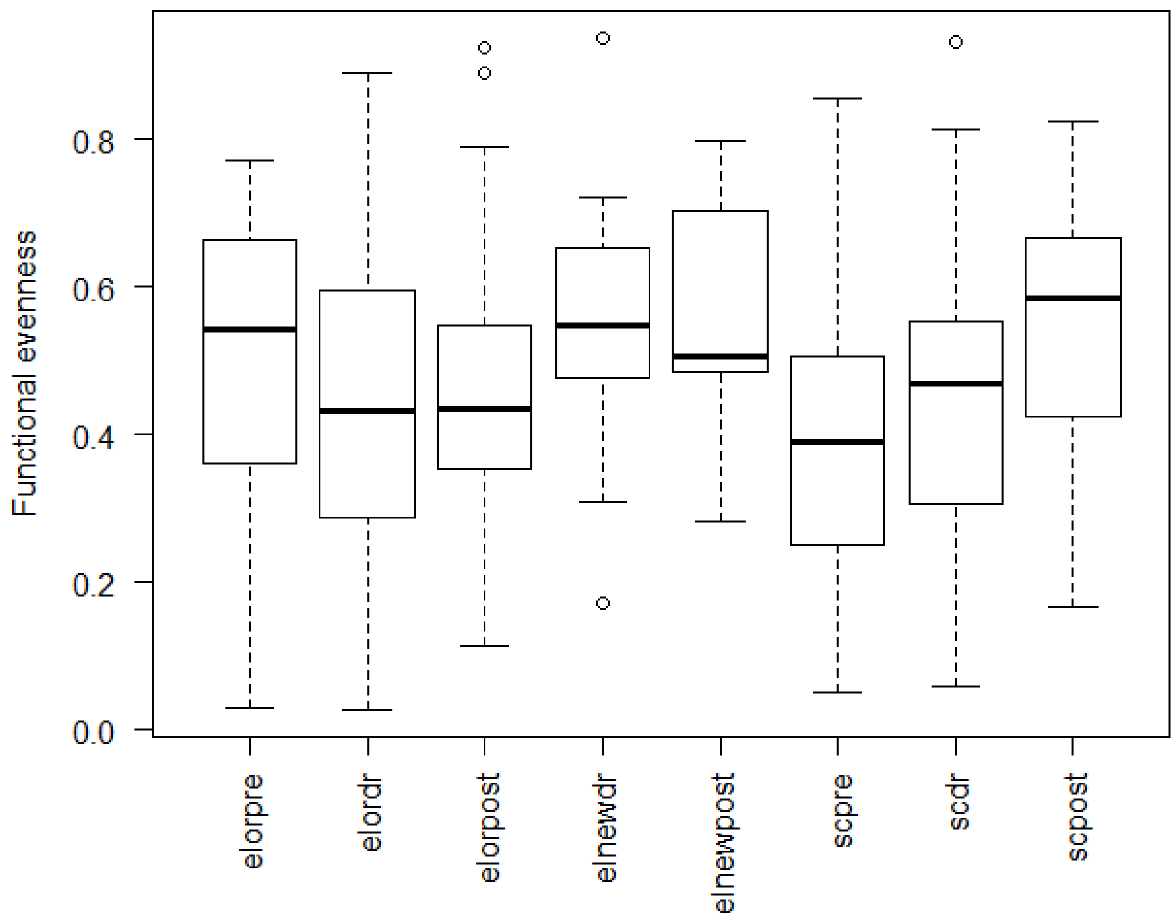


Figure 3.1 Functional richness for the Elwha original and new sites and Salt Creek.

Pre, during, and one year post dam removal. Bold lines are median values; top and bottom of squares are first and third quartiles. Horizontal lines with dashed whiskers are the minimum and maximum values if no outliers are displayed. On boxes with outliers the whiskers represent 1.5 times the interquartile range-or approximately 2 standard deviations. elorpre=Elwha original predam removal; elordr=Elwha original dam removal; elorpo= Elwha original post dam removal; elnewdr=Elwha new dam removal; elnewpo= Elwha post dam removal; scpre= Salt Creek pre dam removal; scdr=Salt Creek dam removal; scpo=Salt Creek post dam removal



Site and dam removal phase

Figure 3.2 Functional evenness for the Elwha original and new sites and Salt Creek
Pre, during, and one year post dam removal. Bold lines are median values; top and bottom of squares are first and third quartiles. Horizontal lines with dashed whiskers are the minimum and maximum values if no outliers are displayed. On boxes with outliers whiskers represent 1.5 times the interquartile range-or approximately 2 standard deviations elorpre=Elwha original predam removal; elordr=Elwha original dam removal; elorpo= Elwha original post dam removal;

elnewdr=Elwha new dam removal; elnewpo= Elwha post dam removal; scpre= Salt Creek pre dam removal; scdr=Salt Creek dam removal; scpo=Salt Creek post dam removal

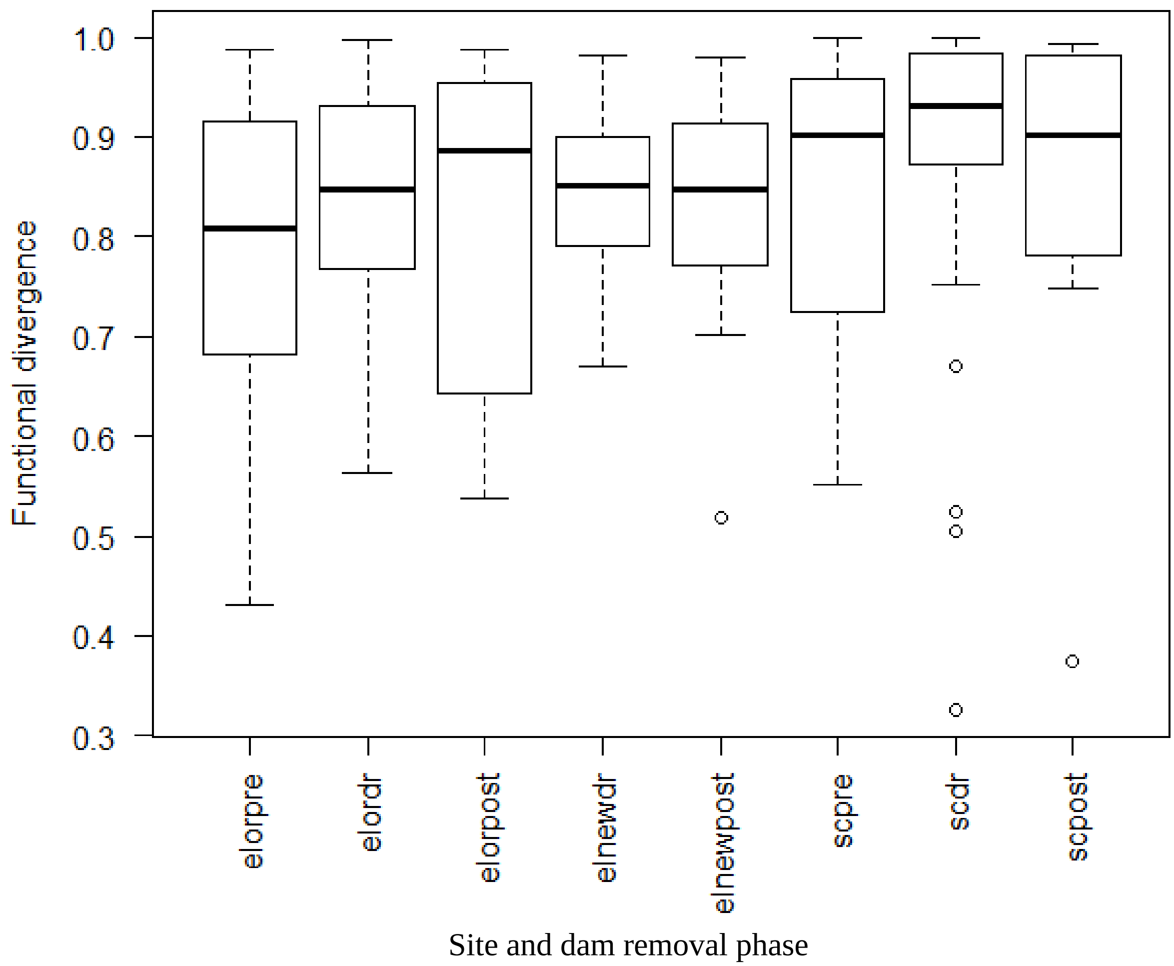


Figure 3.3 Functional divergence for Elwha original and new sites and Salt Creek.
Pre, during, and one year post dam removal. Bold lines are median values; top and bottom of squares are first and third quartiles. Horizontal lines with dashed whiskers are the minimum and maximum values if no outliers are displayed. On boxes with outliers whiskers represent 1.5 times the interquartile range-or approximately 2 standard deviations. elorpre=Elwha original predam removal; elordr=Elwha original dam removal; elorpo= Elwha original post dam removal; elnewdr=Elwha new dam removal; elnewpo= Elwha post dam removal; scpre= Salt Creek pre dam removal; scdr=Salt Creek dam removal; scpo=Salt Creek post dam removal

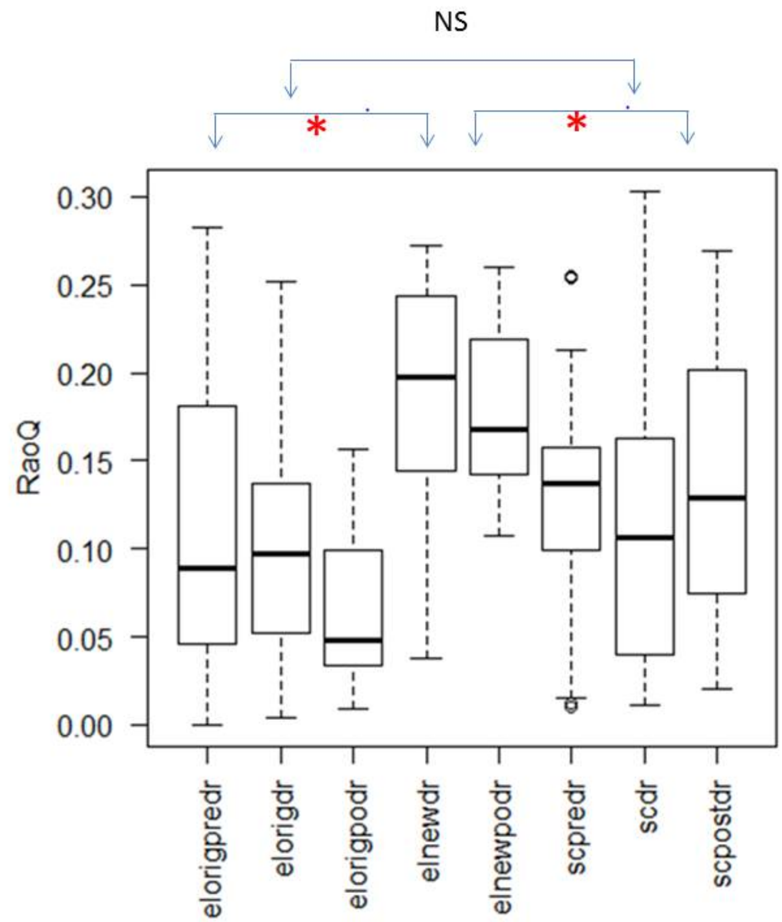


Figure 3.4 Rao's Quadratic entropy (Rao's Q) for the Elwha original and new sites and Salt Creek.

Pre, during, and one year post dam removal. Bold lines are median values; top and bottom of squares are first and third quartiles. Horizontal lines with dashed whiskers are the minimum and maximum values if no outliers are displayed. On boxes with outliers the whiskers represent 1.5 times the interquartile range-or approximately 2 standard deviations. elorpre=Elwha original predam removal; elordr=Elwha original dam removal; elorpo= Elwha original post dam removal; elnewdr=Elwha new dam removal; elnewpo= Elwha post dam removal; scpre= Salt Creek pre dam removal; scdr=Salt Creek dam removal; scpo=Salt Creek post dam removal.*=$p<0.05$; NS=Not significant.

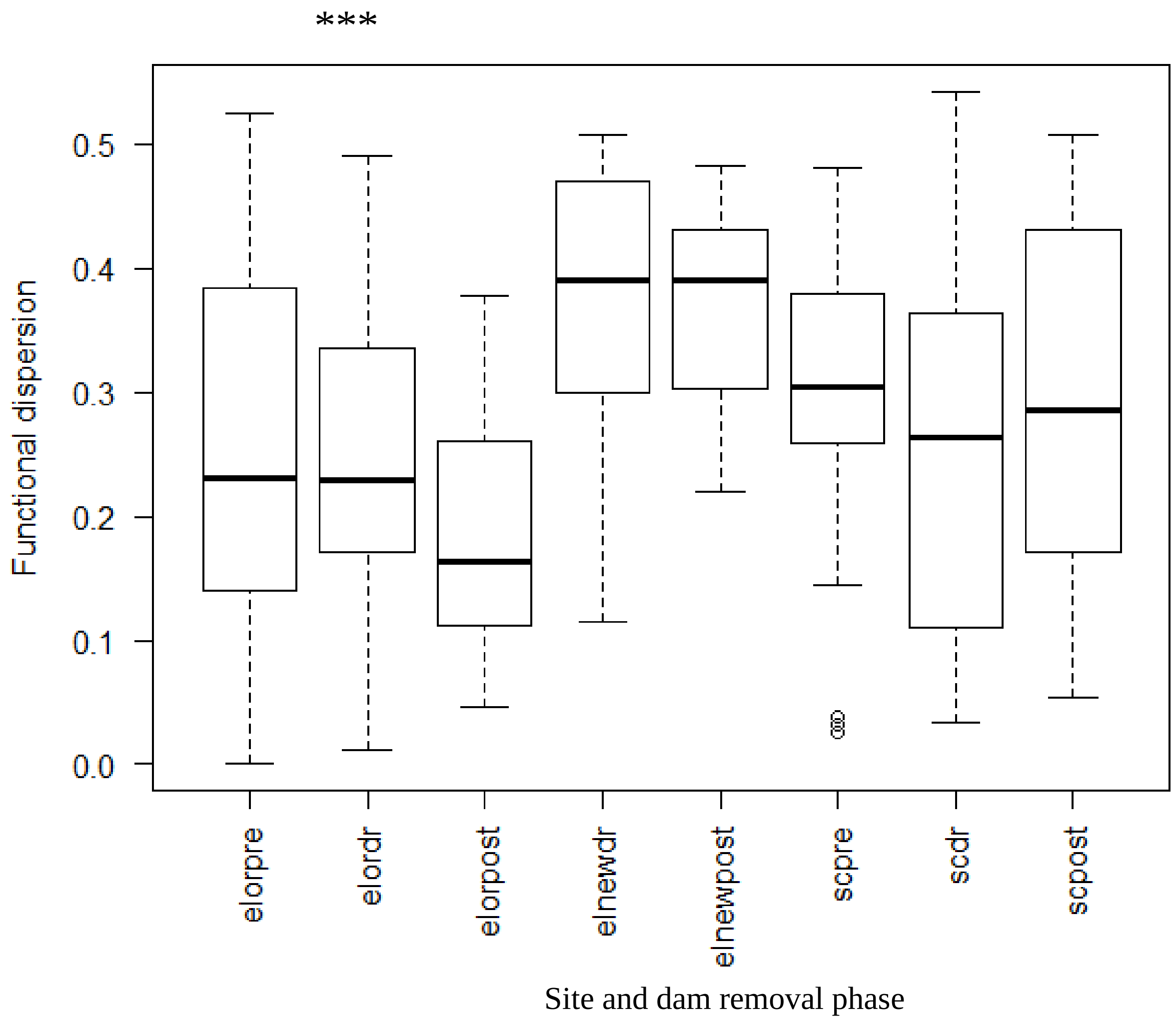
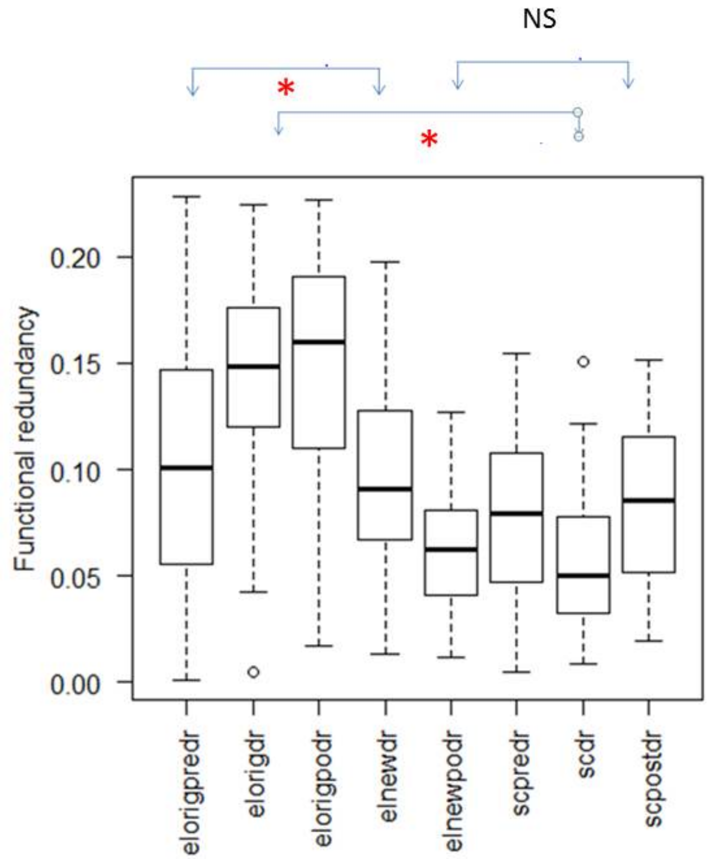


Figure 3.5 Functional dispersion (Functional diversity) for the Elwha original and new sites and Salt Creek

Pre, during, and one year post dam removal. Bold lines are median values; top and bottom of squares are first and third quartiles. Horizontal lines with dashed whiskers are the minimum and maximum values if no outliers are displayed. On boxes with outliers the whiskers represent 1.5 times the interquartile range-or approximately 2 standard deviations. ***= p<0.001; . elorpre=Elwha original predam removal; elordr=Elwha original dam removal; elorpo= Elwha original post dam removal; elnewdr=Elwha new dam removal; elnewpo= Elwha post dam removal; scpre= Salt Creek pre dam removal; scdr=Salt Creek dam removal; scpo=Salt Creek post dam removal



Site and dam removal phase

Figure 3.6 Functional redundancy for the Elwha original and new sites and Salt Creek. Pre, during, and one year post dam removal. Bold lines are median values; top and bottom of squares are first and third quartiles. Horizontal lines with dashed whiskers are the minimum and maximum values if no outliers are displayed. On boxes with outliers the whiskers represent 1.5 times the interquartile range-or approximately 2 standard deviations. *=p<0.05.; NS=Not significant; elorpre=Elwha original predam removal; elordr=Elwha original dam removal; elorpo= Elwha original post dam removal; elnewdr=Elwha new dam removal; elnewpo= Elwha post dam removal; scpre= Salt Creek pre dam removal; scdr=Salt Creek dam removal; scpo=Salt Creek post dam removal.

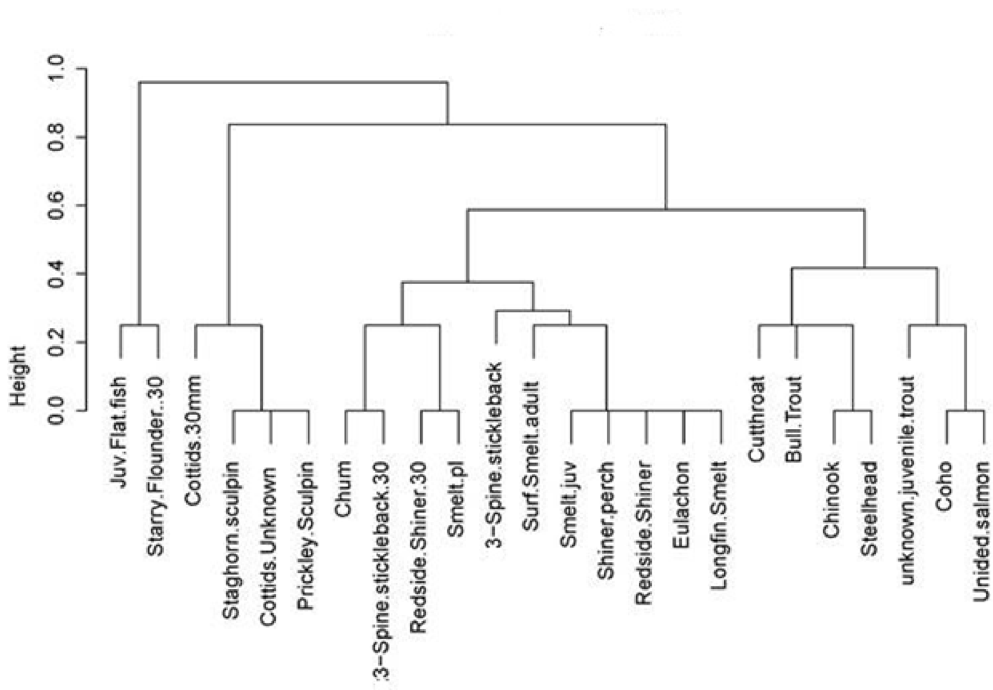


Figure 3.7 Community dendrogram, Elwha estuary original sites 2008-2015.

Naming conventions: .30= under 30 mm; ..30=over 30 mm. pl=post larval; juv=juvenile. Species listed in Figure 6.

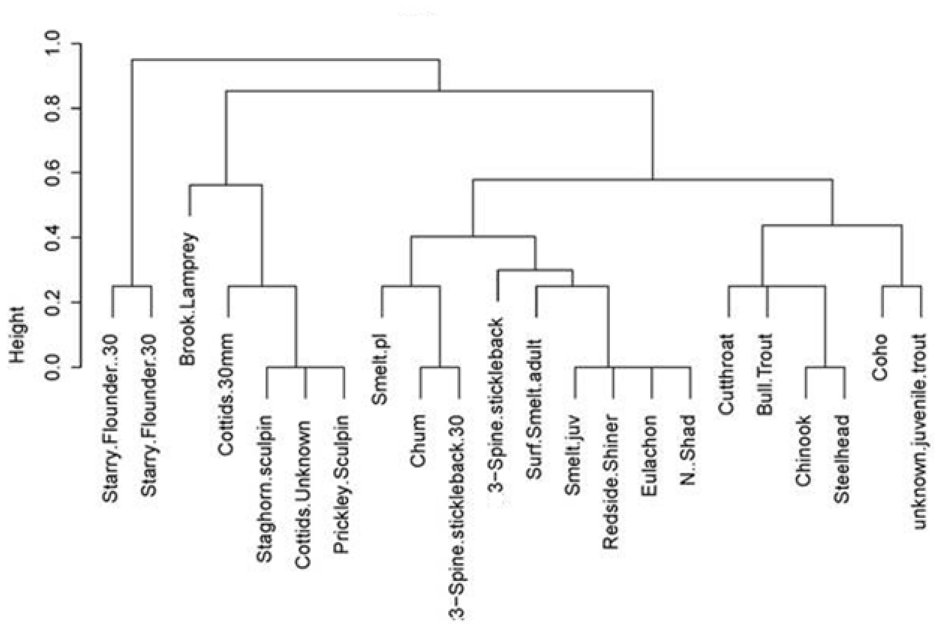


Figure 3.8 Community dendrogram, Elwha estuary new sites 2010-2015.

Species listed in Figure 6. Naming conventions: .30= under 30 mm; ..30=over 30 mm. pl=post larval; juv=juvenile.

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Chapter 4 Implications of Large-Scale Dam Removal for Forage Fish Restoration and Conservation

Abstract

Nearshore habitats are critical for many forage fish species, and an emerging topic for large-scale dam removals. We examined the relationship between forage fish spawning and large-scale dam removal thru a series of collaborative long-term studies associated with the Elwha River. Sand lance were not observed to spawn in the Elwha drift cell during the course of this study despite observations of adults in the area. Surf smelt spawning occurred throughout dam removal at low abundances, and egg distribution shifted towards the river mouth and onto newly formed beach adjacent to the original spawning beach. Abiotic factors associated with spawning (D50, sorting, percent gravel, silt, and sand) were significantly different before and after dam removal, but not among beaches. Thus factors in addition to abiotic sediment conditions appear to regulate surf smelt spawning associated with large-scale dam removals. Forage fish spawning response to dam removal appears to be complex and may be related to multiple factors including high interannual variability in physical habitat conditions, geographic factors and complex life histories of forage fish. Habitat suitability for forage fish spawning should increase as restored ecosystem processes and newly created habitats mature and stabilize, indicating that time is an important factor in nearshore restoration for forage fish spawning. It is therefore important to implement long-term monitoring and incorporate nearshore ecosystem function for multiple life history stages of forage fish into large-scale dam removal restoration and management planning.

Introduction

As the link between autotrophic and heterotrophic systems, forage fish are a cornerstone of marine ecosystems and primary and secondary commercial fisheries worldwide. Pikitch et al. (2014) estimated that the global catch value of forage fisheries was US$5.6 billion and the fisheries supported by forage fish to be more than twice as valuable (US$11.3 billion). Declining trends in forage fish populations worldwide have therefore become a global concern. Primary predictors of forage fish declines include population growth and overfishing (Greene et al. 2015), though, due to complex life histories, impact source and response is challenging to define for forage fish (Englehard et al. 2014). There is growing concern about ecosystem scale ramifications of rapid loss of forage fish stocks. Much of the emerging dialog on forage fish conservation has focused on fishery management (Pew 2015, NOAA 2016).

Much less attention is paid to habitat conservation and restoration. In the northeast Pacific, a number of forage fish species including surf smelt (*Hypomesus pretiosus*), herring (*Clupea pallasi*), eulachon (*Thaleichthys pacificus*) and sand lance (*Ammodytes hexapterus*) have very specific dependence on the nearshore for migration, rearing, spawning, and feeding. For example, eulachon, surf smelt, and sand lance are documented to have very specific seasonal grain size requirements for intertidal spawning (Reeves et al. 1989; Fresh, 2006, Penttila 2007; Simenstad et al. 2006). Surf smelt prefer a mixed sand gravel substrate, and sand lance mixed sandy beaches (Penttila 2007). Over the last two hundred years shorelines crucial to forage fish migration and possibly spawning have been degraded thru development (Pilkey and Cooper 2014, Martin 2015). In particular, disruption of nearshore hydrodynamic and sediment processes can result in major declines in ecosystem function, including for intertidal beach spawning forage fish (Bottom et al. 2005, Rice 2006, Dugan et al. 2008; Quinn 2008, Parks et al. 2013, Toft et al. 2015, Dethier et al. 2016). Conservation and restoration of key nearshore ecosystems for forage fish functions, including spawning, is an emerging and complex component of marine ecosystem management.

Large-scale dams installed over the last century have been directly linked with salmon and marine mammal declines and subsequent listing under federal and state endangered species regulations (See chapters 1 & 2). Removal of aging large-scale dams is becoming an important tool in watershed ecosystem restoration worldwide (see chapter 1 and 2). For the northeast Pacific, the majority of species targeted for restoration thru large-scale dam removals depend on forage fish as a prey base. The relationship of large scale dam removals to forage fish are therefore important to understand.

The Elwha River is a short (75 km) steep system with two large-scale dams installed at the turn of the 20th century approximately 8 and 21 km from the river mouth. The Elwha watershed has recently undergone an unprecedented ecosystem restoration event with the removal of the two dams. Dam removal released approximately 24,000,000 cubic meters of sediment into the watershed, of which 14,000,000 cubic meters of silt, sand, and gravel is anticipated to be delivered to the nearshore (East et al. 2015; Warrick et al. 2015). This dam removal, the largest restoration project implemented in the US, began in September 2011 and concluded in September 2014. The majority of sediment is anticipated to reach the marine shoreline within five years of dam removal (DoI EIS, 1996).

Located along the south shore of the Strait of Juan de Fuca, the nearshore of the Elwha River is a nursery and spawning ground for at least four species of forage fish that spawn in the nearshore (including surf smelt, sand lance, eulachon, and herring) and that are protected thru the US Endangered Species Act (ESA) and essential fish habitat (EFH) designations (Shaffer et al. 2007, Ward et al. 2008, Shaffer et al. 2012). Prior to dam removals, surf smelt and sand lance spawning in the Elwha nearshore was respectively 16% and 9% - lower than in comparative adjacent drift cells (Figure 1; Wefferling 2014) with sediment characteristics significantly different than adjacent intact drift cells (Parks et al. 2013, Parks 2015). These physical and ecological differences are likely due to the sediment starvation from shoreline armoring and in river dams (Shaffer et al. 2008, Shaffer et al. 2012; Parks et al. 2013) as well as associated limited distribution of large woody debris (LWD), a building block for forage fish spawning beaches that are impaired in the Elwha nearshore due to anthropogenic pressures (Rich et al. 2014).

This paper addresses the restoration response of intertidal forage fish spawning along the Elwha nearshore associated with large-scale dam removal. Specifically we quantify surf smelt and sand lance spawning along the embayed shoreline before, during, and after dam removal. We also quantify surf smelt spawning in new habitats formed from sediment deposition following dam removal. We document changes in sediment characteristics of these reaches of the Elwha drift cell, and discuss the response, if any, in forage fish spawning associated with these changes. We interpret these results relative to forage fish conservation, and provide recommendations for future large-scale dam removal considerations for forage fish.

Methods and materials

The six-year long study covered three areas of the Elwha embayed and delta shoreline (Figure 2). The Freshwater Bay shoreline of the Elwha delta was sampled for surf smelt (summer) and sand lance (winter) spawning, as well as abiotic sediment characteristics during three dam removal phases: before (2008-2011), during (2012-2014), and after dam removal (2015). The newly formed beaches of the east and west delta, e.g. habitat that formed after dam removal began, were sampled during, and after dam removal. Portions of the forage fish data have been published elsewhere, and are offered here for baseline comparisons by all the co-authors (Parks et al. 2013; Wefferling 2014).

Surf Smelt and Sand Lance Egg Sampling

In the Strait of Juan de Fuca, surf smelt spawning is primarily during summer months (May-September; Parks et al. 2013, WDFW). Sand lance spawning is during winter months (Pentilla 2007). Prior to this study, sand lance were only documented to spawn along one small stretch at the distal end of the Elwha drift cell (WDFW). For this study, select beaches within the Elwha drift cell were stratified into ~300 m sections and sampled for egg spawn using standard techniques described by Moulten and Penttila (2006) and Quinn et al. (2012). Each region (Freshwater Bay, east and west Elwha delta) was approximately 1600 m long, over which a series of 150 m long transects running parallel to the beach were established. As forage fish spawning and incubation areas are normally in the 2.14-2.74 m above mean low low water region (MLLW; Moulton and Penttila 2006), samples were collected from the upper third of the beach, near the high tide mark, or approximately 0.3-0.6 m waterward of the driftwood log line. Each sample consisted of series of scoops of sediment approximately 7 cm deep collected in ~10 m intervals along the transect to collect a total of 15 kg of substrate per sample. Eight to 14 samples were collected from each of the three regions for each sampling date. The beginning and ending location of each sampling reach was always the same, and all samples were collected within 3 days of each other.

Samples were washed through a series of Nalgene sediment screens, the smallest with a 0.5 mm mesh. After elutriation for 1-2 minutes, the lighter fraction from the 0.5 mm sieve was skimmed from the surface using a 235 ml plastic collecting jar. This winnowing process was repeated twice more on the remainder of the sample, and the skimmed portions were preserved in Stockard's solution. All processed samples were examined under a dissecting microscope and all eggs were identified, counted, and their life-history stage recorded as outlined in Moulton and Penttila (2006).

Sediment sampling and characterization

When surf smelt and or sand lance eggs were detected at any of the study locations, sediment metrics were collected. The Freshwater Bay and newly formed habitats of the east and west Elwha delta were sampled along the seaward extension of the subaerial delta and ~2000 m west across the new delta and along a portion of Freshwater Bay, and ~2000 m east of the mouth of the Elwha River, in cross-shore transects ~100 m apart (Fig. 2). A total of 100 waypoints were collected to document and map their respective locations along the upper intertidal zone of Freshwater Bay and east and west Elwha delta during surf smelt spawning season (June-September).

Two methods were used to determine grain-size distributions: grain-size photograph analysis and physical samples. For photographic analysis, a small blackboard with an attached 15-cm scale was placed on the sediment at each waypoint and a photograph was taken using a standard digital camera. Each photograph was processed using methods modified from Cobble Cam analysis (Warrick et al. 2009b). Analysis of each grain-size photograph provided data about each sample location, and the calculated average grain size (mm) was used for this study.

Sediment samples were collected at 34 locations within the study area using a stratified random design, parallel to the water's edge. A small hand trowel was used to collect sediment samples from the surface to a depth of ~15 cm. Sediment grain-size distribution for beach samples was determined using a dry sieve method modified from Haynes et al. (2007). Samples consisting of only sand, gravel, and cobble were placed in small tins and dried in an oven for approximately 24 hours. After drying, individual samples were added to the top of a stack of 9 sieves ranging from -4ϕ to 4ϕ (16 to 0.063 mm) and agitated in a mechanical shaker for 10 minutes. If a sample contained cobble greater than -4ϕ (16 mm), the individual cobbles were hand-measured with electronic digital calipers to the nearest 0.1 mm. Separate grain-size classes (listed in Table 1), were weighed to the nearest 0.01 g.

Three samples that contained trace amounts of clay and silt were analyzed using the wet sieve method modified from the University of Washington (UW) Sediment Procedures Manual (University of Washington 1998). A subsample ranging from ~30 to 60 g, depending on the sand-gravel consistency for each wet sample, was placed in a 4ϕ (0.063 mm) sieve and rinsed with 0.05% sodium metaphosphate (NaPO4) dispersant to separate clay and silt from larger sediments. Grain-size distributions of clay and silt fractions of wet samples were determined using pipette analysis and the application of Stokes' Law. The sand and gravel fractions of wet samples were then processed as described above.

Grain-size analysis and mapping

The grain-size data for each of the 34 physical samples were analyzed using GRADISTAT (Blott and Pye 2001) for each sample date. Results from GRADISTAT analysis were used to map the median (D50) grain-size distribution for each sample by geographic location within the study area and with respect to their distances from the mouth of the Elwha River, examine the relationship between D50 and sand fractions for each sample, and determine the relationship between the sand fractions and elevation (m MLLW) for each sample. Average surface grain-size data were obtained from Cobble Cam analysis for each of the 98 digital images. Images were run through Cobble Cam analysis three times and mean particle size (mm) was averaged for use in spatial analysis. The average surface grain-size for each of the 98 images was mapped by geographic location within the study area, and their respective distances from the mouth of the Elwha River was calculated. Distances between the mouth of the river and each sample location were calculated in MatLab (Shamshiri 2009). ArcMap was then used to map the grain-size photo and physical sample locations within the study area.

Data analysis

No sand lance eggs were collected over the course of this study. Data analysis therefore focused solely on surf smelt.

Surf smelt egg data

Surf smelt egg data were found to be non-normal due to large numbers of zeros. We therefore conducted Generalized linear models (GLM) using a negative binomial distribution to define the relationship of surf smelt total average egg abundance relative to site, dam removal stage, distance to river mouth and sediment metrics using R (Venables and Ripley 2002, R Core Team 2008). Candidate models with different fixed effects were competed through model dredging and averaging of top models performed with ΔAIC (Wagenmakers and Farrell 2004; Bolker et al. 2009; Gardner et al. 2012, Barton 2015). Multivariate ANOVAs were conducted to determine differences in sediment parameters relative to site and dam removal utilizing R Adonis (Vegan) package to determine significance of factors. To balance data for modeling analysis a subset of the forage fish study samples were randomly chosen so that each site and dam removal phase had equal sample sizes.

Sediment Data

To determine if dam removal impacted sediment conditions (sorting, D50, and proportion of the sample composed of sand, silt, and gravel) at Freshwater Bay, or if sediment conditions varied by distance from the river mouth, data analyses were performed in R, with the PERMANOVA/adonis package within R (Oksanen et al. 2015).

Non-metric multidimensional scaling (nMDS, 100 restarts) plots were used to visualize how the abiotic sediment conditions varied at Freshwater Bay before, during, and after dam removal, and between the Freshwater Bay, west, and east delta, during and after dam removals. Overlaying nMDS plots are vector overlays that represent correlations (Pearson correlation coefficients) between sediment conditions and MDS axes. As stress was < 0.2, these plots are considered a good 2-dimensonal representation of higher dimensional trends (Clarke 1993). nMDS graphs were created in PRIMER (Anderson et al. 2008; Clark 1993, 2015).

Results

Despite annual surveys during sand lance spawning season (November-January), sand lance eggs were not detected at any of the sites over the course of the study and so not considered for further analysis. Surf smelt eggs were found in relatively low numbers, less than 1.5 eggs per sample, along the Freshwater Bay shoreline during all years sampled and three phases of dam removal. Surf smelt eggs were also found in low numbers along the newly formed west delta during and after dam removal. No surf smelt eggs were found along the east delta during or after dam removal (Table 2).

Generalized linear models revealed that site, distance from river mouth, and percent sediment composition (gravel and sand) were the top predictors of egg abundance (Table 3a and b). Dam removal stage was not in the top predictive models. None of the coefficients were significant (Table 3b).

While not a significant predictor of egg abundance, distribution of eggs collected relative to the river mouth shifted during and after dam removal relative to before dam removal (Table 2). Average distance to river mouth of samples where eggs were observed decreased by over 700 meters after dam removal. Maximum distance of eggs relative to river mouth decreased by 1400 meters after dam removal, indicating the egg distribution may have shifted along the beach (Table 3).

Dam removal stage was the only significant predictor of abiotic sediment conditions at Freshwater Bay (Table 4, Figure 3). Sediment conditions at Freshwater Bay varied before and after dam removal, as well as before and during dam removal; however, sediment conditions did not vary significantly during and after dam removal (Table 5). Finally comparing all three sites for sediment conditions during and after dam removal revealed that abiotic sediment conditions of Freshwater Bay, east Delta, and west Delta did not vary by distance from the river mouth, or between sites. Sediment metrics did vary significantly by dam removal status ($p = 0.033$ for during vs. after; Table 5), when all beaches became more fine (Figure 4, Table 5).

Discussion

The lack of sand lance eggs along the Freshwater Bay, west, and east delta continues after dam removal, despite the fact that the sediment grain size of these beaches transitioned to a grain size closer to that used by sand lance for spawning as indicated in this study.

The lack of sand lance eggs and low numbers of surf smelt eggs observed along the Elwha shorelines are inconsistent with observations of other life history stages of these same species along the Elwha shoreline after dam removal. In her long-term beach seining study, Kagley (unpublished data) documented significant increases in smelt densities along the Elwha drift cell after dam removals. Shaffer (unpublished data), recently documented increases in juvenile sand lance abundances along the east and west Elwha delta relative to before dam removals. But the increased number of surf smelt and sand lance migrating along the Elwha delta and bay shorelines are not spawning on, or recruiting from, the Elwha beaches.

Combined, these observations indicate that factors other than sediment composition, sorting, and fish abundance are dictating sand lance and surf smelt use of these intertidal beaches for spawning. Haynes et al. (2006), also observed that intertidal sediment composition was not significantly different between sites with and without sand lance present in British Columbia. Further, Haynes et al. (2007) documented that the sediment composition of nearshore areas with sand lance present differed between intertidal and subtidal regions.

Our findings concerning surf smelt spawning revealed both difference and similarities to other published work. Similar to other studies, surf spawn abundance in our study was highly variable (Hirose and Kamaguchi 2008, Quinn et al. 2012). However, Quinn et al. (2012) regularly observed thousands of eggs per day in nearby Puget Sound. Our observations on surf smelt spawning produced low numbers throughout the study and never reached more than 10 units (Figure 1, Quinn 2012). Further, the spawning documented here from 2008-2015 was consistently lower (7.3 average eggs/site, s.d.=5.987 than in the pilot study conducted by Wefferling (2007).

These results indicate a complex relationship between dam removal and forage fish spawning. Dam removal has played a significant role in changing the sediment composition of Elwha shorelines, but these changes have not yet resulted in changes to forage fish spawning, indicating that other factors in addition to grain size, composition, sediment sorting, and distance from river mouth are contributing to sand lance and surf smelt spawning. On the other hand, while statistically not significant (likely due to consistently low egg abundances), the observed shift in surf smelt egg distribution along the Freshwater Bay beach eastward towards the west river delta and river mouth during and after the second year after dam removal began suggests that sediment from dam removals may be contributing to changes in surf smelt spawn distribution along the shoreline (Figure 5). Finally this spawning beach ‘extension’ indicates that proximity to a current spawning beach is important for establishing new areas of surf smelt spawning.

There may be a number of reasons that explain why sand lance are not using any of the study shorelines, the consistently low surf smelt spawn abundance along the Freshwater Bay and west delta, and lack of surf smelt spawning along the Elwha east delta. First, the sediment delivery to the Elwha nearshore from dam removal was large volume and rivaled both Mt. Saint Helen’s and Typhoon Rob in size (Foley et al. 2015). This sediment delivery did not mimic ‘natural’ riverine sediment delivery events, and overwhelmed both the watershed and nearshore for a number of months. Expecting forage fish to respond to these rapidly transitioned beaches during and immediately after such a large volume event is likely unreasonable. Both surf smelt and sand lance are seasonally pelagic schooling fishes that return to nearshore waters seasonally to spawn. So exposure to abnormally high sediment conditions was at most likely limited to spawning months, and not a mortal event for the very motile juvenile and adult fish. Now that the major sediment delivery is over, we expect conditions associated with multiple forage fish life histories (fish migration and spawning), including better beach sediment composition and water quality, to improve. Even if negatively affected from the high sediment event, given that these fish are not long lived, (most have a life span of under five years) subsequent generations of both surf smelt and sand lance should respond quickly.

Another important consideration for forage fish spawning along these Elwha shorelines is the continued transition of the shoreline. After the dam removal restoration phase (which is expected to largely be over within five years of dam removal by ~2019), the river sediment delivery dynamics will transition from catastrophic levels of dam retained sediment to a lower but relatively consistent annual river sediment delivery and nearshore hydrodynamics. These include a much lower total volume of sediment, and a lower proportion of fine sediments. We anticipate that the intertidal nearshore conditions along the Freshwater Bay, and east and west delta will also settle into a post restoration phase condition. This should include seasonal beach coarsening that is characteristic of this region. This coarsening may result in an increase in grain size heterogeneity and so likely further changes in surf smelt, and possibly sand lance, spawning.

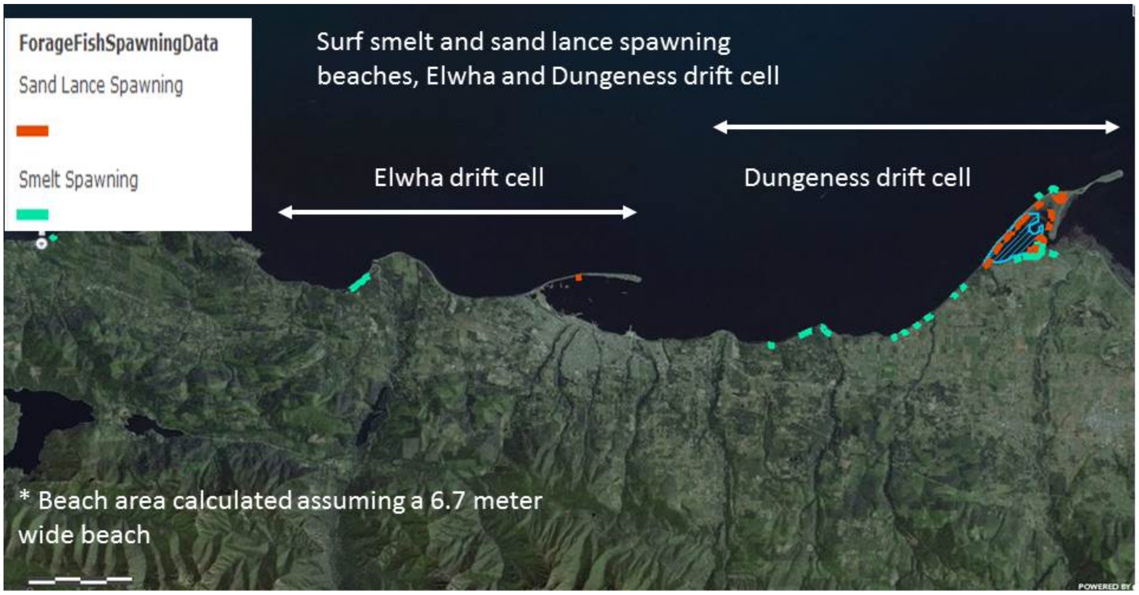
Other geomorphic and hydrodynamic factors that were not assessed in this study, and not related to dam removal, may also contribute to/define the suitability for Elwha beaches for intertidal forage fish spawning. Examples are sediment shape and roundness, packing and porosity, and/or beach and shoreline hydrodynamics, and riverine sediment source. If this is the case we will not observe forage fish spawning along the east delta shoreline in the future, nor will we see an increase in forage fish spawning along Freshwater Bay and the west delta. If this bears out, much more complex management considerations are needed when linking future large-scale dam removals with forage fish, the prey base for a number of species targeted for restoration with large-scale dam removals. However, given that the nearshore changes associated with dam removals will undoubtedly continue for a number of years it is important to continue monitoring both surf smelt and sand lance spawning along the Elwha drift cell for years ahead.

In summary, this study illustrates that forage fish linkages to watershed processes are complex. Others have documented that, at the drift cell scale, large-scale dams have a negative effect on forage fish spawning due to disruption in sediment hydrodynamics and sediment starvation (Parks et al. 2013; Wefferling et al. 2014). However forage fish life histories as well as their site-specific use of nearshore habitats are complex. Simply changing beaches to a more 'suitable' or appropriate grain size does not appear to be the only factor needed to quickly restore/establish forage fish spawning. Adjacency of spawning beaches does appear to play a role in spawning on newly formed beaches, but may not result in a net increase in egg abundance immediately following dam removal. Given the large scale of the restoration event, time may also be an important factor in determining forage fish spawning. It is therefore important to wait until restoration is complete and fish have adjusted to the new nearshore before deeming the success of large-scale dam removal to restoring forage fish spawning.

Further, nearshore habitats are important for a number of uses, including migration, rearing, and/or feeding. Spawning is not the only critical function for forage fish use of the nearshore. And the absence of spawning is not an indicator that other critical functions are not occurring.

Conservation with restoration for all these functions is critical. Concurrent, consistent, and long term assessment of all these life history uses along nearshore habitats are extremely important to fully understand nearshore ecosystem function for forage fish, including spawning, and what they may mean for overall trends in these complex populations of fish.

From a nearshore perspective, large-scale dam removals are foremost sediment delivery projects, and sediment starvation is a well-documented and predictive factor in loss of forage fish habitat. Large-scale dam removals therefore may be ecosystem scale restoration projects to restore lost/ degraded forage fish spawning and migration habitat. The relationships between dams and sediment delivery to the nearshore and functions for forage fish have strong temporal and geographic variation that are just now beginning to be understood in the Elwha. These results have implications for other future large-scale dam removal restoration projects. International losses in our forage fish stocks dictate that we understand, conserve, and restore nearshore ecosystem function for forage fish migration and spawning, and strive to fully understand and optimize functions associated with future large-scale dam removal, as soon as possible.



Species	Drift cell	Length (km)	Total spawning area (sq meters)*
Surf smelt	Dungeness	13	37,500
	Elwha	10	6,197
Sand lance			
	Dungeness	13	22,297
	Elwha	10	1,858

Data source: WDFW http://bit.ly/16eBpJh

Figure 4.1 Documented forage fish (surf smelt and sand lance) spawning beaches in the (impaired) Elwha drift cell prior to dam removals and (intact) Dungeness drift cell.

http://wdfw.maps.arcgis.com/home/webmap/viewer.html?webmap=19b8f74e2d41470cbd80b1af8dedd6b3

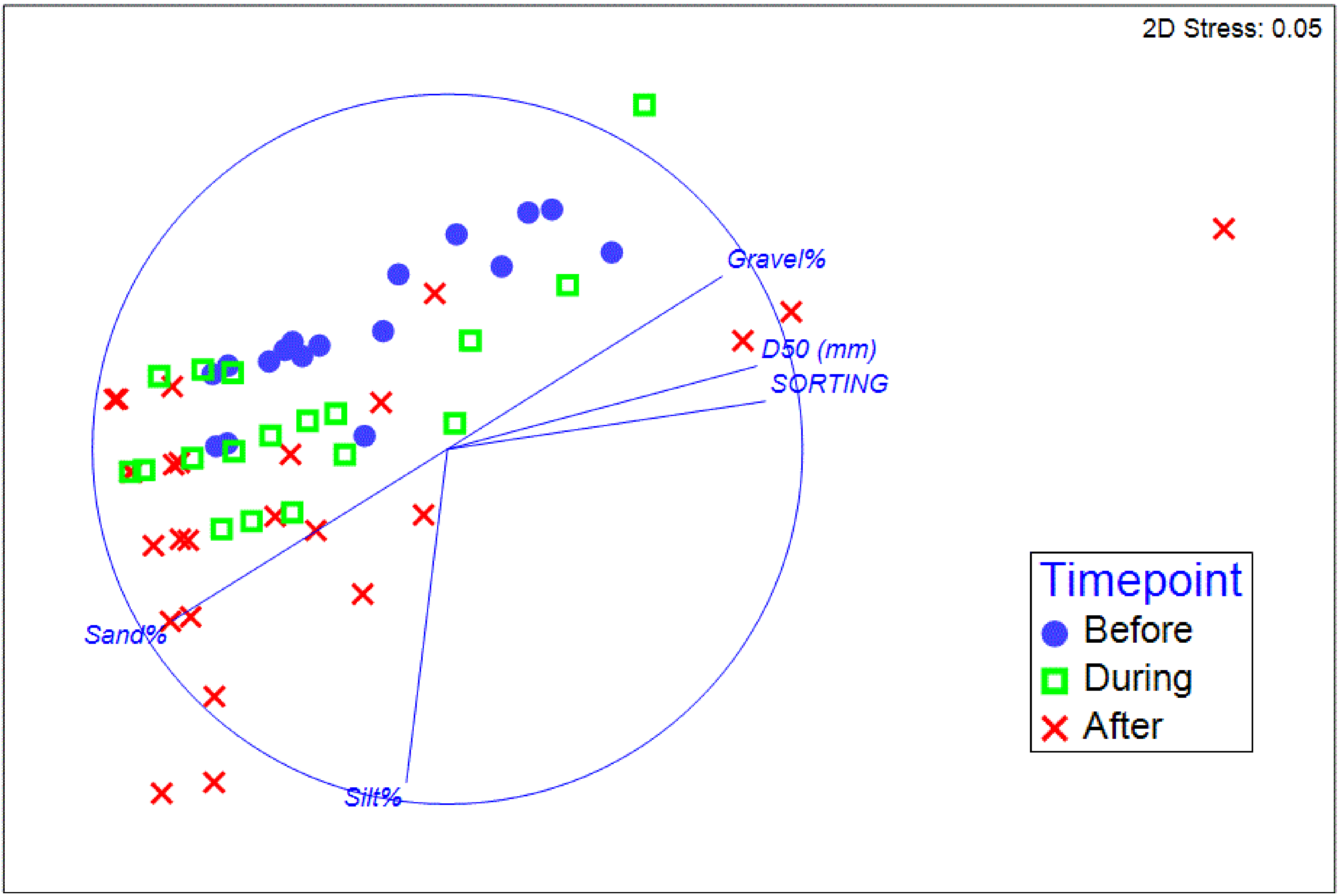
Table 4.1 Grain size definitions and sizes used for surf smelt and sand lance spawning.

Bold size classes are dominant grain sizes of documented surf smelt spawning beaches. Italics are dominant grain sizes of documented sand lance spawning and intertidal migration beaches (Haynes 2006; Penttila 2007).

Sediment type	**Size range (mm)**
Boulder	>256
Cobble	64–256
Very coarse gravel	**32–64**
Coarse gravel	**16–32**
Medium gravel	**8–16**
Fine gravel	**4–8**
Very fine gravel	***2–4***
Very coarse sand	***1–2***
Coarse sand	*0.5–1*
Medium sand	*0.25–0.5*
Fine sand	*0.025–0.250*
Very fine sand	0.0625–0.125
Silt	0.039–0.0625

Figure 4.2 Sample locations, Elwha forage fish study area.

Figure 4.3 nMDS and vector overlay of abiotic sediment conditions at Freshwater Bay, before, during, and after dam removal. Moving out from the center of the vector overlay represents increasing values of that parameter.



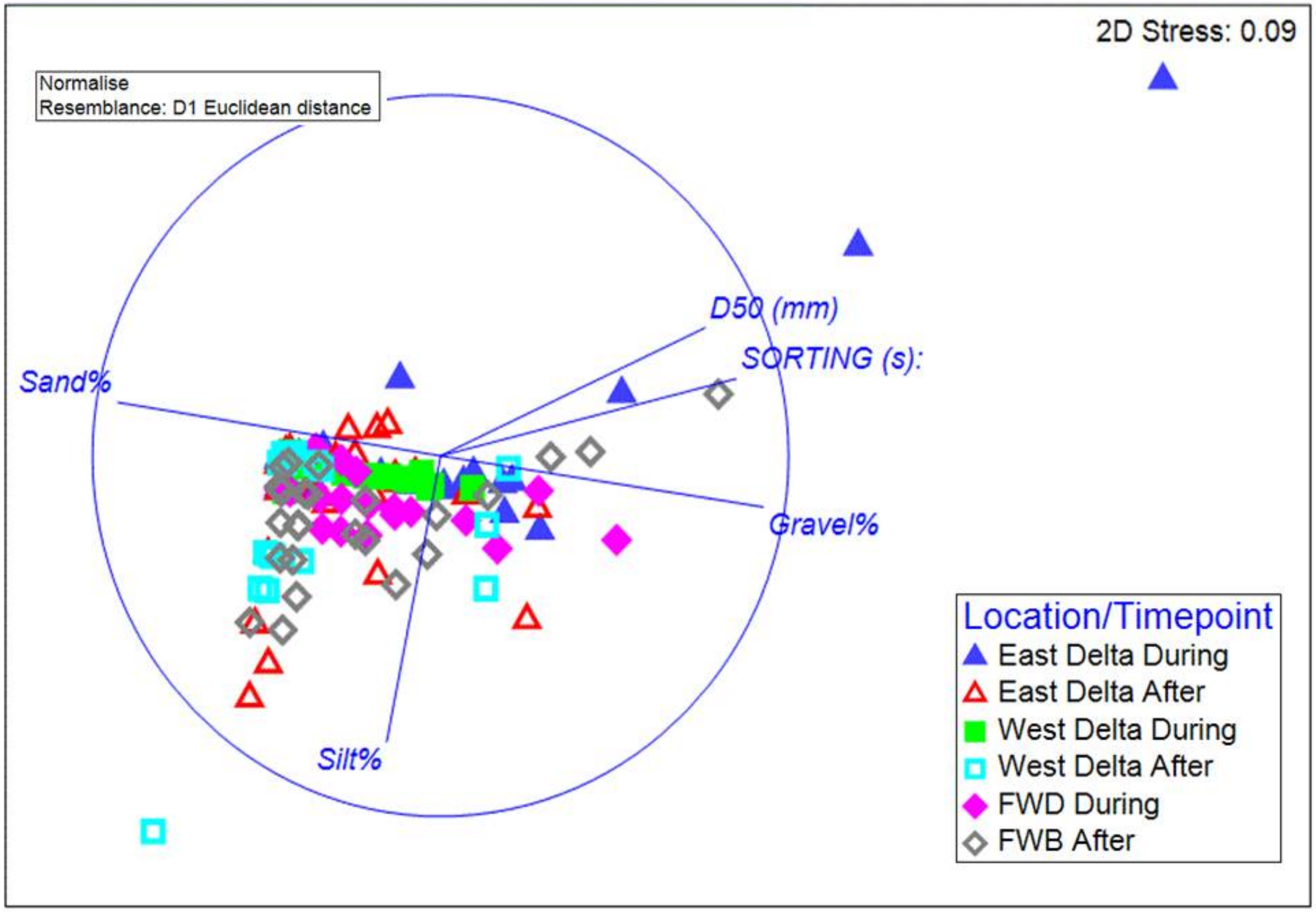


Figure 4.4 nMDS and vector overlay of abiotic sediment conditions at Freshwater Bay, east Delta and west Delta during and after dam removal.

East and west Delta are sites that formed at the river mouth of the Elwha River during and after dam removal. Moving out from the center of the vector overlay represents increasing values of that parameter.

Figure 4.5 Elwha nearshore before and during dam removals. Note increase in fine sediments during dam removals.

Table 4.2 Summary of average and standard deviation surf smelt egg abundance observed during the study.

RS=Dam removal stage; DFRM=Distance from river mouth. Ave=average abundance; SD= standard deviation

Site/DRS	Total eggs (Ave)	Total eggs (SD)	DFRM (Ave,m)	DFRM (SD, m)
Freshwater Bay				
Before	0.5	0.7	1058	421
During	1.33	1.12	869.51	396.58
After	0.29	0.49	1363.49	647.85
West Delta				
During	1.29	1.70	220.76	115.05
After	0.57	1.13	301.81	123.86

Table 4.3a AIC table of GLM Modeling negative binomial results for egg abundance (2008-2015) relative to year, dam removal stage, site, and interaction of the two.

Dam Removal Stage (DRS), distance from river mouth (DFRM), site, and interaction of site and dam removal stage. Δ (AIC) = [AIC*i* – min(AIC)];The AIC weight is given by Wi and represents the probability that a given model is the best among the models presented. When 2 models had ΔAICc < 4, the model with the highest Wi was selected.

Factors	AIC (-)	Δ(AIC)	Wi	best model better relative to this model by factor of
Site	25.06			
DFRM	25.18	0.12	0.74	0.87
Gravel (%)	25.23	0.17	0.72	0.89
Gravel (%), Sand (%)	27.07	2.01	0.29	2.24
Gravel (%), Sand (%), Silt (%), Mean Sorting (s)	27.65	2.59	0.21	3.00
DRS, Site	30.91	5.85	0.04	15.30

Table 4.3b GLM negative binomial modeling results for egg abundance (2008-2015) relative to dam removal stage (DRS), site and interaction of site and dam removal stage.

Coefficient	Estimate	Std. Error	z value	Pr(>|t|)
(Intercept)	0.50	1.28	-0.39	0.699
Site	0.05	0.06	0.84	0.41
East Delta	-21.8	2439	0.00	0.19
FWB	0.19	1.40	0.14	0.89
West Delta	0.42	1.42	0.30	0.775
DFRM	0.00	0.00	0.228	0.820
Gravel	0.00	0.05	0.053	0.957

Table 4.4 PERMANCOVA for Freshwater Bay using Euclidean distance matrix for sediment parameters (Sorting, D50, and % sample composed of sand, silt, and gravel).

Signif. codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05

Terms	Df	Sums of Sqs	MeanSqs	F.Model	R2	Pr(>F)	Significance
DFRM	1	2.3870	2.3870	0.6148	0.00904	0.490	
DRS	2	48.748	24.3739	6.2776	0.18465	0.003	**
DFRM:*DRS	2	3.201	1.6004	0.4122	0.01212	0.764	
Residuals	54	209.664	3.8827		0.79418		
Total	59	264.000			1.00000		

Table 4.5 Average for metrics of intertidal sediment before, during, and after dam removal.

Dam Removal Stage (DRS) along Elwha Freshwater Bay (FWB), east (ED) and west (WD) delta before (2008-2011), during (2011-2014) and after (2014-2015) dam removals.

Site	FWB	FWB	FWB	WD	WD	ED	ED
DRS	*Before*	*During*	*After*	*During*	*After*	*During*	*After*
Gravel%	44	30	21	24	13	26	19
Sand%	56	70	79	76	87	74	81
Silt%	0	0	0	0	0	0	0
Mean (mm)	3	3	3	2	2	6	2
Sorting (s):	3829	3040	3710	2065	1660	5073	3156
Skeewness (Sk):	4	2	3	3	5	3	4
Kurtosis (K):	27	12	22	20	54	24	38
D50 (mm)	2	1	2	1	1	6	1

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Chapter 5 Conclusions

This dissertation defined the nearshore fish community response to large-scale dam removals, and provides a number of important considerations for fisheries management and conservation. From this work we've learned that, from a nearshore perspective, large-scale dam removals are foremost large-scale sediment delivery projects that have profound and complex implications for ecosystem function. In the case of the Elwha after over 100 years of ecosystem disruption thru the blockage of sediment, wood, and fish passage, the dam removals were the equivalent of a geologic-scale event that has spanned (to date) just under four years. It is not surprising then that our results indicate that the Elwha nearshore is still in the restoration response phase. The nearshore fish species response documented to date is promising, but the community response is complex and is anticipated to continue to evolve as the river, and nearshore ecosystems heal. In the case of the nearshore this recovery will only be partial-as many barriers to ecosystem recovery remain in the Elwha nearshore. In a larger context? Nearshore restoration associated with large scale dam removals takes time, and may be offset from dam removals.

In addition, the life histories of the fish that use these river and nearshore systems are complex. Fish species, and guilds, use different areas of the nearshore at different times of year for different life history functions. Overlaying the fish life history, community dynamics, and nearshore hydrologic and sediment elements of large scale dam removals, which may go on for decades, results in a temporal ecological restoration mosaic that cannot be understood just from monitoring the river, nor adequately addressed in riverine restoration context. In the future, fully understanding and optimizing the nearshore ecological implications of large scale dam removals, will require much more focused study specifically on the nearshore than has occurred in the Elwha to date.

Sediment starvation is documented to be a predictive factor in loss of forage fish habitat. Large scale dam removals therefore may be ecosystem scale restoration projects to restore lost/degraded forage fish spawning and migration habitat. Given that forage fish are the basic component for many of our marine and riverine ecosystems, the forage fish benefit associated with large-scale dam removals should be inevitable. However the relationships between dams and sediment delivery to the nearshore and functions for forage fish are complex, and have strong temporal, geographic, and species life history components that ecologists are just now beginning to understand –as clearly illustrated in the Elwha. These components will be important to, and have implications for, other future large-scale dam removal restoration projects. Each large-scale dam removal project will be different for the species and ecosystem function they provide. International declines in forage fish stocks dictate that we understand, conserve, and restore nearshore ecosystem function for forage fish migration and spawning, and strive to fully understand and optimize functions associated with future large scale dam removal, as soon as possible.

Dams installed across the world over the last 100 years have had both unquestionable societal benefit and global ecosystem impact. The Elwha is a microcosm for large-scale dams, and their removal, world wide. The Elwha fisheries and ecosystems, including the nearshore, were reduced by 100 years of in-river dams. In total, the aged and deteriorating Elwha dams cost literally the hundreds of millions of dollars and multiple careers to remove. Once removal began, it took less than five years to complete. The findings of the Elwha dam removal project, including our work determining nearshore restoration, make clear that conservation of our intact river and nearshore ecosystems should be a first and top priority for ecosystem management going forward. In those cases where ecosystem recovery is possible (for example, Snake and Columbia systems), restoration thru large-scale dam removals is a logical, broad and positive nearshore ecosystem benefit-provided adequate planning for nearshore ecosystem response.

Over the course of the last 100 years we've also made great strides in fisheries and ecosystem management. Species complexes, not just the most commercially valued species, are now understood to be critical to the productivity, resilience and stability of healthy functioning river ecosystems. These same species complexes are also therefore critical for restoration, and cannot be simplified, ignored, or artificially recreated if watershed recovery is to occur. Case in point, this study revealed that hatchery management may actually complicate and/or challenge the nearshore function for species needed to provide the backbone for recovery. The details of this impact are unfortunately outside the realm of our study. However we can offer that the role hatchery practices may be playing in the nearshore must be fully considered in an ecosystem context of future large scale restoration planning events.

And finally, as illustrated in this study, planning of large-scale dam removals take a long time, and the likelihood of actually implementing projects of this scale is always in question. It is important, once a dam removal has been identified as a priority, to not give up. Sheer career spanning tenacity is critical for large-scale dam removal, and associated nearshore ecosystem restoration.

In total, results of this work detailing nearshore fish community response to large-scale dam removals provide a better understanding of the linkage between nearshore ecosystem restoration and large-scale watershed restoration, a deeper understanding of linkages between habitat ecosystem restoration and species management actions in the nearshore, and indicate what our next priorities for regional nearshore ecosystem restoration and protection at the Elwha and other areas in the Northeast Pacific, and beyond, should be.

Appendix

Appendix 2A1 Change in areal extent of wetted habitat of the Elwha estuary and lower river due to dam removal sediment delivery prior to (pre 2011), during (2011-2014) and after dam removal (2015), and total area, hectares, of Elwha shoreline and delta habitats. Numbers are generated by mapping of ortho-rectified aerial photographs using ArcGIS. Impounded area is west of dike along west shore of river.

Year	West River Estuary impounded Areas (ha)	West River Estuary Unimpounded Areas (ha)	East River Estuary Unimpounded Area (ha)	**Total East and West Impounded, Unimpounded Area (ha)**	West\west River Wetted Area (ha)	West\East River Wetted Area (ha)	East\West Wetted Area (ha)	East\East Wetted Area (ha)	**Total (ha) River Wetted Area**	**Total Area (hectares) shoreline and delta habitats**
1939	0.00	2.49	4.69	**7.18**	0.37	0.42	1.85	1.91	**4.54**	**120.18**
1956	0.00	1.05	2.50	**3.55**	0.95	1.27	1.40	1.67	**5.29**	**121.30**
1965	2.23	0.00	6.73	**8.97**	0.46	0.52	0.00	0.00	**0.98**	**121.80**
1974	1.66	0.41	2.95	**5.02**	1.58	2.07	0.00	0.00	**3.65**	**119.98**
1981	1.45	0.23	2.76	**4.45**	1.09	1.26	1.45	0.60	**4.39**	**115.90**
1990	1.49	0.00	4.12	**5.62**	1.88	1.66	0.00	0.00	**3.54**	**116.85**
2003	1.74	0.34	3.62	**5.70**	3.10	2.92	0.00	0.00	**6.02**	**122.30**
2006	1.58	0.26	2.71	**4.55**	3.82	1.85	0.00	0.00	**5.67**	**120.63**
2009	1.49	0.89	2.74	**5.12**	3.23	1.57	0.00	0.00	**4.80**	**114.72**
2011	1.92	0.55	2.63	**5.10**	2.08	2.03	0.00	0.00	**4.11**	**115.42**
2013	1.98	0.80	3.52	**6.30**	3.39	2.29	0.00	0.00	**5.69**	**116.81**
2014	2.32	3.795	18.38	24.50	4.895	4.17	0.00			**142.80**
2015	1.74	0.57	11.75	**14.06**	1.47	1.35	0.00	0.00	**2.81**	**157.63**

Appendix 2A2 Total number of hatchery-produced salmonids released into the Elwha River between January-June, 2008-2015. Data provided by Regional Mark Information System (RMIS) system. www.rmpc.org

Species	*Release year*	*Release month*	*Total released*	*Species*	*Release year*	*Release month*	*Total released*
Chinook	2008	04	276,950	Steelhead	2012	05	161,038
Chinook	2008	06	1,868,400	Chinook	2013	04	196,575
Coho	2008	05	323,813	Chinook	2013	05	1,411,171
Steelhead	2008	05	35,710	Coho	2013	3	291,779
Chinook	2009	04	340,946	Steelhead	2013	04	119,623
Chinook	2009	06	939,000	Chinook	2014	02	1,500
Chum	2009	04	24,763	Chinook	2014	03	1,500
Coho	2009	05	444,514	Chinook	2014	04	204,274
Steelhead	2009	05	98,889	Chinook	2014	05	1,366
Chinook	2010	04	203,017	Chinook	2014	06	2,632,405
Chinook	2010	05	8,000	Chum	2014	04	105,770
Chinook	2010	06	3,037,730	Coho	2014	04	77,327
Chum	2010	03	21,396	Steelhead	2014	04	104,082
Chum	2010	04	31,290	Chinook	2015	3	2,400
Coho	2010	05	218,720	Chinook	2015	4	180,545
Steelhead	2010	05	302,798	Chinook	2015	5	674,392
Chinook	2011	02	1,000	Chinook	2015	6	2,000,000
Chinook	2011	03	2,000	Chum	2015	4	49,122
Chinook	2011	04	202,824	Coho	2015	3	294,612
Chinook	2011	05	1,000	Steelhead	2015	3	231,549
Chinook	2011	06	1,230,562				
Coho	2011	05	506,402				
Steelhead	2011	05	229,687				
Chinook	2012	03	1,000				
Chinook	2012	04	213,900				
Chinook	2012	06	1,522,769				
Chum	2012	04	59,851				
Coho	2012	04	165,641				
Coho	2012	07	278,634				

Appendix 2A3 Total salmon, by species, released during study period.

Species	2008	2009	2010	2011	2012	2013	2014	2015	Total
Chinook	2,145,350	1,279,946	3,248,747	1,437,386	1,737,669	1,607,746	2,841,045	2,857,337	17,155,226
Coho	323,813	444,514	218,720	506,402	444,275	291,779	77,327	294,612	2,601,442
Steelhead	35,710	98,889	302,798	229,687	161,038	119,623	104,082	231,549	1,283,376
Chum		24,763	52,686		59,851		105,770	49,122	292,192
Total	2,504,873	1,848,112	3,822,951	2,173,475	2,402,833	2,019,148	3,128,224	3,432,620	21,332,236

Appendix 2 A4 Comparison of percent composition of Pacific salmon in the Elwha River prior to dam construction, the percent composition of salmon released from hatcheries, and catch of juveniles in our study 2008-2015. Hatchery data from Regional Mark Information System (RMIS) system: *www.rmpc.org* NA=bull trout are not released by the hatchery

Species	Prior to dams (from Ward et al. 2008)	After dams installed (Ward et al. 2008)	Prior to, During and after dams removed 2008-2015	
			Released from hatcheries	Estuary (this study)
Chinook	5%	57%	78%	57%
Coho	8%	14%	13%	32%
Chum	13%	7%	1%	10%
Pink	66%	5%	0%	0%
Sockeye	4%	1%	0%	0%
Steelhead	4%	7%	5%	1%
Bull trout	1%	7%	NA	0%

Appendix 2A5. Fixed effects top model coefficients, standard error, and significance *=0.05; **=<0.01; ***=<0.001. DRS2=Dam Removal Stage, DRS3=Post Dam Removal Stage SL=Sample location, Site2=Salt Creek. Month values are averaged to consolidate table.

Category	Model	(AIC)/ Coefficient	SE	P	Significance
Species richness	**DR , (1 | SL) , (1 | Month)**	**(1880.30)**			
	DRS2	0.17	0.50	0.00	**
	DRS3	0.02	0.07	0.77	
	DRS , Site , (1 | SL) , (1 |Month)	**(1882.30)**			
	DR S2	0.17	0.05	0.00	**
	DRS3	0.02	0.06	0.77	
	Site	0.00	0.19	0.97	
	DRS , site , Site:DRS , (1 | SL) , (1 | Month)	**(1883.90)**			
	DRS2	0.23	0.07	0.00	**
	DRS3	0.11	0.08	0.21	
	Site	0.11	0.21	0.59	
	Site2:DRS2	-0.14	0.11	0.20	
	Site2:DRS3	-0.22	0.13	0.11	
Species diversity	**DRS, site, site:DRS, (1 | SL), (1 | Month)**	**(558.90)**			
	DRS2	0.16	0.72	p<0.05	*
	DRS3	0.20	0.09	P<0.05	*
	Site2	-0.01	0.17	p>0.05	
	Site2:DRS2	-0.25	0.10	p<0.05	*
	Site2:DRS3	-0.11	0.13	p>0.05	
	DRS, (1 | SL) , (1 | Month)	**(559.40)**			
	DRS2	0.06	0.05	p>0.05	
	DRS3	0.15	0.07	p<0.05	*
	Site, DRS, (1 | SL), (1 | Month)	**(560.50)**			
	Site2	-0.16	0.15	p>0.05	
	DRS2	0.05	0.05	p>0.05	
	DRS3	0.15	0.07	p<0.05	*
	Site, (1 | SL), (1 | Month)	**(561.38)**			
	Site	-0.18	0.16	p>0.05	
	DRS, site, site:DRS, (1 | SL)	**(563.40)**			
	DRS2	0.15	0.07	p<0.05	*
	DRS3	0.19	0.09	p<0.05	*
	Site2	-0.01	0.17	p>0.05	

	Site2:DRS2	-0.26	0.11	p<0.05	*
	Site2:DRS3	-0.11	0.13	p>0.05	
Chum abundance (both sites all species)	**Chinook, coho, Steelhead, Month, DRS, Site, Site:DRS, (1 | SL)**	**(3429.9)**			
	Chinook	-0.27	0.03	0.00	***
	coho	0.15	0.018	0.00	***
	Steelhead	0.11	0.06	0.07	
	Month	2.45	0.28	0.02	***
	DRS2	-0.36	0.08	0.00	*
	DRS3	1.00	0.15	0.00	***
	Site2	0.99	0.50	0.05	*
	DRS2:Site2	0.99	0.13	0.00	***
	DRS3:Site2	1.69	0.210	0.00	***
	Chinook, Coho, Steelhead, Month, DRS, 1 | SL	**(3514.2)**			
	Chinook	-0.27	0.03	0.00	***
	Coho	0.013	0.018	0.00	***
	Steelhead	-0.056	0.0619	0.37	
	Month	2.11	0.338	0.03	*
	DRS2	0.05	0.06	0.42	
	DRS3	0.199	0.10	0.05	*
Chum abundance Elwha only all species	**Chinook, Coho, Steelhead, Season, DRS, Season:DRS, (1 | Month)**	**(1602.80)**			
	Chinook	0.08	0.03	0.01	*
	Coho	0.10	0.03	0.00	***
	Steelhead	0.66	0.01	0.00	***
	DRS2	0.12	1.40	0.16	
	DRS3	-1.23	0.15	0.00	***
	Season	0.50	0.43	0.67	
	DRS2:Seasonlate	-2.20	0.30	0.00	***
	DRS3:Seassonlate	-1.99	0.47	0.00	***
	Coho, DRS, Season, Steelhead, DRS:Season	**(1606.70)**	**0.00**		
	Coho	0.14	0.02	0.00	***

	Steelhead	0.70	0.11	0.00	***
	DRS2	0.08	0.09	0.34	
	DRS3	-1.20	0.15	0.00	***
	Season	0.73	1.16	0.53	
	DRS2:Seasonlate	-2.31	0.23	0.00	***
	DRS3:Seassonlate	-2.03	0.46	0.00	***
Chum length (both sites)	**Month, DRS, Site, Site:DRS, (1 | SL)**	**(5158.43)**	**0.00**		
	Month	0.3	0.00	0.00	***
	DRS2	0.30	0.03	0.00	***
	DRS3	-0.03	0.02	0.05	*
	Site2	-0.07	0.03	0.01	**
	Site2:DRS2	0.08	0.02	0.00	**
	Site2:DRS3	-0.18	0.04	0.00	***
	Month, DRS, Site, Site:DRS, Site:Month, (1 | SL)	**(5161.60)**	**3.17**		
	Month	0.30	0.06	0.00	***
	DRS2	-0.03	0.02	0.07	
	DRS3	0.04	0.03	0.18	
	Site2	-0.09	0.03	0.01	**
	Site2:DRS2	0.07	0.29	0.01	*
	Site2:DRS3	-0.18	0.04	0.00	***
	Site2:Month (&NS)	0.03	0.05	0.5	
Chum length (Elwha only)	**Season, DRS, (1 | Month)**	**(3703.90)**	**0.00**		
	SeasonLate	0.27	0.08	0.00	***
	DRS2	-0.03	0.02	0.06	
	DRS3	0.04	0.03	0.12	
	Season, SL, DRS, (1 | Month)	**(3704.68)**	**0.78**		
	Season Late	0.27	.008.	0.01	***
	Sample location (SL)	0.03	0.02	0.26	
	DRS2	-0.03	0.02	0.03	*
	DRS3	0.03	0.03	0.31	

Appendix 3.

Appendix 3.A1. > ANOVA and Tukey analysis, Functional Disp and abundance data

Df Sum Sq Mean Sq F value Pr(>F)
7 0.617 0.08817 5.464 7.58e-06 *** Residuals 245 3.953 0. Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Appendix 3A2. Tukey multiple comparisons of means 95% family-wise confidence level. elwhaorigpredr=Elwha orginal pre-dam removal; elwhaorigdr=Elwha original dam removal; elnewpodr=elwha new post dam removal; elnewpredr=Elwha new pre dam removal;elnewpodr=Elwha original post dam removal; scpredr=Salt Creek pre-dam removal; scdr=Salt Creek dam removal; scpostdr=Salt Creek post dam removal.Bold indicates statistical significance ($p<0.05$)

	diff	lwr	upr	p adj
elnewpodr-elnewdr	0.006313046	-0.12560692	0.138233008	0.9999999
elorigdr-elnewdr	**-0.118733093**	**-0.21440244**	**-0.023063747**	**0.0045564**
elorigpodr-elnewdr	**-0.179575669**	**-0.28950897**	**-0.069642367**	**0.0000306**
elorigpredr-elnewdr	**-0.101812029**	**-0.19673305**	**-0.006891010**	**0.0258671**
scdr-elnewdr	**-0.113725945**	**-0.21020659**	**-0.017245298**	**0.0089448**
scpostdr-elnewdr	-0.069974100	-0.18905442	0.049106215	0.6230408
scpredr-elnewdr	-0.067636649	-0.16702130	0.031747999	0.4303885
elorigdr-elnewpodr	**-0.125046139**	**-0.24733098**	**-0.002761296**	**0.0409823**
elorigpodr-elnewpodr	**-0.185888714**	**-0.31962835**	**-0.052149080**	**0.0007906**
elorigpredr-elnewpodr	-0.108125075	-0.22982536	0.013575207	0.1226247
scdr-elnewpodr	-0.120038991	-0.24295959	0.002881610	0.0610992
scpostdr-elnewpodr	-0.076287146	-0.21764159	0.065067303	0.7192568
scpredr-elnewpodr	-0.073949694	-0.19916258	0.051263192	0.6168746
elorigpodr-elorigdr	-0.060842575	-0.15900589	0.037320743	0.5557101
elorigpredr-elorigdr	0.016921064	-0.06407712	0.097919250	0.9982896
scdr-elorigdr	0.005007148	-0.07781327	0.087827565	0.9999996
scpostdr-elorigdr	0.048758993	-0.05954995	0.157067939	0.8672357
scpredr-elorigdr	0.051096444	-0.03508949	0.137282374	0.6121505
elorigpredr-elorigpodr	0.077763639	-0.01967051	0.175197787	0.2269630
scdr-elorigpodr	0.065849723	-0.03310445	0.164803897	0.4608414
scpostdr-elorigpodr	0.109601568	-0.01149151	0.230694651	0.1082623
scpredr-elorigpodr	0.111939020	0.01015139	0.213726649	0.0199319
scdr-elorigpredr	-0.011913916	-0.09386877	0.070040934	0.9998423
scpostdr-elorigpredr	0.031837929	-0.07581059	0.139486448	0.9854618
scpredr-elorigpredr	0.034175381	-0.05117912	0.119529879	0.9241227
scpostdr-scdr	0.043751845	-0.06527439	0.152778077	0.9232649
scpredr-scdr	0.046089297	-0.04099633	0.133174921	0.7390444
scpredr-scpostdr	0.002337451	-0.10926681	0.113941717	1.0000000

Appendix 3.A3..ANOVA and Tukey results, functional redundancy aov(formula = syncsafdcsv ~ Location, data = fredun)

```
Terms:
                 Location Residuals
Sum of Squares  0.2602777 0.5295353
Deg. of Freedom         8       243

Residual standard error: 0.04668145
Estimated effects may be unbalanced
1 observation deleted due to missingness
> rredunanova=aov(formula = syncsafdcsv ~ Location, data = fredun)
> fredunanova=aov(formula = syncsafdcsv ~ Location, data = fredun)
> summary(fredunanova)
             Df Sum Sq Mean Sq F value Pr(>F)
Location      8 0.2603 0.03253   14.93 <2e-16 ***
Residuals   243 0.5295 0.00218
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
1 observation deleted due to missingness
> TukeyHSD(fredunanova)
  Tukey multiple comparisons of means
    95% family-wise confidence level

Fit: aov(formula = syncsafdcsv ~ Location, data = fredun)

$Location
```

	diff	lwr	upr	p adj
elnewpodr-elnewdr	-0.037754938	-0.087716617	0.012206741	0.3080388
elodr-elnewdr	-0.053373195	-0.202379134	0.095632744	0.9705832
elorigdr-elnewdr	**0.042110051**	**0.005515610**	**0.078704491**	**0.0113125**
elorigpodr-elnewdr	**0.047284109**	**0.005529029**	**0.089039189**	**0.0137302**
eloripredr-elnewdr	0.006519781	-0.029649030	0.042688591	0.9997451
scdr-elnewdr	**-0.044370210**	**-0.081118500**	**-0.007621920**	**0.0060765**
scpostdr-elnewdr	-0.015318081	-0.060484419	0.029848257	0.9789991
scpredr-elnewdr	-0.021133129	-0.058960999	0.016694741	0.7156501
elodr-elnewpodr	-0.015618257	-0.167246203	0.136009688	0.9999965
elorigdr-elnewpodr	**0.079864988**	**0.033741057**	**0.125988920**	**0.0000051**
elorigpodr-elnewpodr	**0.085039047**	**0.034722541**	**0.135355552**	**0.0000096**
elorigpredr-elnewpodr	0.044274718	-0.001512254	0.090061691	0.0668837
scdr-elnewpodr	-0.006615272	-0.052861362	0.039630818	0.9999558
scpostdr-elnewpodr	0.022436856	-0.030744551	0.075618264	0.9244282
scpredr-elnewpodr	0.016621809	-0.030486702	0.063730319	0.9731658
elorigdr-elodr	0.095483246	-0.052280138	0.243246629	0.5291789
elorigpodr-elodr	0.100657304	-0.048467983	0.249782591	0.4671193
elorigpredr-elodr	0.059892976	-0.087765574	0.207551525	0.9391638
scdr-elodr	0.009002985	-0.138798575	0.156804546	0.9999999
scpostdr-elodr	0.038055114	-0.112061050	0.188171277	0.9969718
scpredr-elodr	0.032240066	-0.115833605	0.180313737	0.9989753
elorigpodr-elorigdr	0.005174058	-0.031903353	0.042251470	0.9999635
elorigpredr-elorigdr	**-0.035590270**	**-0.066240401**	**-0.004940139**	**0.0101121**
scdr-elorigdr	**-0.086480260**	**-0.117812105**	**-0.055148415**	**0.0000000**
scpostdr-elorigdr	**-0.057428132**	**-0.098309005**	**-0.016547259**	**0.0005503**
scpredr-elorigdr	**-0.063243180**	**-0.095834520**	**-0.030651840**	**0.0000002**
elorigpredr-elorigpodr	**-0.040764328**	**-0.077421718**	**-0.004106939**	**0.0169636**
scdr-elorigpodr	**-0.091654319**	**-0.128883584**	**-0.054425054**	**0.0000000**
scpostdr-elorigpodr	**-0.062602190**	**-0.108160718**	**-0.017043663**	**0.0008176**

scpredr-elorigpodr	**-0.068417238**	**-0.106712526**	**-0.030121950**	**0.0000021**
scdr-elorigpredr	**-0.050889990**	**-0.081723645**	**-0.020056335**	**0.0000175**
scpostdr-elorigpredr	**-0.021837862**	**-0.062338177**	**0.018662453**	**0.7535827**
scpredr-elorigpredr	-0.027652910	-0.059765605	0.004459786	0.1549859
scpostdr-scdr	0.029052128	-0.011966520	0.070070777	0.3980989
scpredr-scdr	0.023237081	-0.009526911	0.056001073	0.3961691
scpredr-scpostdr	-0.005815048	-0.047803623	0.036173528	0.9999655