Fish Communities in the Tidal Freshwater Wetlands of the Lower Columbia River

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Abstract

We investigated fish species richness, community composition, density, and diversity along a spatial gradient of tidal influence in the shallow wetlands of the Columbia River. Our findings revealed distinct seasonal and spatial patterns in fish community composition, proportions of native and non-native fish species, and occurrence of fish that are potential juvenile salmon competitors and predators. We observed increased species richness and diversity with increased distance from the mouth of the Columbia River. Proportions of non-native species increased as well, and were especially high near the urban areas of the lower Columbia River. Species richness, density, and proportion of non-native species were higher during the summer months and positively correlated with water temperature. Juvenile salmonid density was highest in the spring, and salmonids were largely absent in the summer when non-native fish species were most abundant. Future increases in temperature, as expected with climate change, will favor further expansion of warm-water species, likely changing food web dynamics and having unpredictable effects on salmonids and other native fish populations.

Keywords: salmonids, native, non-native, Columbia River, piscivores

Introduction

The Columbia River basin historically supported diverse and abundant populations of fish and wildlife, and is known to have been one of the largest producers of Pacific salmonids in the world (Netboy 1980, Cone 1995, NRC 1996, Weitkamp et al. 2012). Anthropogenic changes since the 1860s, including construction of the hydropower system, have significantly reduced the quantity and quality of habitat available to salmon and other fish and wildlife species (Sherwood et al. 1990, Kareiva et al. 2000, Marcoe and Pilson 2017). Factors further contributing to salmonid decline include changes in river flows, degraded water quality and increased concentrations of chemical contaminants, introduction of non-native species, and altered food web dynamics (see Bottom et al. 2005a, 2005b; Fresh et al. 2005; Johnson et al. 2013; Sagar et al. 2015).

The introduction of non-native fish species into the Columbia River is concerning, as non-native species might affect the health and survival of threatened and endangered salmon species (ISAB 2008, 2011; Sanderson et al. 2009). Non-native species are generally harmful to native fish communities and ecosystems (Courtenay and Robins 1989, Tyus and Saunders 2000), contributing to extinctions of native species (Miller et al. 1989). While there have been studies on the impacts of individual non-native species on salmonids and other native fish in the Columbia River basin (ISAB 2011, 2012), the relationship between multiple

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non-native species and the resulting food web and community-level effects remains under-researched, particularly in the tidal freshwater portion of the lower Columbia River.

Of the possible impacts of non-native fish species on listed Columbia River salmonids, predation is perhaps the best documented (ISAB 2008, Sanderson et al. 2009). A review by Sanderson et al. (2009) quantified predation of salmonids by non-native species in the Pacific Northwest and reported that several non-native fish species, in particular smallmouth bass (*Micropterus dolomieu*), consumed significant numbers of juvenile salmon. The impacts of certain native fish species on juvenile salmonids are also concerning. For example, northern pikeminnow (*Ptychocheilus oregonensis*) is a native piscivorous fish species that is known to feed on migrating Columbia River juvenile salmonids (Sanderson et al. 2009). Northern pikeminnow have expanded their distribution and increased in abundance due to habitat modifications along the Columbia and Snake rivers (Sanderson et al. 2009, ISAB 2011), to the point where bounty programs are in place to encourage their collection in order to reduce the number of larger and older fish (WDFW 2020).

In addition to predation, non-native fish may compete with juvenile salmonids for food and habitat. For example, anadromous American shad (*Alosa sapidissima*) were introduced into the Sacramento River, California, and subsequently became established in the Columbia River, with an increasing abundance in the lower Columbia River during recent years (Petersen et al. 2003; Weitkamp 1994, 2012; Hasselman et al. 2012a, 2012b). Shad have impacted *Daphnia* abundance and size in Columbia River reservoir habitat (Haskell et al. 2006) and thus reduced the zooplankton food base available to sub-yearling Chinook salmon (*Oncorhynchus tshawytscha*). River temperature increases and flow decreases in the summer may exacerbate this problem by causing zooplankton abundance to peak earlier in the summer, perhaps allowing juvenile shad to deplete this important food source before downstream migrating juvenile Chinook salmon have the opportunity (Haskell et al. 2006). Also, the abundance of native forage fish, threespine stickleback (*Gasterosteus aculeatus*) in particular, in the lower Columbia River have reportedly increased (Weitkamp et al. 2012), although the impacts of this trend on juvenile salmonids remain uncertain.

Since the mid-1980s, resident fish assemblages in shallow off-channel habitats of the Columbia River have changed substantially. In particular, introduced taxa such as sunfishes and yellow perch have replaced native taxa such as chiselmouth (*Acrocheilus alutaceus*), northern pikeminnow, suckers (*Catostomus* spp.), and sand rollers (*Percopsis transmontana*) (Barfoot et al. 2002). High summer water temperatures in these off-channel and backwater habitats are thought to be a major contributing factor to changes observed in fish community composition (Gadomski and Barfoot 1998), causing native taxa to move out of these habitats, and non-native warm-water taxa to move in (Barfoot et al. 2002). Similarly, other studies have reported that concurrent with temperature increases in backwater and shallow water habitats, introduced warm-water fishes, such as centrarchids (e.g., bass [*Micropterus* spp.], bluegill [*Lepomis macrochirus*], and crappies [*Pomoxis* spp.]) and percids (e.g., walleye [*Sander vitreus*] and perch [*Perca* spp.]) are expanding their distribution and abundance (Poe et al. 1994). Future increases in temperature, as expected with climate change, will certainly favor further expansion of warm-water species, including piscivores such as bass and channel catfish (*Ictalurus punctatus*) that may prey on juvenile salmon (Poe et al. 1991). Beyond changes in species composition, non-native fishes may likely change food web dynamics by increasing predation on native fishes, competing for resources, and contributing pathogens and parasites, with unpredictable consequences (Petersen et al. 2001, 2003; Kuehne et al 2012; Dietrich et al. 2014).

In this paper, we describe seasonal and spatial patterns in fish assemblages in emergent marsh habitats in the tidal freshwater wetlands of the lower Columbia River. Several studies have examined fish assemblages and the relationship between juvenile salmon and non-salmonid fishes in the lowest portion of the Columbia River where saltwater influences species diversity and seasonal abundance (e.g., McCabe et al. 1986; Bottom et al. 2005a, 2005b, 2011; Weitkamp et al. 2012). However, studies on the tidal freshwater portion of the Columbia River are limited (Bottom et al. 2011, Johnson et al. 2011, Sather et al. 2016).

The objectives of this study were 1) to compare fish community characteristics along a spatial gradient of tidal influence in the shallow wetlands of the lower Columbia River using data collected from 2008 to 2016, and 2) to evaluate the relationships between the density of juvenile salmonids and that of native/non-native competitors and predators. Juvenile salmonids use these tidal wetlands extensively for rearing as they migrate to the ocean, and the data can be used for management efforts directed towards the recovery of endangered salmonids in the lower Columbia River.

Methods

Sampling Design

This study was conducted as part of a long-term status and trends monitoring program initiated in 2005 (Sagar et al. 2015). This program focuses on providing an inventory of salmon habitats across the lower Columbia River, defined as all tidally influenced areas of the mainstem and tributaries from Bonneville Dam (river kilometer 234) to the estuary plume and stratified by hydrogeomorphic reaches. The lower Columbia River is divided into eight major hydrogeomorphic reaches, each with unique characteristics and physical processes (Figure 1, Simenstad et al. 2011). Reach boundaries are based on the Environmental Protection Agency (EPA) Levels III and IV Ecoregions, which were modified to include important parameters such as salinity intrusion, maximum tide level, upstream extent of current reversal, geology, and major tributaries. The focus of the fish monitoring aspect of the program was to describe the fish communities over time and according to habitats and by hydrogeomorphic reach (Sagar et al. 2015).

From 2008 to 2016, we sampled six of the eight hydrogeomorphic reaches of the lower Columbia River (19 sites), ranging in location from the upper limit of saltwater influence area to the upper limit of tidal influence area just below the Bonneville Dam (Figure 1). The monitoring program focused on minimally disturbed, tidally influenced emergent wetland habitats (Sagar et al. 2015). Due to the lack of minimally disturbed sites, Reach D was not sampled, and Reach F contained only one site. For this study, we excluded the marine-dominated Reach A. To characterize fish communities in the lower Columbia River reaches (i.e., to assess the status of the reaches), one reach was sampled intensively each year. Most of these sites were sampled for only one year (status sites) (Table 1). Additionally, five sites (typically one per reach) were monitored for trends (trend sites) and were therefore sampled for multiple years (Table 1) (see Sagar et al. 2015 for detailed description of monitoring program study design).

Fish Monitoring and Sample Collection Methods

From 2008 to 2010, fish monitoring was generally started in April and continued on a monthly basis through August or September. Beginning in 2011, the sampling period was expanded, typically beginning in February and extending through December. Sampling was generally not possible in January because of the time needed to renew fish collection permits, and sampling was also precluded at times by extremely high or low water levels (USGS 2020).

Fish were collected using a Puget Sound beach seine (PSBS) (37 × 2.4 m, 10-mm mesh size), following the recommended guidelines for beach seining in Puget Sound (PSEP 1990). Generally, up to three sets were performed at each site and at each sampling time (i.e., month), as site conditions and sampling permit limitations allowed. All fish in each set were identified to the species level and counted. For each set, the coordinates of the sampling location, the time of sampling, water temperature (measured with the boat's onboard thermometer or handheld thermometer), and the area covered by the beach seine was estimated for calculation of fish density.

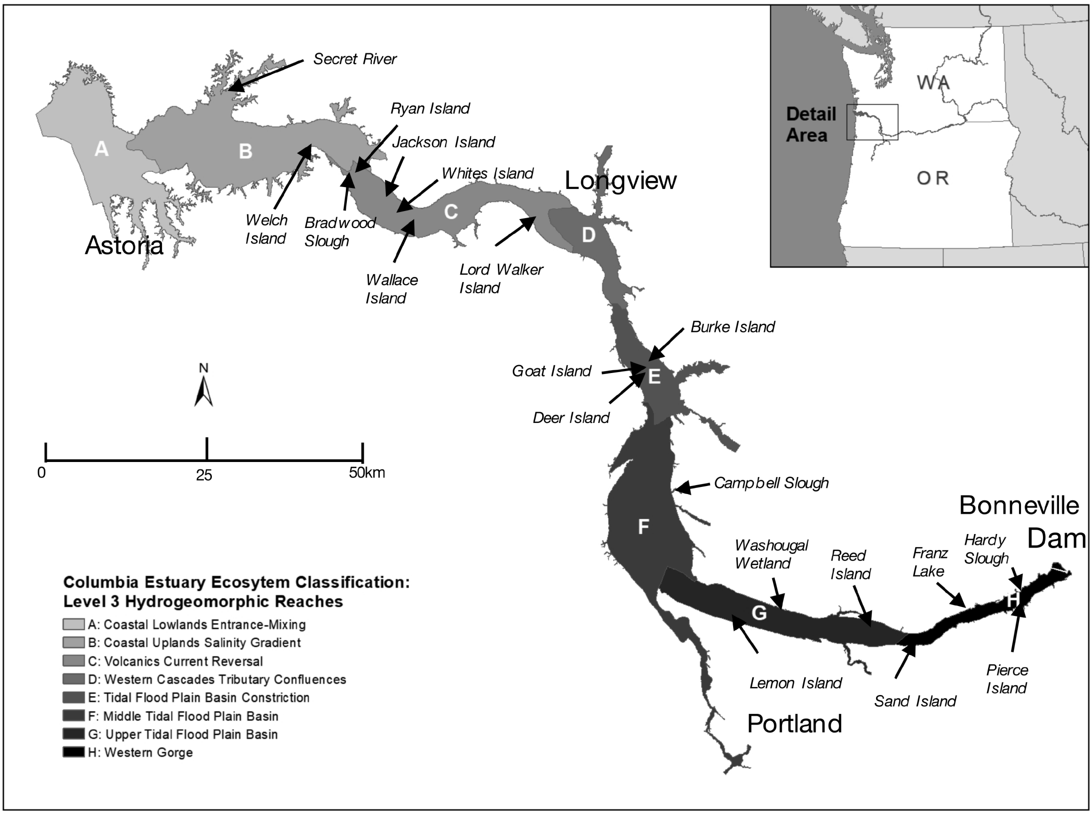

Figure 1. Sampling sites in the lower Columbia River with hydrogeomorphic reaches (A through H) indicated.

Calculations and Statistical Analyses

As described above, we were unable to sample all reaches uniformly by month or year. For example, not all reaches were sampled for multiple years (status sites), and only a few sites within six separate reaches (trend sites) were sampled for multiple years. Because of the unbalanced nature of the data, complex statistical analyses accounting for the influence of multiple factors on fish community measures were considered inappropriate. Therefore, results are presented primarily in a descriptive manner (e.g., without explicitly including factors such as year × site interactions).

For each set, the number of fish captured was determined, then standardized to the number of fish captured per 1,000 m^2 (Roegner et al. 2009), to provide a measurement of fish density similar to fish densities reported in other studies in the lower Columbia River (Bottom et al. 2008, Johnson et al. 2011, Sather et al. 2016). The fish collected were categorized into the following groups: salmonids, native non-salmonids, non-native fish, and piscivorous salmon predators, following criteria outlined in Wydowski and Whitney (2003) and Sather et al. (2016). Density values were calculated for each of these categories, as well as for American shad and threespine stickleback, two species of interest considered to be potential competitors to salmonids (Harvey and Kareiva 2005, Weitkamp et al. 2012, Haskell et al. 2013).

To account for both abundance and evenness of the species present, species diversity was calculated using the Shannon-Wiener diversity index (Shannon and Weaver 1949, Margalef 1958). Species richness (number of species), percentage of the total catch for individual species, density for each individual species, and diversity were calculated

TABLE 1. Sample site information including site coordinates (decimal degrees), river km, and years sampled from 2008 to 2016. River km 0 is the mouth of the Columbia River; river km 234 is the Bonneville Dam and the height of tidal influence in the river. Asterisk (*) denotes trend sites. From 2008 to 2010, sites were sampled from April through September; from 2011 to 2015, sites were sampled from January through December.

Site Name	Reach	Latitude	Longitude	River km	Years Sampled
Secret River*	B	46.3044	–123.690467	37	2011 to 2013
Welch Island*	B	45.783867	–122.75485	53	2011 to 2016
Ryan Island	C	46.2066	–123.414817	61	2009
Bradwood Slough	C	46.203183	–123.447733	62	2010
Jackson Island	C	46.169417	–123.3506	71	2010
Whites Island*	C	46.15935	–123.340133	72	2009 to 2016
Wallace Island West	C	46.140467	–123.2831	77	2009
Lord/Walker Island	C	46.137216	–123.040278	99	2009
Burke Island	E	45.938867	–122.789683	131	2011
Deer Island	E	45.926917	–122.819683	132	2011
Goat Island	E	45.932317	–122.815417	131	2011
Campbell Slough*	F	45.783867	–122.75485	149	2008 to 2016
Lemon Island	G	45.590233	–122.560917	180	2012
Washougal Wetland	G	45.580917	–122.03945	195	2012
Reed Island	G	45.555217	–122.297517	201	2012
Sand Island	H	45.55335	–122.211117	221	2008
Franz Lake*	H	45.600583	–122.103067	221	2008, 2009, 2011 to 2016
Pierce Island	H	45.620967	–122.0108	228	2008
Hardy Slough	H	45.628217	–122.01215	230	2008

for each set. Pearson's correlation was used to examine the relationships between temperature and various fish community parameters, as well as the relationship between the densities of non-native species, predatory fish, competitive species (American shad and threespine stickleback), and salmonids. Analyses were conducted with the JMP statistical package.

Results

Water Temperature

Water temperatures followed a similar pattern in all reaches. Seasonal differences in water temperature were observed (Figure 2). Temperatures were lowest during the mid-fall and mid-winter months (October through January), increased to a high during the summer months (July and August, with peak in July), then declined during the fall months (September through November). The summer water temperature was generally the highest in Reach F, and the lowest in Reach B.

Fish Community Characteristics

Twenty-four native species and nineteen non-native species were captured at the sampling sites over the course of this study (Figure 3, Table 2). In all reaches, species richness and diversity were generally higher during the summer months and early fall (July through September) than in other months (Figures 4 and 5, Table 3). Also, species richness and diversity were highest in Reach F, and consistently lower in Reaches B and C, which are closest to the mouth of the river (Figures 4 and 5, Table 2).

Native Species—The percentage of native species captured in Reach F was lower than in other reaches (Table 2). Of the native species, threespine stickleback was the most dominant species, ranging from 35 to 91% of the catch, with the highest percentages in Reaches B and C. Chiselmouth was also found in high percentages, ranging from < 1 to 25%, with the highest percentage in Reach H. Salmonids were found in all reaches (2 to 17%), with the highest percentage in Reach

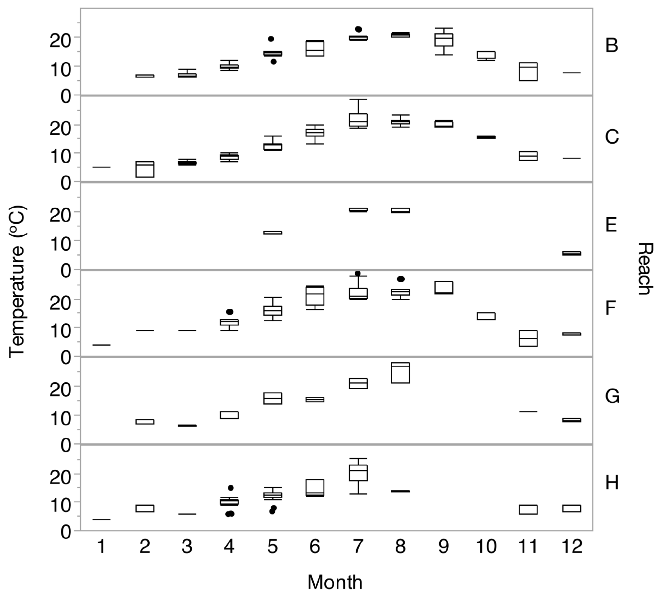

Figure 2. Boxplot of water temperatures (°C) at sampling locations by month and reach. The box represents 1st quartile (Q1) and 3rd quartile (Q3), 25 to 75 percentile range. IQR = Q3 quartile minus Q1. Whiskers are drawn to the furthest point within 1.5 × IQR for the box, and the data falling outside the IQR are plotted as outliers (dots).

non-native species, common carp (*Cyprinus carpio*), banded killifish *(Fundulus diaphanous)*, and yellow perch (*P. flavescens*) were the most abundant, accounting for up to 13 to 17% of the catch in Reach F. Shad made up only 0.5% of the total catch at our tidal freshwater sites. In Reaches B, C, E, G, and H, the percentage of shad in the catch ranged from < 0.1 to 0.7%, but it was more common in Reach F, where it made up 2.9% of the catch (Table 2). The percentage of non-native fish also varied by season. Non-native fish were generally more prevalent during late spring through early fall months (June through September), although a high percentage of fish captured in January were carp and killifish (Table 3).

Salmon Predators—One or more predators of juvenile salmon were present in all reaches, but comprised only a small percentage of the total catch. The fewest predatory species were present in Reaches B and C; they were more abundant in Reaches E through H, with the highest abundance in Reach F (Figure 6).

In terms of specific predators, smallmouth and largemouth bass (*M. salmoides)* together made up 0.2% of the total catch; catfish and walleye made up < 0.1% of the total catch; crappie made up 0.2% of the total catch; northern pikeminnow made up 0.3%; and yellow perch made up 2.3% of the total catch (Table 2). The proportion of predatory fish also varied seasonally, with higher values in the summer months and early fall (July through September) (Table 3).

G. Native species composition showed seasonal patterns (Table 3). Salmonid species, including Chinook salmon, coho salmon *(O. kistuch),* and chum salmon *(O. keta)* were generally found in the greatest proportions in the spring. Some native non-salmonid species, such as chiselmouth, tui chub *(Gila bicolor)*, and largescale sucker *(Catostomus macrocheilus)*, were most abundant in the summer. Threespine stickleback was present in high numbers throughout the sampling period, with highest numbers caught during the summer months and early fall (July through September) (Table 3).

Non-Native Species—The percentage of non-native species captured was generally higher in Reach F (Table 2). Overall, of the total number of species captured, Reaches B, C, and G had lower percentages of non-natives (2 to 5%), whereas Reaches E and H had higher percentages of non-natives (14 to 57%) (Table 2). Of the introduced

Fish Density

We estimated salmonid density, non-salmonid native fish density, non-native fish density, and piscivorous salmon predator density. The density of salmon did not vary greatly by reach (Figure 7a). Salmonid density varied throughout the sampling season, but was the highest in May and June and the lowest in September and October

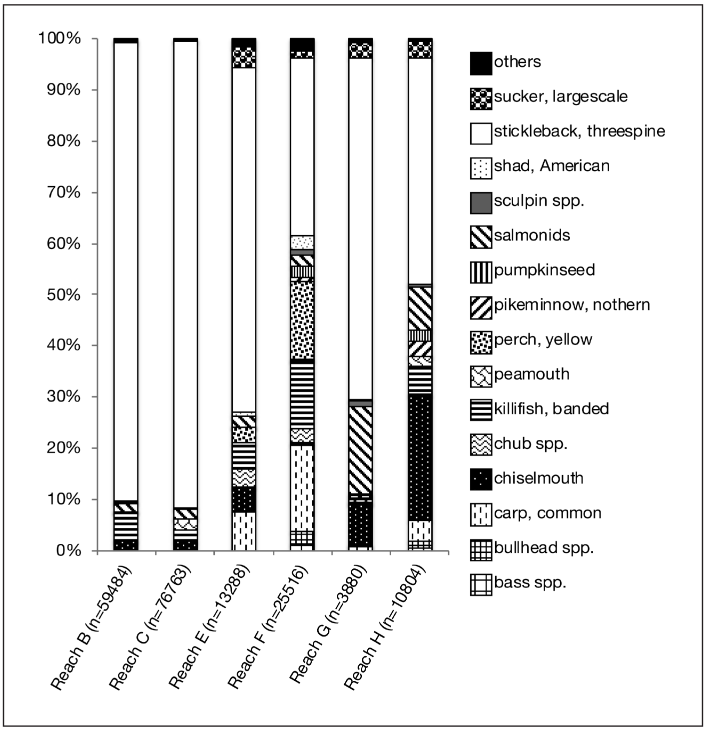

Figure 3. Species composition by reach, pooled across months and years sampled. n indicates total number of fish caught at each reach. Other species are those making up less than 1% of the catch in any reach (see Table 2).

(Figure 7a). The density of native non-salmonid fish tended to be higher in Reaches B through E than in Reaches F through H, and higher during the summer months (Figure 7b). The density of non-native fish (Figure 7c) and potential salmon predators (Figure 7d) tended to be higher in Reaches E and F than in other reaches, and higher during the summer months. In terms of potential competitive species, the density of threespine stickleback was higher in Reaches B through E (Figure 8a), but the density of shad did not vary between reaches (Figure 8b). Densities of shad and threespine stickleback were higher during the summer months.

Densities of non-native fish and predatory fish were negatively correlated with the density of salmonids; whereas the densities of native non-salmonid fish, and competitive fish (shad and threespine stickleback) were not correlated with the salmonid density. The density of non-native fish was positively correlated to the density of predatory fish and the density of shad (Table 4).

Temperature and Fish Community Characteristics

Water temperature was positively correlated with species richness and diversity, as well as with the densities of native non-salmonid fish, non-native fish, predatory fish, shad, and threespine stickleback in the catch (Table 4). Water temperature was negatively correlated with the density of salmonids (Table 4), with low densities during summer months when the temperatures were higher. A correlation between salmon density and temperature, and a positive correlation between non-native species density and temperature was observed not only for all months, which would be consistent with seasonal differences in habitat occurrence, but also when only summer months were considered, suggesting that higher summer temperatures are associated with lower salmonid densities and higher densities of non-native species. Higher densities of non-native species were observed at higher temperatures (Figure 9a), while salmonids were largely absent from our sampling sites when the water temperature was above 20 °C (Figure 9b).

Discussion

Our findings reveal several patterns in fish community composition in the lower Columbia River that could be relevant to the management of salmon and other fish species. First, fish assemblages tended to vary along the gradient of tidal influence in shallow tidal freshwater habitats throughout the lower Columbia River. In Reaches B and C, which are near the mouth of the Columbia River and experience strong tidal influences, catches were overwhelmingly dominated by threespine stickleback, and non-native species were rare. The number of species, species diversity, and percentage of non-native species all tended to increase with increasing river km, reaching a peak in Reach F, and remaining relatively high in Reaches G and H. In Reaches E through H, threespine stickleback remained a dominant species, but other native species such as largescale sucker, chiselmouth, and chub were more common, as well as a variety of non-native species.

The effects of human activity were also apparent, as indicated by the presence of non-native species, especially abundant in Reaches E and F. Out of 41 non-native fish species introduced in the United States west of the Rocky Mountains (Wydowski and Whitney 2003, ISAB 2008), a total of 19 non-native species were found in this study. Many of the species were introduced intentionally for food or game, while some were introduced through various other vectors (e.g., recreational boats and cargo barges/tugs, intentional or accidental release of bait, and releases from home aquaria), and many of the species have become established in the Pacific Northwest (Wydowski and Whitney 2003, ISAB 2008, Sanderson et al. 2009). Reach F, where non-native species were especially predominant, is just downstream of the Vancouver/Portland metropolitan area. Higher non-native species counts, as well as higher proportions of non-native species and piscivorous predators in Reaches F through H sites, may be reflective of their proximity to disturbed areas and areas with higher boat traffic (Cohen and Carlton 1998). Sanderson et al. (2009) also noted high numbers of non-native species in the heavily developed areas of the Columbia and Willamette rivers, and mentioned dams and reservoirs as having a potential role in establishing non-native species in the Columbia River, which could contribute to higher numbers of non-native species in Reaches F through H.

Fish assemblages in the lower Columbia River showed distinctive seasonal patterns. The density of salmonid species was generally highest in the spring, while the density of other species, including non-native fish as well as some native non-salmonid fish, tended to be highest during the summer months. The non-native species that were especially abundant in the summer may be more suited to higher temperatures, and the reproductive timing of these species may coincide with higher summer temperatures. This appears to be the case for banded killifish (Chippett 2003), bass (Rubenson and Olden 2016), and carp (Cudmore and Mandrak 2004). A positive correlation between water temperature and the density of non-native species suggests that the current trend in increasing water temperatures within the mainstem Columbia (EPA 2018) may encourage their increase. Some studies predict significant range expansions over this century for warm-water species such as smallmouth bass and common carp (both of which are present in the lower Columbia River) as a result of climate change (Minns and Moore 1995, Sharma et al. 2007, Rahel and Olden 2008).

The spatial and seasonal patterns we observed in the prevalence of non-native species are consistent with those reported in other studies. For example, Bottom et al. (2011) and Weitkamp et al. (2012) reported relatively low presence of non-native species in Reaches B and C. Bottom et al. (2011) reported that 14% of species collected in these reaches were non-native. Similarly, the fish assemblages documented by Weitkamp et al. (2012) in the saltwater portion of the river were primarily made up of native species. The patterns of occurrence of native and non-native species that we observed in Reaches F through H are much like those reported by Johnson et al. (2011) and Sather et al. (2016) at the sites they sampled in these reaches. The most common species observed in the Sandy River delta (Reach G) by Johnson et al. (2011) and Sather et al. (2016) were threespine stickleback, banded killifish, peamouth, and northern pike minnow, and Johnson et al. (2011) reported that 53% of species collected were non-native. In Reaches E and F, Sather et al. (2016) reported that the primary species observed were threespine stickleback, banded killifish, and yellow perch, and these species were especially abundant in the summer and fall. Sather et al. (2016) also reported that for the sites within these regions (i.e., Sandy River delta in Reach G, and in Reaches E and F), variation in fish communities was more

TABLE 2. Fish species caught in the lower Columbia River by hydrogeomorphic reach. Numbers in parentheses indicate percent of the total catch (native plus non-native fish) at each reach. The superscript 1 indicates salmonid species; superscript 2 indicates piscivorous salmon predators, and superscript 3 indicates potential competitor species. Species that are greater than 10% of the total catch at any reach are highlighted with gray shading.

Common name	Scientific name	Reach B	Reach C	Reach E	Reach F	Reach G	Reach H	Total
Native species								
chiselmouth	*Acrocheilus alutaceus*	1,153 (1.9)	1,298 (1.7)	648 (4.9)	91 (0.4)	320 (8.2)	2,651 (24.5)	6,161 (3.2)
chub, lake	*Couesius plumbeus*				39 (0.15)			39 (0.02)
chub, tui	*Gila bicolor*	24 (< 0.1)		462 (3.5)	734 (2.9)	4 (0.1)	17 (0.2)	1,241 (0.7)
dace, speckled	*Rhinichthys osculus*				2 (< 0.1)	2 (< 0.1)		4 (< 0.1)
flounder, starry	*Platichthys stellatus*	216 (0.4)	168 (0.2)	3 (< 0.1)	3 (< 0.1)	23 (0.6)		413 (0.2)
herring, Pacific	*Clupea pallasii*	4 (< 0.1)						4 (< 0.1)
eulachon	*Thaleichthys pacificus*	7 (< 0.1)	7 (< 0.1)					14 (< 0.1)
peamouth	*Mylocheilus caurinus*	2 (< 0.1)	1,544 (2.0)	1 (< 0.1)	58 (0.2)	14 (0.4)	193 (1.8)	1,812 (1.0)
pikeminnow, northern2	*Ptychocheilus oregonensis*	8 (< 0.1)	27 (< 0.1)	16 (0.1)	222 (0.9)	23 (0.6)	307 (2.8)	603 (0.3)
salmon, Chinook[1]	*Oncorhynchus tshawytscha*	1,071 (1.8)	1,459 (1.9)	256 (1.9)	541 (2.1)	548 (14.1)	517 (4.8)	4,392 (2.3)
salmon, chum[1]	*Oncorhynchus keta*	23 (< 0.1)	90 (0.1)		8 (< 0.1)	2 (< 0.1)	53 (0.5)	176 (< 0.1)
salmon, coho[1]	*Oncorhynchus kisutch*	22 (< 0.1)	57 (< 0.1)	1 (< 0.1)	4 (< 0.1)	104 (2.7)	329 (3.0)	517 (0.3)
salmon, sockeye[1]	*Oncorhynchus nerka*	2 (< 0.1)	7 (< 0.1)		1 (< 0.1)	1 (< 0.1)	2 (< 0.1)	13 (< 0.1)
sculpin (Cottidae)*	*Cottida* spp.	129 (0.2)	108 (0.1)	30 (0.2)	219 (0.9)	49 (1.3)	57 (0.5)	592 (0.3)
sculpin, Pacific staghorn	*Leptocottus armatus*	2 (< 0.1)						2 (< 0.1)
shiner, redside	*Richardsonius balteatu*				9 (< 0.1)			9 (< 0.1)
smelt **	*Osmeridae* spp.	11 (< 0.1)			87 (0.3)			98 (< 0.1)
stickleback, threespine	*Gasterosteus aculeatus*	53,341 (89.7)	70,048 (91.3)	8,928 (67.2)	8,856 (34.7)	2,589 (66.7)	4,772 (44.2)	148,534 (78.3)
sturgeon, white	*Acipenser transmontanus*						6 (< 0.1)	6 (< 0.1)
sucker, largescale	*Catostomus macrocheilus*	177 (0.3)	145 (0.2)	556 (4.2)	355 (1.4)	115 (3.0)	350 (3.2)	1,698 (0.9)
trout, cutthroat[1]	*Oncorhynchus clarkii*	1 (< 0.1)			1 (< 0.1)	2 (< 0.1)	1 (< 0.1)	5 (< 0.1)
trout, steelhead[1]	*Oncorhynchus mykiss*		1 (< 0.1)			1 (< 0.1)	3 (< 0.1)	5 (< 0.1)
whitefish, mountain	*Prosodium williamsoni*				1 (< 0.1)		1 (< 0.1)	2 (< 0.1)
whitefish, pygmy	*Prosopium coulterii*						1 (< 0.1)	1 (< 0.1)

TABLE 2. (cont.)

Common name	Scientific name	Reach B	Reach C	Reach E	Reach F	Reach G	Reach H	Total
Total number of native fish caught		56,193 (94.5)	74,959 (97.6)	10,901 (82.0)	11,231 (44.0)	3,797 (97.9)	9,260 (85.8)	166,341 (87.7)
Number of native species at each reach		14	13	11	18	15	16	24
Non-native species								
bass, largemouth[2]	*Micropterus salmoides*				19 (< 0.1)			19 (< 0.1)
bass, smallmouth[2]	*Micropterus dolomieu*	1 (< 0.1)	1 (< 0.1)	4 (< 0.1)	299 (1.2)	27 (0.7)	57 (0.5)	389 (0.2)
bluegill	*Lepomis macrochirus*		2 (< 0.1)	82 (0.6)	220 (0.9)		12 (0.1)	316 (0.2)
bullhead, brown	*Ameiurus nebulosus*				43 (0.2)		3 (< 0.1)	46 (< 0.1)
bullhead, yellow	*Ameiurus natalis*				571 (2.2)	2 (< 0.1)	148 (1.4)	721 (0.4)
carp, common	*Cyprinus carpio*		3 (< 0.1)	988 (7.4)	4,340 (17.0)	6 (0.2)	431 (4.0)	5,768 (3.0)
catfish, blue	*Ictalurus furcatus*						1 (< 0.1)	1 (< 0.1)
catfish, channel	*Ictalurus punctatus*						1 (< 0.1)	1 (< 0.1)
crappie[2]	*Pomoxis* spp.			114 (0.9)	175 (0.7)		2 (< 0.1)	291 (0.2)
goby	*Rhinogobius brunneus*				13 (< 0.1)			13 (< 0.1)
killifish, banded	*Fundulus diaphanus*	3,218 (5.4)	1,790 (2.3)	692 (5.2)	3,365 (13.2)	12 (0.3)	594 (5.5)	9,671 (5.1)
mosquitofish	*Gambusia affinis*				1 (< 0.1)			1 (<0.1)
perch, yellow[2]	*Perca flavescens*	16 (< 0.1)	6 (< 0.1)	406 (3.1)	3,883 (15.2)	11 (0.3)	10 (< 0.1)	4,332 (2.3)
pumpkinseed	*Lepomis gibbosus*			3 (< 0.1)	598 (2.3)	12 (0.3)	255 (2.4)	868 (0.5)
shad, American[3]	*Alosa sapidissima*	56 (< 0.1)	2 (< 0.1)	98 (0.7)	752 (2.9)	13 (0.3)	15 (0.1)	936 (0.5)
shiner, golden	*Notemigonus crysoleucas*				1 (< 0.1)			1 (< 0.1)
walleye[2]	*Sander vitreus*						1 (< 0.1)	1 (< 0.1)
warmouth[2]	*Lepomis gulosus*				1 (< 0.1)			1 (< 0.1)
weatherfish, oriental	*Misgurnus anguillicaudatus*				4 (< 0.1)			4 (< 0.1)
Total number of non-native fish caught		3,291 (5.5)	1,804 (2.4)	2,387 (18.0)	14,285 (56.0)	83 (2.1)	1,530 (14.2)	23,380 (12.3)
Number of non-native species at each Reach		4	6	8	16	7	13	19
Grand total of native and non-native fish caught		59,848	76,763	13,288	25,516	3,880	10,804	189,721

*Includes prickly sculpin (*Cottus asper*), mottled sculpin (*Cottus bairdi* complex), riffle sculpin (*Cottus gulosus*), slimy sculpin (*Cottus cognatus*) and other juvenile sculpin that could not be identified to species.
**Includes Columbia River smelt, or eulachon (*Thaleichthys pacificus*), and other larval and juvenile smelt that could not be identified to genus and species.

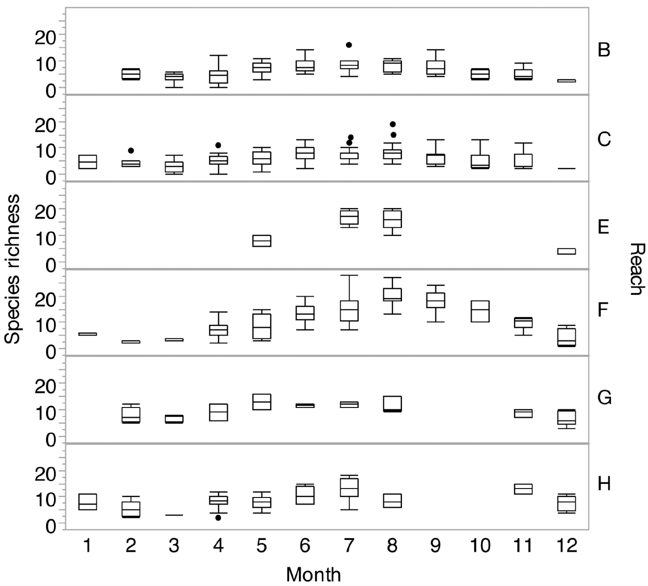

Figure 4. Boxplot of species richness (number of species) by sampling month for each hydrogeomorphic reach. The box represents 1st quartile (Q1) and 3rd quartile (Q3), 25 to 75 percentile range. IQR = Q3 quartile minus Q1. Whiskers are drawn to the furthest point within 1.5 × IQR for the box, and the data falling outside the IQR are plotted as outliers (dots).

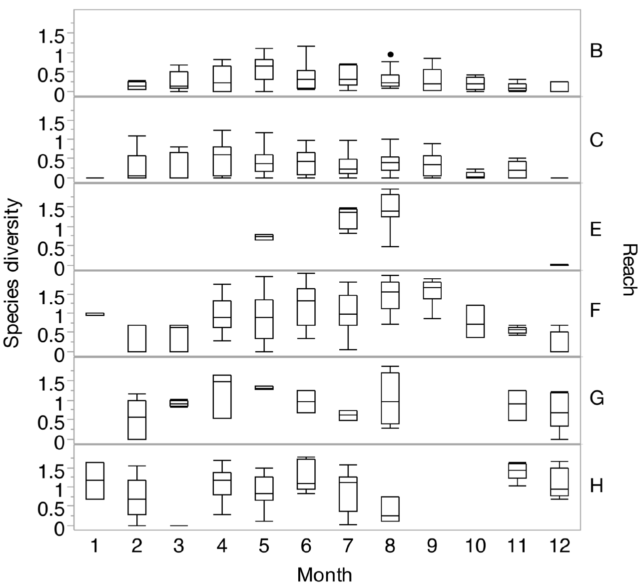

Figure 5. Boxplot of species diversity by sampling month for each hydrogeomorphic reach. The box represents 1st quartile (Q1) and 3rd quartile (Q3), 25 to 75 percentile range. IQR = Q3 quartile minus Q1. Whiskers are drawn to the furthest point within 1.5 × IQR for the box, and the data falling outside the IQR are plotted as outliers (dots).

closely linked to season than to spatial gradients. This is consistent with our findings that there was considerable similarity in fish community composition among Reaches F through H, and that sampling month and water temperature were among the most important factors influencing fish density.

While this survey focused on relatively undisturbed sites in the lower Columbia River, the characteristics of the fish assemblages at Reaches E and F are consistent with somewhat reduced habitat quality in these areas, based on measures such as the Index of Biotic Integrity (Karr et al. 1986, Hughes and Gammon 1987, Waite and Carpenter 2000). These reaches were characterized by having higher proportions of introduced species, as well as species that are omnivorous and tolerant of disturbed environmental conditions, such as carp. This is perhaps not surprising, as these reaches are downstream of the urban and industrialized Portland/Vancouver area, and so would be the most likely to exhibit the influences of pollution and anthropogenic disturbances associated with this region. Hughes and Gammon (1987) also observed declining fish assemblage quality at sites closest to the Portland metro area, in conjunction with declining water quality as indicated by downstream increases in temperature, turbidity, total organic carbon, nitrite-nitrate, and total phosphorus. Similarly, in the Willamette River, Waite and Carpenter (2000) observed a relationship between fish assemblages and disturbance, with sites having low dissolved oxygen, high total phosphate, high pesticides, and high maximum water temperature tending to support fish assemblages dominated by tolerant species and introduced species, such as yellow bullhead, pumpkinseed, bluegill, and warmouth.

Natural resource and fisheries managers are increasingly concerned about how associated fish species could affect the abundance of threatened and endangered salmon in the lower Columbia River. Introductions of non-native species have been associated with declines in native species (ISAB 2008, Sanderson et al. 2009), and may negatively affect juvenile salmon as predators or as competitors for similar prey resources (Sanderson et al. 2009). More specific concerns have been raised about the impacts of shad, as well as predators such as walleye, small and largemouth bass, and northern pikeminnow on juvenile salmon in the Columbia River (ISAB 2008, Sanderson et al. 2009). Managing native predators (e.g., northern pikeminnow) and targeted removal of specific non-native species (e.g., walleye, catfish and shad) was predicted to benefit salmon in the upper Columbia River reservoir (Harvey and Kareiva 2005).

In our study, the fish species common in our catches included several, predominantly non-native piscivorous predators of juvenile salmon. The major piscivores preying on juvenile salmon in the Columbia River are northern pikeminnow, largemouth and smallmouth bass, walleye, channel catfish, yellow perch, and crappie (Rieman et al. 1991, Vigg et al. 1991, Tabor et al. 1993, Petersen and Kitchell 2001, Fritts and Pearsons 2006). Of these, only northern pikeminnow is native to the Columbia River basin (Petersen and Kitchell 2001). Walleye were rarely observed at our tidal freshwater sites, but northern pikeminnow, bass, yellow perch, and crappie were all commonly encountered. These predatory fish species were rarely found at sites in Reaches B and C, but were present more often in Reaches E through H, especially during the summer months. As with the density of non-native species, the density of piscivorous predators was positively correlated with water temperature. Although fish length was not recorded in this study (other than for salmonids), the predatory fish in the catch included both adults and juveniles. While juvenile predatory fish would have minimal impact on juvenile salmonids, adult predatory fish could potentially have greater impact on them. Also, in our study, negative correlations were observed between salmonid density and densities of predatory fish, though this may be more a reflection of differing life cycles and patterns of habitat use than any causal relationship.

In addition to piscivorous predators, species that have been suggested as possible salmon competitors were also present in tidal freshwater habitats in the lower Columbia River. These included American shad and threespine stickleback. American shad was introduced from the east coast to the Sacramento River in 1871, and Columbia River in 1885 (Parks 1978). Populations of shad along the west coast have increased, and the population in the Columbia River has increased to become the largest in the world (Petersen et al. 2003, Sanderson et al. 2009). For example, Weitkamp et al. (2012) reported that adult shad made up 1%, 2%, and 10% of their catch in April, May and June, respectively, at sites in Reaches A and B sampled by purse seine, which they report as roughly twice the levels reported in 1978 to 1980 (Dawley et al. 1985). At our nearshore tidal freshwater sites, all of the shad that were captured were juveniles (about 5 to 10 cm in length) compared to > 280 mm adults captured by Weitkamp et al. (2012), possibly because our sampling was conducted in much shallower water at off-channel sites and in tidal freshwater areas and with different sampling gear. The highest proportions of juvenile shad observed in our study were 6.3% in Reach G in November and 6.8% in September in Reach F. Some hypothesize that planktivory by shad may reduce the availability of prey for juvenile salmonids, and that the presence of shad may encourage increases in native and non-native predators that may also prey on salmon (Petersen et al. 2003, Haskell et al. 2006). In our study, we did not observe any strong correlation between shad density and juvenile salmon density, although shad density and predatory fish density were positively correlated. Additional research is needed to verify whether or not shad influence predatory fish density, with possible indirect impacts on juvenile salmon abundance.

TABLE 3. Fish species caught in the lower Columbia River by month of capture. Numbers in parentheses indicate percent of the total catch (native plus non-native fish) for each month fish were collected. The superscript 1 indicates salmonid species; superscript 2 indicates piscivorous salmon predators, and superscript 3 indicates potential competitor species. Species that are greater than 10% of the total catch for each month highlighted with gray shading.

	Month of capture												
Common name	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Native species													
chiselmouth		48 (1.7)		41 (1.0)	1,763 (10.4)	371 (6.8)	1,272 (2.7)	1,988 (4.0)	56 (0.3)	27 (1.4)	117 (1.4)	28 (0.6)	6,161 (3.2)
chub, lake							2 (< 0.1)	37 (< 0.1)					39 (< 0.1)
chub, tui	9 (9.1)	1 (< 0.1)			1 (< 0.1)	2 (< 0.1)	319 (0.7)	84 (0.2)	65 (0.3)	9 (0.5)	13 (0.2)		1,241 (0.7)
dace, speckled			1 (< 0.1)		1 (< 0.1)				2 (< 0.1)				4 (< 0.1)
flounder, starry		1 (< 0.1)	13 (0.3)	16 (0.4)	68 (0.4)	177 (3.2)	56 (0.1)	22 (< 0.1)	15 (< 0.1)	2 (0.1)	29 (0.3)	5 (< 0.1)	413 (0.2)
herring, Pacific									4 (< 0.1)				4 (< 0.1)
eulachon			14 (0.3)										14 (< 0.1)
peamouth		3 (0.1)		1 (< 0.1)	39 (0.2)	758 (14.0)	681 (1.5)	319 (0.6)		2 (0.1)			1,812 (1.0)
pikeminnow, northern[2]	17 (17.2)				3 (0.2)	55 (1.0)	343 (0.7)	51 (0.1)	44 (0.2)		54 (0.6)		603 (0.3)
salmon, Chinook[1]		88 (3.0)	193 (4.7)	846 (20.5)	1,828 (10.8)	117 (2.1)	344 (0.7)	3 (< 0.1)	1 (< 0.1)		4 (< 0.1)	41 (0.8)	4,392 (2.3)
salmon, chum[1]		3 (0.1)	14 (0.3)	125 (3.0)	33 (0.2)	1 (< 0.1)							176 (< 0.1)
salmon, coho[1]	1 (1.0)	2 (< 0.1)		51 (1.2)	325 (1.9)	23 (0.4)	17 (< 0.1)	84 (0.2)	1 (< 0.1)		3 (< 0.1)	1 (< 0.1)	517 (0.3)
salmon, sockeye[1]				2 (< 0.1)	1 (< 0.1)							1 (< 0.1)	13 (< 0.1)
sculpin *		8 (0.3)	4 (< 0.1)	83 (2.0)	4 (< 0.1)	1 (< 0.1)	163 (0.3)	152 (0.3)	7 (< 0.1)	19 (1.0)	15 (0.2)	1 (< 0.1)	592 (0.3)
sculpin, Pacific staghorn						2 (< 0.1)							2 (< 0.1)
shiner, redside							9 (< 0.1)						9 (< 0.1)
smelt**							1 (< 0.1)	96 (0.2)	1 (< 0.1)				98 (< 0.1)
stickleback, threespine	11 (11.1)	2,724 (93.8)	3,852 (94.0)	2,835 (68.7)	11,986 (70.6)	2,363 (43.4)	35,577 (76.3)	39,569 (80.5)	17,661 (81.9)	1747 (93.8)	7,278 (87.5)	4,931 (97.2)	148,534 (78.3)
sturgeon, white				6 (0.14)									6 (< 0.01)
sucker, largescale	3 (3.0)	5 (0.2)	2 (< 0.1)	52 (1.3)	155 (0.9)	141 (2.6)	117 (0.3)	836 (1.7)	13 (< 0.1)	5 (0.3)	23 (0.3)	49 (1.0)	1,698 (0.9)
trout, cutthroat[1]				4 (< 0.1)	1 (< 0.1)								5 (< 0.1)
trout, steelhead[1]		1 (< 0.1)		3 (< 0.1)		1 (< 0.1)							5 (< 0.1)
whitefish, mountain		1 (< 0.1)		1 (< 0.1)									2 (< 0.1)
whitefish, pygmy		1 (< 0.1))											1 (< 0.1)
Total number of native fish caught	41 (41.4)	2,886 (99.4)	4,093 (99.9)	4,066 (98.6)	16,244 (95.6)	4,012 (73.6)	38,901 (83.4)	43,241 (88.0)	17,870 (82.8)	1,811 (97.)	7,536 (90.6)	5,057 (99.7)	166,341 (87.7)
Number of native species	5	13	8	14	14	13	13	12	12	7	9	8	

TABLE 3. (Cont.)

Common name	Month of capture: Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Non-native species													
bass, largemouth[2]							12 (< 0.1)	7 (< 0.1)					19 (< 0.1)
bass, smallmouth[2]				2 (< 0.1)	25 (0.1)	2 (< 0.1)	43 (< 0.1)	77 (0.2)	214 (1.0)	6 (0.3)	2 (< 0.1)		389 (0.2)
bluegill					1 (< .1)		44 (< 0.1)	166 (0.3)	79 (0.4)	7 (0.4)	18 (0.2)	1 (< 0.1)	316 (0.2)
bullhead, brown							42 (< 0.1)				4 (< 0.1)		46 (< 0.1)
bullhead, yellow				1 (< 0.1)	2 (< 0.1)	1 (< 0.1)	171 (0.4)	111 (0.2)	429 (2.0)	1 (< 0.1)	5 (< 0.1)		721 (0.4)
carp, common	23 (23.2)	1 (< 0.1)		1 (< 0.1)	2 (< 0.1)	69 (1.3)	2,643 (5.7)	267 (0.5)	273 (1.3)	1 (< 0.1)	76 (< 0.1)		5,768 (3.0)
catfish, blue							1 (< 0.1)						1 (<0.1)
catfish, channel							1 (< 0.1)						1 (< 0.1)
crappie[2]						7 (0.1)	97 (0.2)	163 (0.3)	21 (< 0.1)		2 (< 0.1)	1 (< 0.1)	291 (0.2)
goby			1 (< 0.1)		5 (< 0.1)	1 (< 0.1)	1 (< 0.01)	(< 0.1)					13 (< 0.1)
killifish, banded	26 (26.3)	15 (0.5)	4 (< 0.1)	14 (0.3)	578 (3.4)	954 (17.5)	2,332 (5.0)	3,164 (6.4)	1,816 (8.4)	25 (1.3)	651 (7.8)	2 (< 0.1)	9,671 (5.1)
mosquitofish								1 (< 0.1)					1 (< 0.1)
perch, yellow	1 (1.0)	1 (< 0.1)	1 (< 0.1)	35 (0.8)	117 (0.7)	287 (5.3)	2,189 (4.7)	1,327 (2.7)	358 (1.7)	6 (0.3)	2 (< 0.1)	8 (0.2)	4,332 (2.3)
pumpkinseed	8 (8.1)			5 (0.1)	9 (< 0.1)	23 (0.4)	31 (< 0.1)	165 (0.3)	274 (1.3)	1 (< 0.1)	8 (< 0.1)	2 (< 0.1)	868 (0.5)
shad, American[3]					3 (< 0.1)	93 (1.7)	146 (0.3)	437 (0.9)	238 (1.)	4 (0.2)	14 (0.2)	1 (< 0.1)	936 (0.5)
shiner, golden							1 (< 0.1)						1 (< 0.1)
walleye[2]					1 (< 0.1)								1 (< 0.1)
warmouth[2]										1 (< 0.1)			1 (< 0.1)
weatherfish, oriental						1 (0.01)		3 (< 0.01)					4 (< 0.1)
Total number of non-native fish caught	58 (58.6)	17 (0.6)	6 (0.1)	58 (1.4)	743 (4.4)	1,438 (26.4)	7,754 (16.6)	5,893 (12.0)	3,702 (17.2)	52 (2.8)	782 (9.4)	15 (0.3)	23,380 (12.3)
Number of non-native species	4	3	3	6	10	10	15	13	9	9	10	6	
Grand total of native and non-native fish caught	99	2903	4099	4124	16987	5450	46655	49134	21572	1863	8318	55072	189721

*Includes prickly sculpin (*Cottus asper*), mottled sculpin (*Cottus bairdi* complex), riffle sculpin (*Cottus gulosus*), slimy sculpin (*Cottus cognatus*) and other juvenile sculpin that could not be identified to species.
**Includes Columbia River smelt, or eulachon (*Thaleichthys pacificus*), and other larval and juvenile smelt that could not be identified to genus and species.

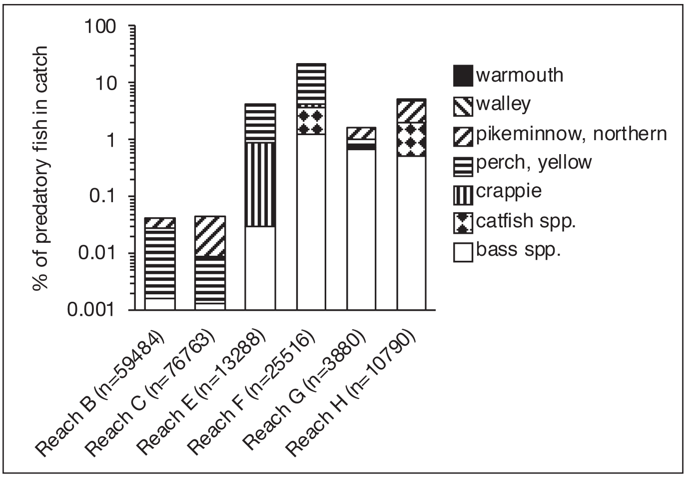

Figure 6. Percentages of potential salmon predators for each hydrogeomorphic reach combined across all sets collected in different years, months, and sites. Warmouth was < 0.001% of the total catch at Reach F, and walleye was 0.05% of total catch at Reach H.

Threespine stickleback numbers have possibly increased in the lower Columbia River in recent years, which could have an impact on juvenile salmon population. The dominance of threespine stickleback we observed is similar to patterns observed in other monitoring studies conducted in the lower Columbia River (Bottom et al. 2008, Roegner et al. 2008, Weitkamp et al. 2012). Weitkamp reported much higher densities of threespine stickleback in 2007 to 2010 compared to 1969 and 1978 to 1980. In the shallow tidal freshwater habitats we sampled, we observed high proportions of threespine stickleback in catches, with overall proportions ranging from 90% or more in Reaches B and C to 35% in Reaches F and H. However, our findings show little relationship between salmonid and threespine stickleback densities, and little to suggest that threespine stickleback, while very abundant and possibly increasing in the estuary, are having a negative influence on salmonid abundance. This is consistent with the findings of Spilseth and Simenstad (2011), who showed Chinook salmon and threespine stickleback exhibit sufficient diel and seasonal differences in diet composition in the Columbia River to suggest that these species do not compete with each other.

We observed a significant negative correlation between juvenile salmonid density and water temperature. The preferred water temperature for juvenile Chinook salmon is between 10 and 16 °C (Marine and Cech 1998, McCullough 1999). In all reaches, the average water temperatures in July, August, and September were above this range, exceeding 25 °C in some cases. These findings are consistent with many reports of water quality impairment due to elevated summer temperatures in the lower Columbia River (e.g., Fresh et al. 2005, EPA 2018). We observed higher salmonid density during mid-spring and early summer months (April through June) (a period of relatively lower water temperatures), and lower salmonid density during mid-summer and early fall months (July through September) (when temperatures were highest). Juvenile salmon were largely absent from our sampling sites when the water temperature was above 20 °C. Moreover, even when only summer months were considered, we observed a negative correlation between salmon density and temperature, suggesting that in periods of especially high summer temperatures, salmon densities tend to be lower.

Migration patterns vary across different species of juvenile salmon, and each species is known to use different parts of the lower river during their migration to the ocean (Groot and Margolis 1991). Roegner and Teel (2014) identified differences in migration for specific genetic stocks of Chinook salmon, but concluded that most large yearlings and many subyearlings migrated in late winter or spring and therefore were never exposed to high temperatures. However, it is also true that salmon life history diversity was much greater early in the twentieth century (Rich 1920, Bottom et al. 2005b) before salmon populations were strongly affected by anthropogenic changes such as estuarine habitat loss and degradation, dams and flow regulation, and hatchery production. It is possible

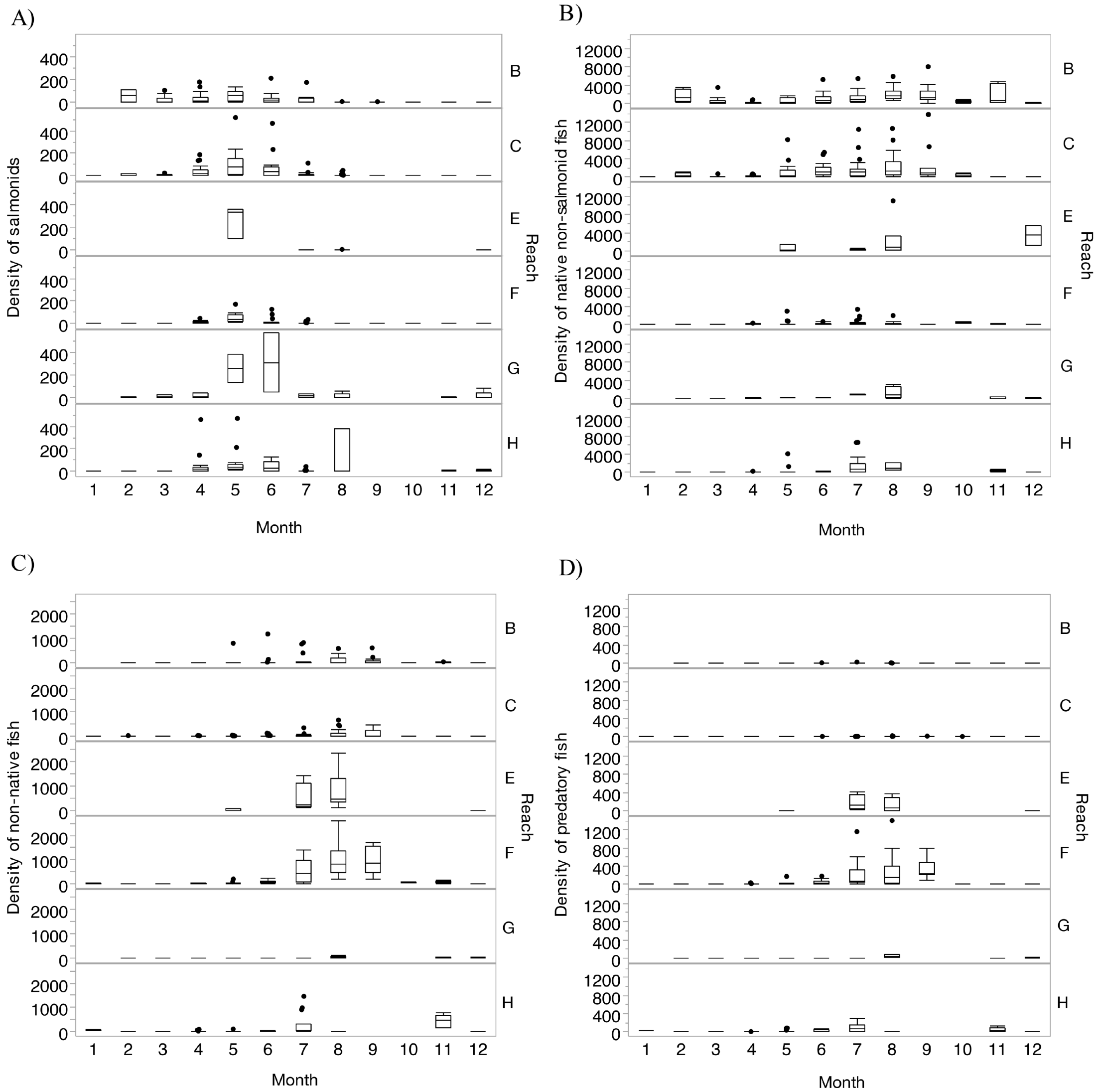

Figure 7. Density (fish per 1,000 m^2) of a) salmonids, b) non-salmonid native fish, c) non-native fish, and d) piscivorous predatory fish by sampling month for each hydrogeomorphic reach. The box represents 1st quartile (Q1) and 3rd quartile (Q3), 25 to 75 percentile range. IQR = Q3 quartile minus Q1. Whiskers are drawn to the furthest point within 1.5 × IQR for the box, and the data falling outside the IQR are plotted as outliers (dots).

that more moderate temperature regimes would encourage recovery of life history diversity in the tidal freshwater region.

As described in the methods, the focus of our fish monitoring program in the lower Columbia River was to characterize the fish communities by hydrogeomorphic reaches (Sagar et al. 2015). The program focused on minimally disturbed, tidally influenced emergent wetland habitats to provide an assessment of baseline conditions that could serve as references for restoration actions, as well as a baseline for future trends assessment (Sagar et al. 2015). Because of these constraints, as well as the need to select sites suitable for fishing, site selection was not fully random. Moreover, due to limited availability of resources, various reaches

TABLE 4. Correlation between density of various fish community parameter and fish groups as well as temperature. Correlation derived from Pearson's correlation test (r). Superscript a denotes significant correlation, $P < 0.05$.

	native fish (non-salmonid)	non-native fish	predatory fish	shad American	stickleback threespine	Water temperature	
						all months	July-September
salmonids	$r = 0.05$ $P = 0.24$	$r = -0.11$ $P < 0.01$[a]	$r = -0.09$ $P = 0.04$[a]	$r = -0.04$ $P = 0.30$	$r = 0.06$ $P = 0.16$	$r = -0.09$ $P = 0.03$[a]	$r = -0.23$ $P < 0.01$[a]
native fish (non-salmonid)		$r = 0.06$ $P = 0.89$	$r = -0.04$ $P = 0.29$	$r = -0.02$ $P = 0.64$	$r = 0.99$ $P < 0.01$[a]	$r = 0.26$ $P < 0.01$[a]	$r = -0.12$ $P = 0.08$
non-native fish			$r = 0.62$ $P < 0.01$[a]	$r = 0.29$ $P < 0.01$[a]	$r = -0.018$ $P = 0.66$	$r = 0.37$ $P < 0.01$[a]	$r = 0.20$ $P < 0.01$[a]
predatory fish				$r = 0.24$ $P < 0.01$[a]	$r = -0.06$ $P = 0.16$	$r = 0.33$ $P < 0.01$[a]	$r = 0.32$ $P = <0.01$[a]
shad, American					$r = -0.03$ $P = 0.56$	$r = 0.18$ $P < 0.01$[a]	$r = 0.16$ $P = 0.02$[a]
stickleback, threespine						$r = 0.24$ $P < 0.01$[a]	$r = -0.15$ $P = 0.04$[a]
species richness						$r = 0.54$ $P < 0.01$[a]	$r = 0.33$ $P < 0.01$[a]
species diversity						$r = 0.21$ $P < 0.01$[a]	$r = 0.32$ $P < 0.01$[a]

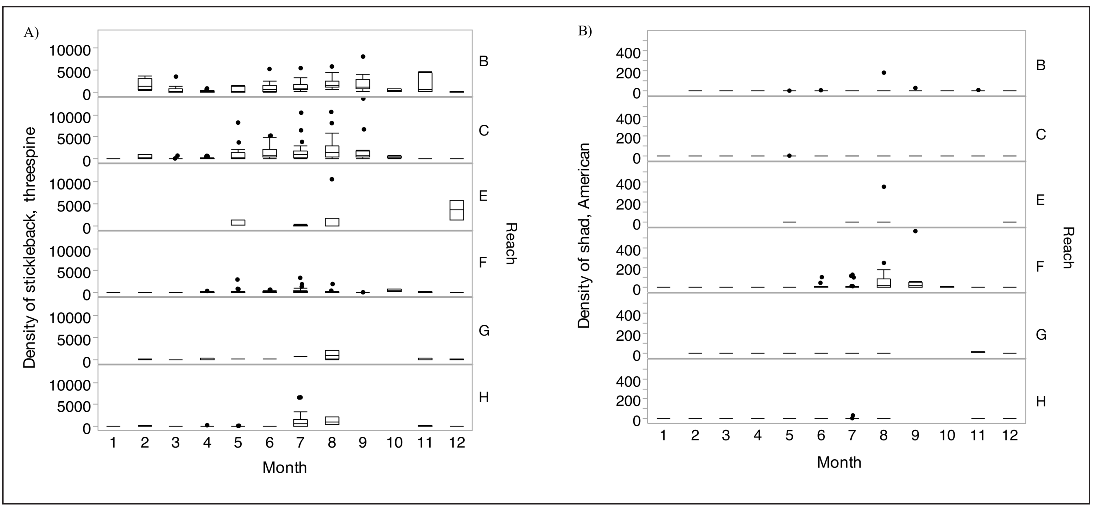

Figure 8. Density (fish per 1,000 m^2) of potential competitors to salmon, a) American shad and b) threespine stickleback by sampling month for each hydrogeomorphic reach. The box represents 1st quartile (Q1) and 3rd quartile (Q3), 25 to 75 percentile range. IQR = Q3 quartile minus Q1. Whiskers are drawn to the furthest point within 1.5 × IQR for the box, and the data falling outside the IQR are plotted as outliers (dots).

were sampled in different years, and only a limited number of sites were sampled for multiple years. Additionally, high and low water levels, influenced by spring runoffs and discharges from Bonneville Dam (USGS 2020), influenced our ability to fish during some months. The resulting unevenness of the study design makes interpretation of the data somewhat difficult, and may introduce biases into our analyses. For example, the sites sampled might not fully capture the characteristics of each reach, and could be biased to reflect the characteristics of the trend site, which was sampled more frequently. This may be true for Reach F, where only one site, Campbell Slough, was sampled.

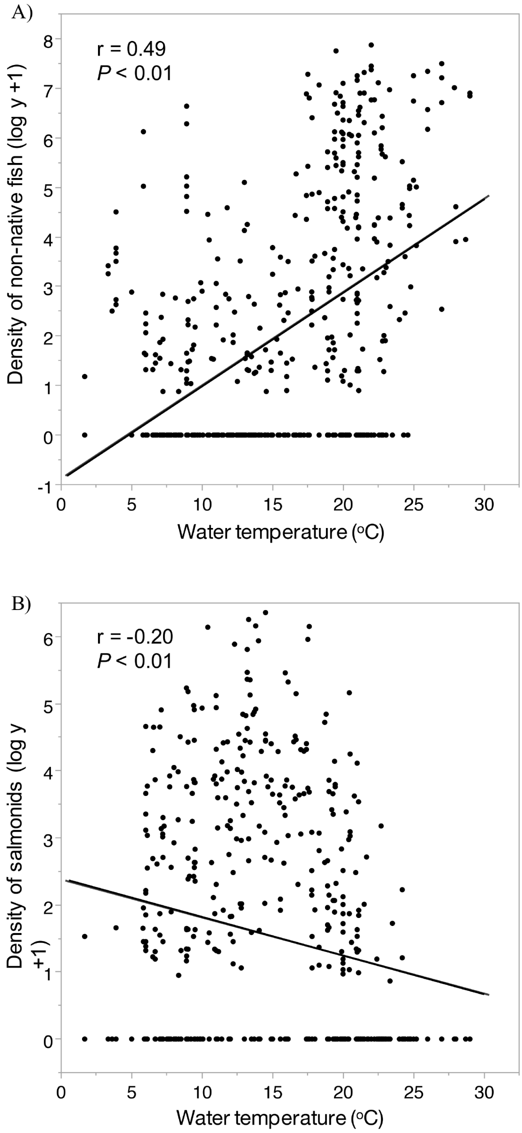

Figure 9. Relationship between water temperature (°C) and density (fish per 1,000 m^2) of a) non-native fish and b) salmonids.

Changes in the sampling design in 2011 to include expanding the sampling season may have caused bias for those reaches that were sampled more intensively before this change was instituted. It is also possible that unusual conditions during the year when one particular reach was sampled may have biased data for that reach. A more consistent sampling design, in which a larger number of sites per reach were sampled over the same time frame, with more equal number of sites per reach, would eliminate the unevenness and make a more robust statistical analysis possible.

However, despite these limitations, our results 1) capture the presence of distinctive fish communities in different reaches of the lower Columbia River, with a fish community of low diversity and dominated by native species in lower reaches with greater tidal influence, and a community with higher diversity and more non-natives in reaches E through H; 2) establish that non-native species are present in tidal freshwater habitats used by juvenile salmon, particularly in Reaches E and F, though the extent to which their presence influence salmon abundance and habitat use patterns is uncertain; 3) highlight potential effects in the integrity of fish assemblages and associated habitats in Reaches E and F; and 4) establish a correlation between water temperature and density of non-natives, suggesting that potential increases in water temperature could contribute to the spread of invasive fish species in the lower Columbia River.

Even with an improved study design, some questions cannot be fully addressed through field surveys and correlative analyses alone, and will require specialized studies. For example, a variety of factors may influence the temporal and geographical distribution and density of non-native fish species, including the seasonal reproductive and life cycles, water temperature, and proximity to areas of disturbance or invasive species introductions. Correlational data from field assessments alone cannot determine which of these factors are most critical. Similarly, while we observed negative correlations between density of salmonids and densities of non-native species and predatory species, it is uncertain whether these relationships are driven by species differences in seasonal reproductive and migratory cycles, or if negative interactions are occurring. Targeted studies to address interactions of non-native species with salmonids, and their effects on the food web are needed to resolve these questions.

It will be important to understand the impacts and interactions of temperature and non-native, predatory and competitive species on juvenile salmon abundance, especially in view of projected temperatures increases associated with climate change. As the temperature continues to rise, snowpack is expected to decline in the mountains, peak spring runoffs are projected to occur earlier, and summer warm periods will lengthen (Stewart et al. 2004, US Global Change Research Program 2009), so the lower Columbia River may be less suitable to support salmonids (Payne et al. 2004). In addition, climate change will favor further expansion of warm-water species, including some non-native species and piscivorous salmon predators (Poe et al. 1991, 1994).

In summary, the findings presented in this paper can be used as an important tool for the effective management of fish communities and for the recovery of endangered Columbia River salmonids by better characterizing the region's fish communities and highlighting areas where additional research may be needed, such as the potential impacts of non-native species and threats associated with increased temperatures and climate change. Additionally, the quality of these tidal freshwater habitats can be maintained and improved by taking steps to reduce the spread of non-native species, and where possible, to moderate summer water temperatures. Many restoration projects have been completed or are ongoing to protect the habitat and native species in the lower Columbia River. Between 2000 and 2019, over 236 projects restoring or protecting 11,488 ha of habitat have been completed (LCEP 2020). Studies indicate that restoration efforts to remove/modify dams, dikes, and culverts, and to improve the connectivity, flow, and temperature of the water, have been beneficial for improving salmonid assemblages in the Pacific Northwest (see review by Roni et al. 2008, 2014; Roni 2019). Continued habitat restoration efforts and monitoring the patterns and changes in juvenile salmon habitat over time will help managers mitigate for anthropogenic impacts on the lower Columbia River and climate change.

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