The abundance, distribution, and diversity of ichthyoplankton in the Puget Sound estuary and San Juan Islands during early spring

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Non-Technical Summary

Most bottom-dwelling marine fishes produce eggs and larvae that disperse into the water column. Larval fish abundance, distribution, and diversity impact the same properties of adult fish populations. Larval fishes are carried through an environment by marine currents, and can be affected by many biological and physical factors. It is therefore important to consider larval fish communities when placing marine protected areas (MPA's).

The objectives of this study are to 1) obtain a greater understanding of the abundance, distribution, and diversity larval fishes in Puget Sound 2) determine if diversity decreases southward within Puget Sound or 3) remains uniform throughout Puget Sound and 4) determine if oceanic species are transported into Puget Sound.

If diversity decreases southward it may indicate that the Pacific Ocean is an important source of larval fishes. A decreasing diversity could indicate poor ecosystem health is affecting larval fishes. A change in species composition may indicate local recruitment, where larvae are kept within close proximity to the adult populations.

This study used a bongo net to collect samples from five stations in Puget Sound and Strait of Juan de Fuca. The results of the study found that diversity decreases slightly through Puget Sound. Pacific hake were the most abundant species caught in the study, entirely in Hood Canal. This may indicate the importance of Hood Canal as a nursery for this species. There were some anomalies to the study, including a higher diversity than expected at the southernmost station. However, data in the study did not provide any explanation for this observation. Future studies would benefit from sampling of more stations.

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Abstract

The abundance, distribution, and diversity of ichthyoplankton were examined from five stations during early spring 2007 in Puget Sound, Hood Canal, and San Juan Islands, collected using a 60 cm bongo net. Twenty-six taxa representing fourteen families were collected. Species diversity was calculated for each station using the Shannon-Wiener Diversity Index (H'). The highest diversity was found near the San Juan Islands (H'=2.36), while the lowest was found in Central Hood Canal (H'=0.42). The most abundant taxa caught was *Merluccius productus*, Pacific hake (n=139). Species diversity correlated negatively with mean photosynthetically active radiation (PAR) ($r^2 = 0.779$), but only slightly with mean oxygen, temperature, chlorophyll *a*, and depth. The diversity of day and night catches significantly differed (p=0.03, t=3.76). The results of this study could have implications for management of marine resources as well as indications of the importance of Puget Sound as a nursery. Specifically, the placement of marine protected areas (MPA's) may depend on the results of this study.

Introduction

Dispersal

Most demersal marine fishes inhabiting shallow waters produce pelagic eggs and larvae, which then recruit to the benthic environment. The advantage of planktonic larvae may be to increase accessibility to food or to reduce predation from demersal predators (Swearer et al. 2002). Marine fish larvae vary in length at each stage of development and duration to develop to juvenile stages (Matarese et al. 1989) and play an important role in understanding the ecology and evolution of fishes and their populations (Moser and Smith 1993). Understanding how larvae are influenced by oceanographic processes and exchanged between populations are fundamental to forecasting population dynamics (Knights et al. 2006).

Transport of ichthyoplankton impacts the distribution and abundance of fishes, as well as the retention or dispersal of larval fishes (Boehlert and Mundy 1994). In estuaries such as Puget Sound, estuarine flow is the controlling factor of water properties in the ecosystem. This flow is characterized by freshwater river runoff on the surface flowing to the Pacific Ocean and saline water entering from the ocean on the bottom layer (Ebbesmeyer and Cannon 2001). Generally, salinity in Puget Sound decreases southward due to the input from rivers.

Both abiotic and biotic factors influence larval fish settlement, distribution, and abundance within an environment (Kingsford et al. 2002). Larval and juvenile fish that live in estuaries must first locate, enter and remain there (for some species) (Boehlert and Mundy 1988), and this is done through a variety of ways. Within estuaries, directional information can be found in chemical stimuli (Mullineaux and France 1995). Visual cues from celestial bodies and sunlight from the surface are also sources of cues (McFarland 1986, Thorson 1964). Audio cues, created by other organisms or physical sources, such as waves, in addition to vibration, may have impacts on the directionality of larval fishes (Rogers and Cox 1988, Janssen et al 1990, Cato 1992). These cues provide information for fishes to find suitable habitat.

Larval fish assemblages are affected by temperature and salinity (Ramos et al. 2006), factors that influence water density. In addition, larval fishes identify unique water masses through varying temperature (Mann and Lazier 1991). In estuaries, plumes are characterized by vertical and/or horizontal gradients in salinity or temperature which may be exploited by some larvae (Forward 1989, 1990).

Some evidence indicates larval fishes do not navigate, but rather orient themselves in the water column to increase their chance of survival through physical transport; especially in partially enclosed areas, such as estuaries (Rothlisberg et al. 1996). However, Klinger and Kido (2003) found little correlation between surface currents and larval dispersal. Although larval fishes have weak sensory and swimming abilities after hatching, they possess olfactory and visual senses. Our limited knowledge of sensory and swimming behavior is due to changes with development and taxon-specific differences (Kingsford et al. 2002).

Estuaries as Nurseries

Estuaries provide food, diverse and productive habitats, and protection from predation for many commercially and recreationally important fishes (Monaco et al. 1992). Many species of fishes spend a portion of their lives within estuaries, frequently as larvae and juveniles (Elliott and Hemingway 2002). A comprehensive study of 28 Pacific west coast estuaries found over 300 species of larval and juvenile fishes (Monaco et al. 1992). In Beaufort Inlet, North Carolina, Warlen and Burke (1990) showed that adult fishes spawned offshore and that the ichthyoplankton immigrated into the estuarine nursery of Newport River. Marine transient fishes have been found to have the largest representation in estuaries (52.3%; Nordlie 2003), implying that estuaries are indeed important rearing grounds for oceanic species. *Leptocottus armatus*, the Pacific staghorn sculpin and *Parophrys vetulus*, English sole have both been shown to utilize estuaries as nurseries, and *P. vetulus* has been found to be estuarine dependent (Bottom et al. 1987, Boehlert and Mundy 1988). Both of these species are found within the waters of Puget Sound.

Fishes found in the coastal Northeast Pacific

Ichthyoplankton studies in Puget Sound region are limited; however, extensive work has been done in the Gulf of Alaska and Bering Sea. The Gulf of Alaska is recognized as an important region for commercially important fishes. In autumn of 2000 and 2001, seventeen taxa were collected, representing nine taxonomic families (Lanksbury et al. 2005). Several of the fishes collected in this study are also found within Puget Sound (i.e. *Parophrys vetulus, Theragra chalcogramma, Lepidopsetta bilineata, Podothecus acipenserinus, Sebastes* spp., and others). In a wide study by Doyle et al. (2002), specimens were collected from the Bering Sea, Gulf of Alaska, and the U.S. West Coast from California to Washington State over a 25 year period, and yielded 59 taxa from twenty taxonomic families.

In Coos Bay, Oregon, the larvae of many demersal spawning fishes were collected. The most common species collected during this study were *Apodicthys flavidus, Engraulis mordax, Ascelichthys rhodorus, Sardinops sagax,* and *Hypomesus pretiosus* (Miller and Shanks 2005). In total, 35 taxa were collected, many of which are found within Puget Sound.

Adult and juvenile fishes of the Skagit River estuary and Hood Canal in Puget Sound have been examined, categorizing fishes from these estuaries to one of six functionally different estuaries (Monaco et al. 1992). Both locations were grouped into the Fjord Group. This group included several Scorpaeniform, Pleuronectid, and other groups of fishes.

Dabob Bay, Hood Canal was studied between 1985-1987, and 49 taxa were identified (Bollens, et al. 1992). Peak species richness and larval abundance was found in March and April at one station located in central Dabob Bay. Nearly 20 species were collected during this peak, which coincided with peak chlorophyll *a* measurements. Ichthyoplankton were also sampled in the Strait of Juan de Fuca from early March to mid-May 1978 (Daggett 1982). A total of 33 taxa were identified, representing thirteen taxonomic families of fishes. The samples were dominated by nineteen taxa, including *Clupea pallasi, Ammodytes hexapterus,* Liparidae spp., Pholidae spp., Stichaeidae spp., and Cottidae spp. A decadal dip-net study in Clam Bay, Puget Sound examined seasonal assemblages of ichthyoplankton (Busby et al. 2000). A total of 65 taxa were collected. In late winter and early spring, *Ammodytes hexapterus, Liparis* spp, *Apodichthys flavidus, Hexagrammos stelleri,* and *H. decagrammus* were common.

Diveristy distribution

Decreasing diversity, or a change in species composition, southward may indicate that some oceanic species rely on Puget Sound as a nursery, and that the Pacific Ocean is a source of ichthyoplankton. These results may have important ramifications for the management of marine habitat in the area. This may be especially true if commercially important species are found in high abundance. Adults may spawn, releasing their eggs into the estuary to develop. This would require certain considerations for designing and placing Marine Protected Areas (MPA's; Lubchenco et al. 2003).

In contrast, low diversity may signify that Puget Sound is not an important nursery. A homogenous or low diversity may also be an indicator of poor health. Anthropogenic effects on the region have biologically degraded the quality of Puget Sound. It has been shown that pollutants from sewage plumes have adverse health effects on larval fishes (Kingsford et al.

1996). Alternatively, much of the recruitment in Puget Sound may be local, and not dependent on the Pacific Ocean as a source. Indeed, Levin (2006) suggests that retention of larvae in the natal area is more common than estimated, and that populations may be more closed off from other areas.

The objectives of this study are to 1) obtain a greater understanding of the abundance, distribution, and diversity of ichthyoplankton in Puget Sound 2) determine if diversity decreases southward or remains uniform within Puget Sound or 3) determine if oceanic species are transported into Puget Sound.

Methods

Ichthyoplankton was collected from five different locations within Puget Sound using a 60 cm bongo net with 505 µm mesh towed obliquely. The bongo nets were fitted with flowmeters, the readings from which were used to calculate the volume of water passing through the net. The Seabird CTD was used to measure water properties (temperature, salinity, photosynthetically active radiation [PAR], oxygen, pressure, fluorescence). Five stations were sampled in Puget Sound; including San Juan Island, Discovery Bay in the Strait of Juan de Fuca, Dabob Bay, Central Hood Canal, and the Great Bend in Hood Canal (Table 1, Fig. 1). All samples were collected aboard the R/V *Thomas G. Thompson* between 19-23 March 2007.

Data and Specimen Collection

The echosounder aboard the ship was used to record the depth of each station in meters. The CTD was then lowered and retrieved at a rate of 50 meters min^{-1} to obtain salinity, temperature, PAR, fluorescence, pressure and oxygen data.

The 60 cm bongo net was lowered into the water at a 45° angle with the winch down to a depth 10 meters above the bottom. Wire angle was measured with the use of a handheld inclinometer and an angle between 38-52º was maintained for all stations. The net was deployed at a rate of 40 meters $\text{min}^{-1}$and recovered at a speed of 20 meters min^{-1}. The ship speed during the tow was 0.75 to 1.2 m sec^{-1}. Depth of the tow was determined by the following equation:

1. Depth -10 m= (Meters of wire out)(cosine wire angle).

Once brought aboard, the nets were gently washed with a hose so that the specimens in the net could be collected in the codend. Ichthyoplankton collection procedures followed Brown et al. (1999).

Preservation

Samples were washed through a 500 µm sieve and transferred into 32 oz. glass jars with 5% formaldehyde with sodium borate buffer, and seawater. All specimens are stored at the Alaska Fisheries Science Center (AFSC)[1].

Identification of Specimens

Samples were transferred into distilled water, where ichthyoplankton and zooplankton were separated. The ichthyoplankton were then enumerated and identified to the lowest possible taxa using a dissecting stereomicroscope following the lab guide by Matarese et al. (1989).

Analytical Methods

The density of the sample was calculated from the flowmeter, which recorded the number of rotations. The calibration factor (Y) for each flowmeter was calculated with the following formula for a line;

2. $Y= a + b(X)$

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where Y is meters revolution^{-1}, X is revolutions s^{-1}, a is intercept, and b is the slope. The standard haul factor was then calculated using:

3. SHF= (10 * depth fished)/ (#revolutions * mouth area * Y)

The SHF value allowed the catch per 10 m^{2} to be estimated using the equation:

4. Catch 10 m^{-2} = SHF * # fish caught

The catch was compared between each station.

Species richness, a count taxa that are collected at each site, provided a rough estimate of diversity. A more accurate estimate of diversity was achieved with the use of the Shannon-Wiener Diversity Index. The Shannon-Wiener Diversity Index accounts for dominant taxa. A site with many of one species was not as diverse as a site with many species distributed evenly. Both of these calculations were compared for each site. The Shannon-Wiener Diversity Index was calculated using the equation:

5.
$$\left(H' = -\sum_{i}^{S} p_i \ln p_i \right)$$

where *S* is species richness, *pi* is the proportion of the total number of taxa made up of the *i*th species (Shannon 1948). The Shannon-Wiener Diversity Index was compared with abundance, species richness, and several physical factors using least squares linear regression. In addition a t-test was done to compare diversity of day and night catches.

Results

Ichthyoplankton diversity

A total of twenty-six taxa representing fourteen families was collected from five stations within Puget Sound (Table 2). For all diversity analyses, only ichthyoplankton from net 1 was utilized due to a codend failure of net 2 at the San Juan Island station (AF1). This was done so that the diversity index and richness would not be skewed in favor of stations with a higher catch. The most common species collected throughout the survey was Pacific hake, *Merluccius productus*, collected only in Hood Canal in high abundance. Overall abundance increased southward, with the highest abundance (n=106) in Central Hood Canal (AF4; Fig. 2).

Analysis of habitat use by adults of species caught showed that *M. productus* was the only pelagic species and was only found in Hood Canal. Both demersal and benthic species were caught at all stations. For this study, demersal was classified as species that are associated with the seafloor, but extend their range into the water column. Benthic was defined as species that remain on the seafloor for most of their adult life and rarely enter the water column. *Sebastes* sp. and *Parophrys vetulus* were ubiquitous in the study area (Fig. 3).

Calculations of Shannon-Wiener Diversity Index and species richness showed an overall southward decreasing trend. The highest species diversity and species richness (H’= 2.4, S=12) was found at San Juan Island. The lowest species diversity (H’= 0.42) was found at Central Hood Canal, and the lowest species richness (3) was found at the Central Hood Canal and Dabob Bay (AF5) stations. In contrast, catch, a measure of abundance, shows an increasing trend (Fig. 4).

Species diversity varied significantly between light and dark tows (p=0.03, t=3.76). Mean diversity during tows during light hours was 0.58 while diversity during dark hours was 1.87. The station with the highest diversity was sampled during nighttime, while the station with the lowest diversity was sampled during daylight (Fig. 5). However, abundance did not significantly differ (p=0.59, t=0.59) between day and night tows.

Species diversity increased linearly with species richness (r^2=0.88; Fig. 6). The Shannon-Wiener diversity was also compared with catch (fish 10m^{-2}), and was found to negatively correlate (r^2=0.43).

Physical conditions

The physical conditions of the water column had little variability between sites (Fig. 8a-f). Mean temperature of the water column slightly increased southward (7.89-9.90 ºC). Salinity and density showed only slight difference between stations (29.5-30.7 psu, 22.8-23.9 kg m^{-3}). Mean oxygen concentration decreased southward with a wide range (237.2-338.1 µmol kg^{-1}).

When the Shannon-Wiener Index was compared with physical parameters of the water column at each station, very little correlation was found in nearly all factors. A comparison with depth of the tow showed no significant correlation (r^2<0.001; Fig. 9a). When diversity was compared with dissolved oxygen concentration, a slight positive correlation (r^2=0.233) was observed (Fig. 9b). A slight negative correlation (r^2=0.365) was found between mean diversity and temperature (Fig. 9c). Integrated chlorophyll *a* was also slightly negatively (r^2=0.259) correlated with diversity (Fig. 9d).

Discussion

Caveats

While this study yielded several interesting results, there are a few caveats that must be considered. First, the lack of data from net 2 at the San Juan Island station did not allow for full analysis of diversity in the study area. Ideally both net samples would have been analyzed, however to allow consistency, all data from net 2 was omitted with the exception of Table 2.

In addition, many more stations and samples would need to be taken for any conclusions to be made with any degree of certainty. Because no samples were taken in the main basin of

Puget Sound, it is unknown what effects this would have on the latitudinal trend in diversity in Puget Sound. Due to time limitations, only one replicate was taken at each station, which was disadvantageous to the completeness of the study. Timing of the study may not have been optimal for larval fishes. Many species spawn in late spring (April-May) and may not have been present in this study (Matarese 1989); however, the results of the study are still pertinent .

Fish eggs, which are also included in ichthyoplankton, were also not considered. These data were not crucial to the study, however they would have shown another interesting facet of the ichthyoplankton of Puget Sound. In addition, length measurements and developmental stage examination of specimens were not made. This did not permit classification of fishes into flexion stages.

Collection and identification of phyto- and zooplankton was also not completed. A complete idea of the structuring of the plankton populations would have been advantageous to see biotic trends. For this reason, it is difficult to extrapolate whether there was a spring bloom at the time of the study. In addition, it is unknown whether prey of larval fishes were abundant.

Multivariable analyses may yield additional data that benefit the results of the study. Programs such as BIOENV, which analyses larval fish assemblages and measured oceanographic features, and ANOSIM, which analyzes the similarity of species composition between stations, may have shown different trends or influences on diversity. However, time constraints did not allow for these analyses to be conducted.

Finally, specimen collection may have been erroneous due to inexperience with the bongo nets. There was a reported incidence of collision with the seafloor, however no evidence of damage to the net or specimens was observed. The depth of the tow in relation to the seafloor may have varied as well. Although the net was intended to be lowered to a depth 10 m above the bottom, this likely varied. It is unknown what the effects of this variability were.

Ichthyoplankton diversity

Diversity and richness in Puget Sound show a decreasing trend with latitude (Fig. 4). Comparison with species collected on the U.S. West Coast shows that many species were also found in Puget Sound (Doyle et al. 2002). Many flatfishes, including *P. vetulus, G. zachirus,* and *P. stellatus*, were found both in the Pacific Ocean and as far south in the Puget Sound as the Great Bend, Hood Canal. It is therefore possible that the Pacific Ocean is a contributor to diversity in Puget Sound. In addition, although the study site was in the main basin of Puget Sound, Busby et al. (2000) found a much higher species richness. This is probably an artifact of a longer study period, and sampling during both day and night.

There is, however, a marked increase in both diversity and richness in the Great Bend, Hood Canal (H'=1.52, S=7). Explanation of this phenomenon from physical conditions data is unlikely. There is no major difference in any of the measured conditions that may explain this. The expected current and mixing differences near the river may have had an impact on fishes, however these properties were not measured. With available data, the proximity of the Skokomish River does not appear to have any substantial influence, as the salinity of the top layer is not the lowest at this station (28.6 psu). However, the presence of *Cottus asper*, an estuarine species (Hart 1973), indicates that the river may have some local influence from the river.

The likeliest explanation is self-recruitment, which occurs in many fauna and environments (Swearer et al. 2002). This retention of larvae allows species to remain present in their environment, ensuring the success of their species. In Hood Canal, there were several species that were found only there (i.e. *Platichthys stellatus, Lyopsetta exilis, Theragra chalcogramma,* and *Cottus asper*). This is indicative of self-recruitment, however, it is also possible that the Hood Canal subpopulation of these species spawns at a slightly different time than the northern populations due to more favorable conditions.

Of particular interest is Pacific hake, *Merluccius productus*. This species was caught throughout Hood Canal in high numbers, 93 in central Hood Canal. One explanation for the large catch is that this species spawns in aggregations or that the larvae shoal. Isolation of *M. productus* is also indicative of local recruitment. This is further evidenced by the lack of specimens collected on the U.S. West Coast (Doyle et al. 2002).

Interestingly, there is a decrease of oxygen concentration with latitude (Fig. 8f). This shows low oxygen in Hood Canal. The cause of this low oxygen is unknown, however a decreased oxygen concentration would likely yield a lower abundance and diversity of fishes. It has been shown that oxygen concentration can have adverse effects on metabolism of developing fishes. Hypoxia has a number of effects on developing fishes, and the extent of the effect depends on species, developmental stage, and level and duration of hypoxia. Sublethal responses to hypoxic conditions include decreased growth rate, changes in morphology and behavior, and metabolic adjustments (Rombaugh 1988). This would expectedly cause a reduced survivorship, allowing only the most resilient species to survive.

Contradictory to expectations, the mean oxygen concentration of Great Bend (237.2 ± 3.7 μmol kg^{-1}) coincided with a relatively high diversity (H'=1.52). Data from this study yielded no explanation for this occurrence. Many of the species found at this station are benthic or demersal, inferring that they are adapted to environments of low oxygen. These species may be highly resilient, thus allowing survival. The abundance of benthic species (Table 2) supports this claim.

Demersal species prevailed throughout most of the study area, however in Great Bend, Hood Canal, many of the taxa are benthic.

Comparison with previous work in Hood Canal shows that there are no taxa collected that match previous studies; however, the study by Monaco et al. (1992) examined adult and juvenile fishes. The previous study also did not collect specimens, but utilized previous data. Therefore, a direct comparison can't be made.

It was also somewhat unexpected that there was no trend seen between diversity and depth (Fig. 9a). At greater depths, there are likely more adult demersal fishes, which would possibly account for a higher diversity of larvae, and certainly a greater abundance. This would, however, be dependent on the diversity of adults, and the currents in the local area.

The trend of abundance is also somewhat unexplained (Fig. 2). The large abundance of *M. productus* is the most likely cause of this trend. The data was skewed upwards due to the tremendous catch in central Hood Canal (n=93). However, there were also high catches of *P. vetulus* possibly attributed to the adaptations to a low oxygen environment, or local recruitment.

The low catch in Discovery Bay is somewhat contrary to expectations. It was expected that the northern stations would have a high diversity and abundance. This station did have a fairly high diversity (H'= 1.75), but it had a very low catch (n=7). While the physical conditions of the station do not explain this low abundance, observations of the station may. Phytoplankton and zooplankton concentrations collected at the station were very sparse. The decreased prey population may account for the decreased abundance of fishes.

Contrastingly, Dabob Bay had a very high concentration of phytoplankton and a healthy concentration of zooplankton, but had a low diversity and abundance (H'=0.73, n=8). Again, physical conditions of the water column do not provide explanations for this. The low diversity may be an artifact of daylight conditions (Fig. 5).

The significant difference between day and night catches (p=0.03, t=3.76) indicates diel vertical migration of at least some taxa. During day tows, only three species were caught; *Sebastes* sp., *M. productus,* and *P. vetulus.* However, these species were caught during both day and night tows, indicating that other species may migrate downwards during the day to avoid predation. The net tows went to 10 m above the seafloor, hence there is substantial depth for larval fishes to retreat to. This is consistent with Busby et al. (2000) who collected more taxa during day tows. Abundance, on the other hand, did not significantly differ (p=0.59, t=0.59). This is likely due to the ubiquitous presence of *M. productus*, found in high numbers during both day and night tows. This is contrary to what was expected, that there would be a higher diversity during day tows (Busby et al. 2000).

There were two taxa found throughout the study area; *Sebastes* sp. and *P. vetulus*. *Sebastes* sp, rockfish, are found throughout Puget Sound as adults (DeLacy et al. 1972). Due to the omnipresence of adults and the inability to discern different species of the genus, it is a cosmopolitan taxa. The English sole, *P. vetulus* is also a common species throughout Puget Sound (DeLacy et al. 1972) and has also been shown to be estuary dependent (Bottom et al. 1987, Boehlert and Mundy 1988). It is no surprise that the larvae of this species were found throughout Puget Sound.

As expected, species diversity strongly correlates with species richness (Fig. 6), because the calculation of species diversity, species richness is one of the factors. Relating to this, a high abundance loosely correlated to a decreased diversity (Fig. 7). This is somewhat expected, because a station with a high abundance, will not necessarily have a high species richness, thus have a decreased Shannon-Wiener diversity.

Because no physical factors of the water column were significantly correlated with species diversity, it is unlikely that any of these are strongly impacting diversity in the study area.

Implications

The presence of MPA's in the San Juan Islands (Murray 1998) may have contributed to the high diversity of ichthyoplankton at that site. This could indicate that MPA's are advantageous to larval fish abundances. Economically important species may benefit from the creation of MPA's designed for larval fish communities as well. Pacific hake, *M. productus* clearly have areas of high larval abundance in Hood Canal. If other recreationally or commercially important fishes demonstrate a similar pattern, then these areas may be important nurseries.

Conclusions

The results of the study demonstrate a decreased southward diversity. Although this trend is not steep, it does show that diversity is highest in northern Puget Sound and the Strait of Juan de Fuca and decreases through Hood Canal. It is difficult to analyze anthropogenic effects as no nutrient analyses were done. Oxygen concentration data show no negative effects on diversity; however, further analyses would need to be completed for more conclusive results. Because of inadequate data, it remains unknown whether there are any anthropogenic effects on the diversity of fishes.

It appears that the Pacific Ocean may be supplying taxa found within Puget Sound. All taxa collected were ubiquitous as adults in Puget Sound (DeLacy 1972), but were also collected on the U.S. West Coast (Doyle et al. 2002). While it cannot be concluded that the Pacific Ocean is a source of unique ichthyoplankton for Puget Sound, it may be supplying larvae, supplemental to local recruitment.

The Great Bend ichthyoplankton assemblage is a curiosity as it has yet to be explained from available data or literature. Though it was the closest station to a river, there was little evidence of impacts from the river. Future research on this may want to analyze substrate, prey populations, adult populations, or sample more stations in the area.

Generalizations should be made with caution when grouping species to a higher order of grouping (i.e. family, genus). It becomes apparent that the life histories of the adult fishes must be considered for each taxon. The differences in egg size, fecundity, size of larvae at hatching, yolk size, etc. can have adverse effects on the survival, growth, and distribution of larval fishes (Rochet 2000). While this analysis is outside the scope of this study, the results would allow some insight into the differences between taxa.

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Table 1. Station locations and depths for ichthyoplankton collection in Puget Sound and Strait of Juan de Fuca.

Station	**Latitude**	**Longitude**	**Depth (meters)**
San Juan Island, AF1	48° 27.3' N	123° 3.3' W	140.4
Discovery Bay, AF2	48° 2.0' N	122° 50.9' W	35.9
Dabob Bay, AF3	47° 43.7' N	122° 52' W	73.1
Central Hood Canal, AF4	47° 35' N	122° 59' W	134.0
Great Bend, Hood Canal, AF5	47° 22.3' N	123° 08' W	80.0

Table 2. List of ichthyoplankton taxa collected in Puget Sound and Strait of Juan de Fuca.

Family	**Taxa**		**Common Name**
Merluccidae	*Merluccius*	*Productus*	Pacific hake
Gadidae	*Theragra*	*Chalcogramma*	walleye pollock
Scorpaenidae	*Sebastes*	sp.	rockfish
Hexagrammidae	*Hexagrammos*	*Decagrammus*	kelp greenling
Cottidae	*Artedius*	sp.	sculpin
----	*Artedius*	*Harringtoni*	scalyhead sculpin
----	*Chitonotus*	*Pugetensis*	roughback sculpin
----	*Cottus*	*Asper*	prickly sculpin
----	*Radulinus*	*Asprellus*	slim sculpin
Rhamphocottidae	*Rhamphocottus*	*Richardsoni*	grunt sculpin
Psychrolutidae	Psychrolutidae	sp.	sculpin
Agonidae	*Bathyagonus*	*Infraspinatus*	spinycheek starsnout
Liparidae	*Liparis*	*Pulchellus*	showy snailfish
----	*Liparis*	*Fucensis*	slipskin snailfish
Cryptacanthodidae	*Cryptacanthodes*	*Aleutensis*	dwarf wrymouth
Stichaeidae	*Anoplarchus*	*Insignis*	slender cockscomb
----	*Anoplarchus*	*Purpurescens*	high cockscomb
----	*Lumpenus*	*Sagitta*	snake prickleback
Pholididae	*Pholis*	sp.	gunnel
Ammodytidae	*Ammodytes*	*Hexapterus*	Pacific sand lance
Pleuronectidae	*Lyopsetta*	Exilis	slender sole
----	*Glyptocephalus*	*Zachirus*	rex sole
----	*Psettichthys*	*Melanostictus*	sand sole
----	*Platichthys*	Stellatus	starry flounder
----	*Isopsetta*	*Isolepis*	butter sole
----	*Parophrys*	*Vetulus*	English sole

Figure 1. Study site locations within Puget Sound and the Strait of Juan de Fuca.

Figure 2. Catch (# fish $10m^{-2}$) data for stations in study area.

Figure 3. Analysis of habitat types of adults for species caught as larvae. Pelagic species represented by light gray boxes. Demersal species represented by dashed boxes. Benthic species represented by dark gray boxes.

Figure 4. Species richness (S) and Shannon-Wiener diversity (H') on first y-axis, catch (fish $10m^{-2}$) on second y-axis.

Figure 5. Comparison of day and night diversity (H').

Figure 6. Species diversity (H') shows a high correlation (r^2=0.88) with species richness (S).

Figure 7. Species diversity (H') shows a loose negative correlation (r^2= 0.42) with abundance.

Figure 8a. Depth of tow (m) at each station of study area.

Figure 8b. Mean temperature (°C) of water column at each station of study area. Standard deviation shown in bars.

Figure 8c. Mean salinity (psu) of water column at each station of study area. Standard deviation shown in bars.

Figure 8d. Mean density (kg m^{-3}) of water column at each station of study area. Standard deviation shown in bars.

Figure 8e. Mean PAR of water column at each station of study area. Standard deviation shown in bars.

Figure 8f. Mean oxygen (μmol kg^{-1}) of water column at each station of study area. Standard deviation shown in bars.

Figure 9a. Species diversity (H') shows no correlation with depth (m) of the station (r^2<0.001).

Figure 9b. Species diversity (H') shows a slight positive correlation with mean oxygen (μmol kg^{-1}) at each station (r^2=0.233). Error bars present.

Figure 9c. Species diversity (H') shows a slight negative correlation with mean temperature (ºC) at each station (r^2=0.365). Error bars present.

Figure 9d. Species diversity (H') shows a slight negative correlation with integrated chlorophyll *a* (mg m^{-3}) at each station (r^2=0.260).

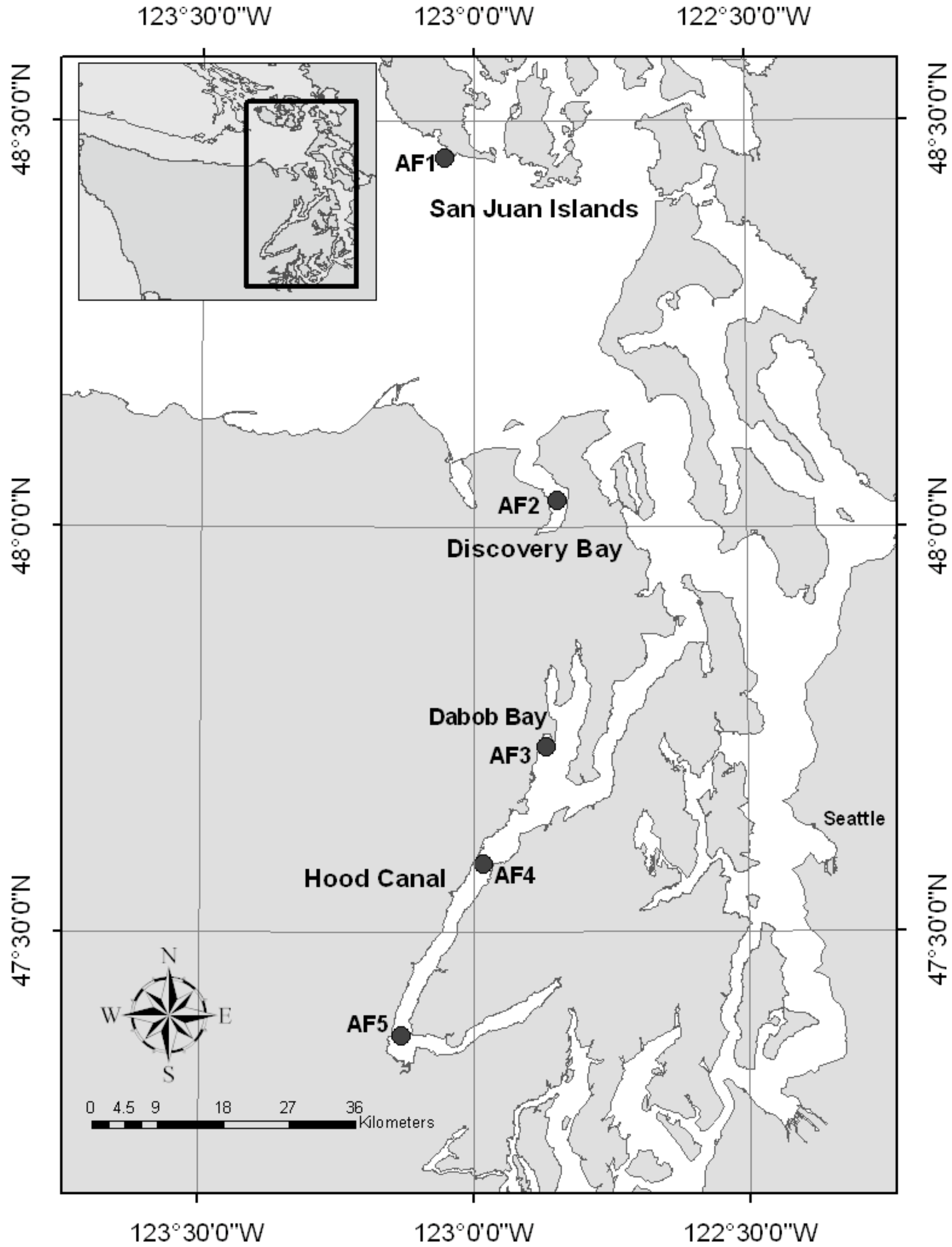

123°30'0"W
123°0'0"W
122°30'0"W
48°30'0"N
48°0'0"N
47°30'0"N
AF1
San Juan Islands
AF2
Discovery Bay
Dabob Bay
AF3
Seattle
Hood Canal
AF4
AF5
N
W
E
S
0 4.5 9 18 27 36
Kilometers

Figure 1.

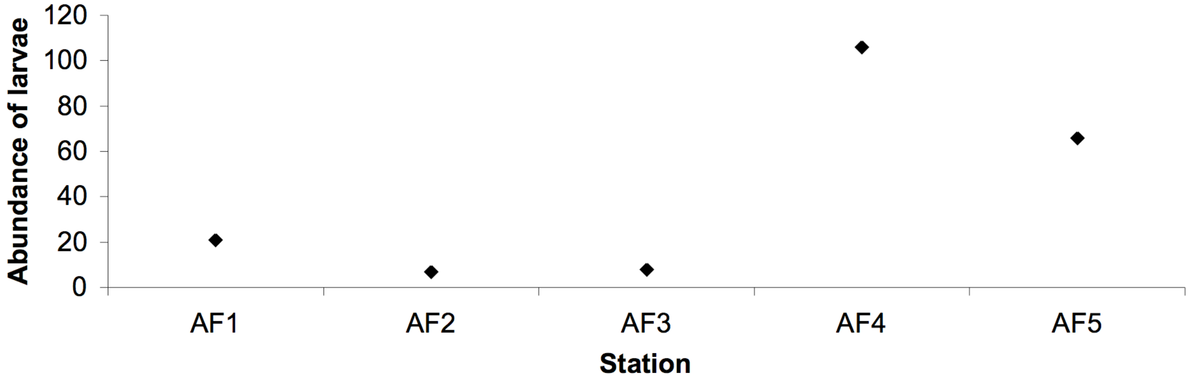
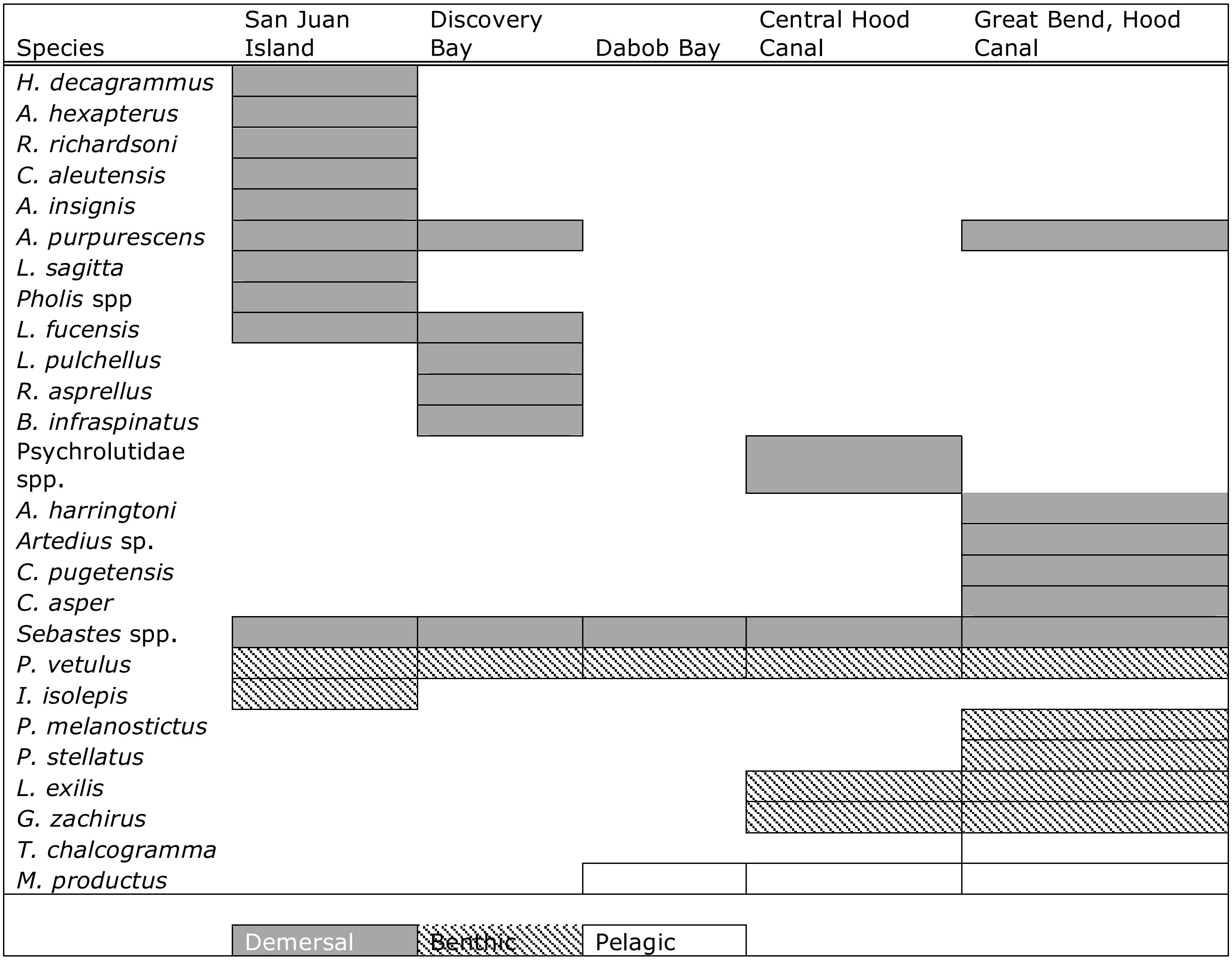

Abundance of larvae
120
100
80
60
40
20
0
AF1
AF2
AF3
AF4
AF5
Station

Figure 2.



Species	San Juan Island	Discovery Bay	Dabob Bay	Central Hood Canal	Great Bend, Hood Canal
H. decagrammus	■				
A. hexapterus	■				
R. richardsoni	■				
C. aleutensis	■				
A. insignis	■				
A. purpurescens	■	■			■
L. sagitta	■				
Pholis spp	■				
L. fucensis	■	■			
L. pulchellus		■			
R. asprellus		■			
B. infraspinatus		■			
Psychrolutidae spp.				■	
A. harringtoni					■
Artedius sp.					■
C. pugetensis					■
C. asper					■
Sebastes spp.	■	■	■	■	■
P. vetulus	▨	▨	▨	▨	▨
I. isolepis	▨				
P. melanostictus					▨
P. stellatus					▨
L. exilis				▨	▨
G. zachirus				▨	▨
T. chalcogramma					□
M. productus			□	□	□

■ Demersal ▨ Benthic □ Pelagic

Figure 3.

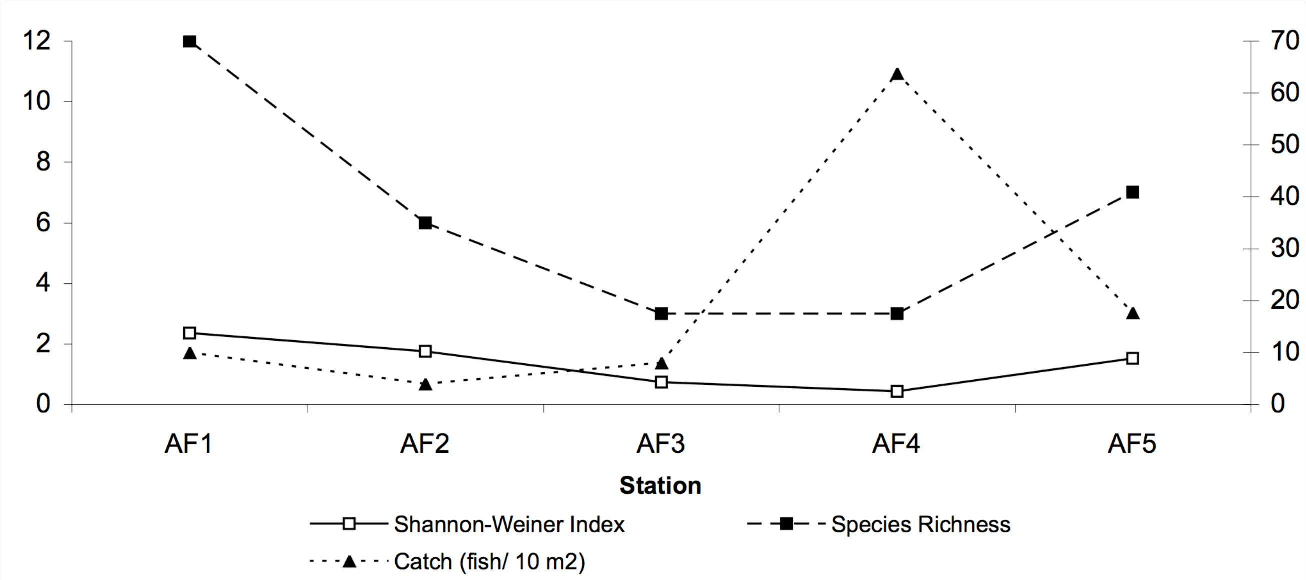

12
10
8
6
4
2
0
70
60
50
40
30
20
10
0
AF1
AF2
AF3
AF4
AF5
Station
Shannon-Weiner Index
Species Richness
Catch (fish/ 10 m2)

Figure 4.

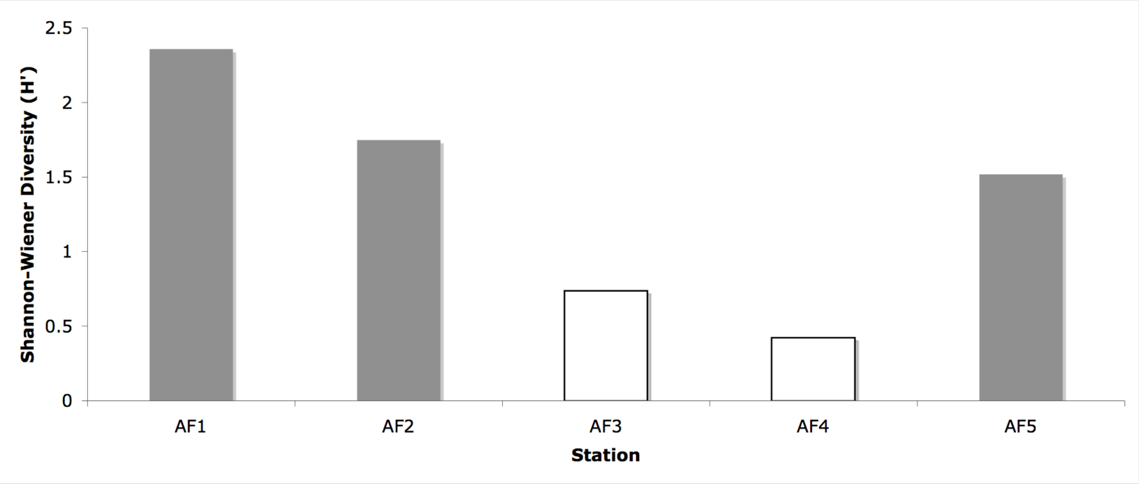

2.5
2
1.5
1
0.5
0
Shannon-Wiener Diversity (H')
AF1
AF2
AF3
AF4
AF5
Station

Figure 5.

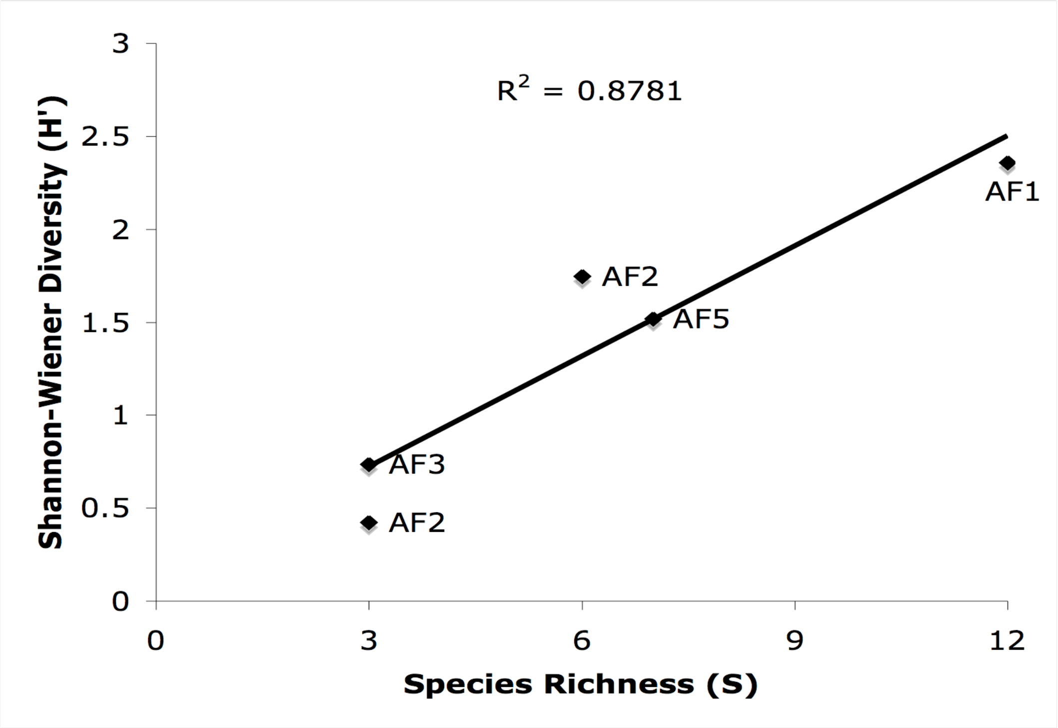

$R^2 = 0.8781$
AF1
AF2
AF5
AF3
AF2
Shannon-Wiener Diversity (H')
Species Richness (S)
0
0.5
1
1.5
2
2.5
3
0
3
6
9
12

Figure 6.

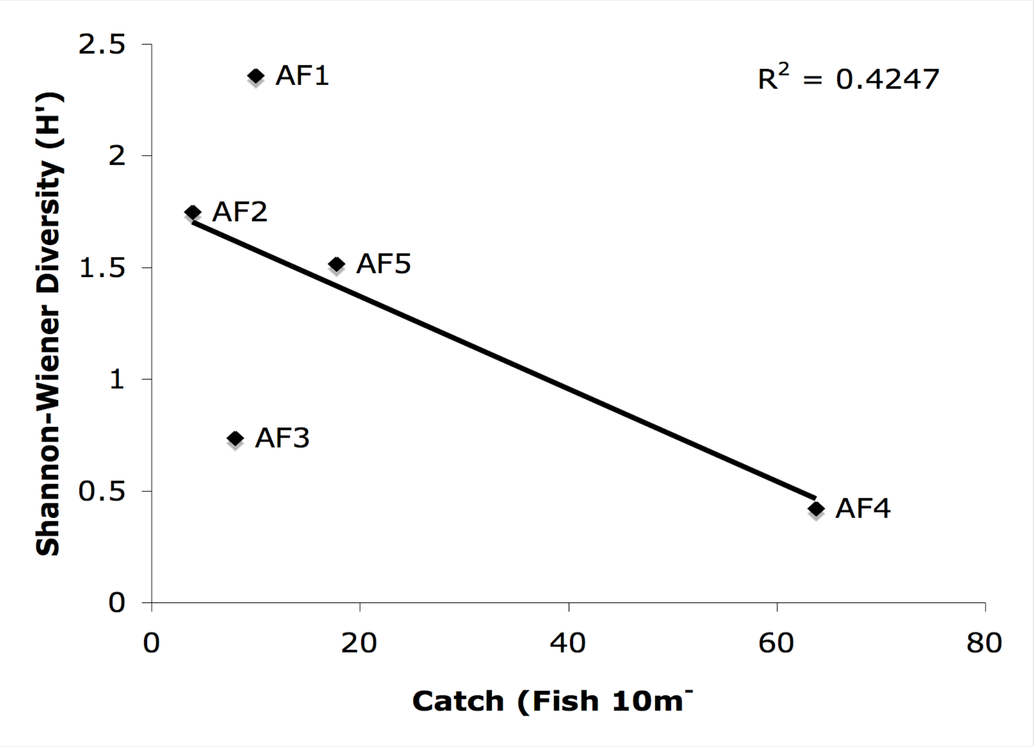

2.5
2
1.5
1
0.5
0
Shannon-Wiener Diversity (H')
AF1
AF2
AF5
AF3
AF4
$R^2 = 0.4247$
0
20
40
60
80
Catch (Fish 10m⁻

Figure 7.

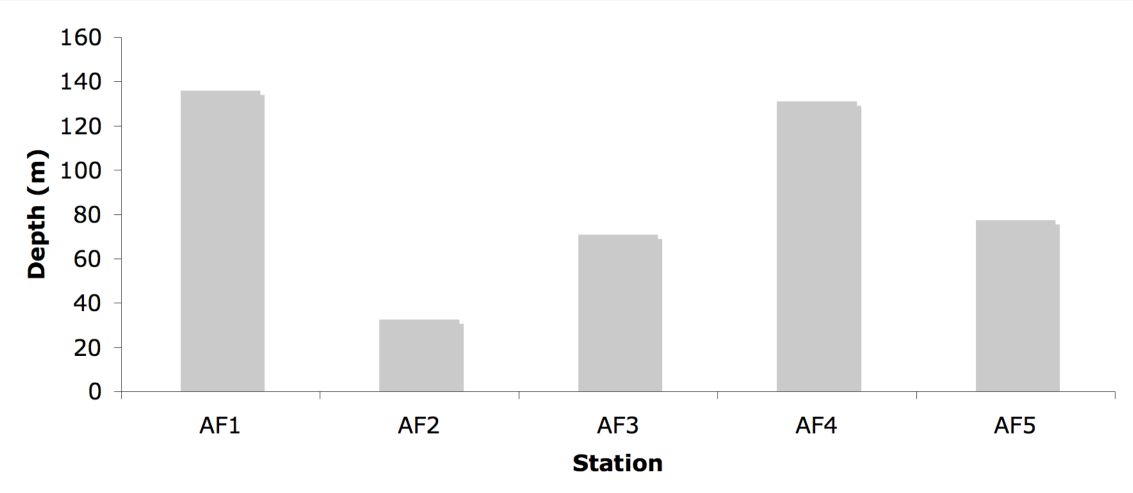


Figure 8a.

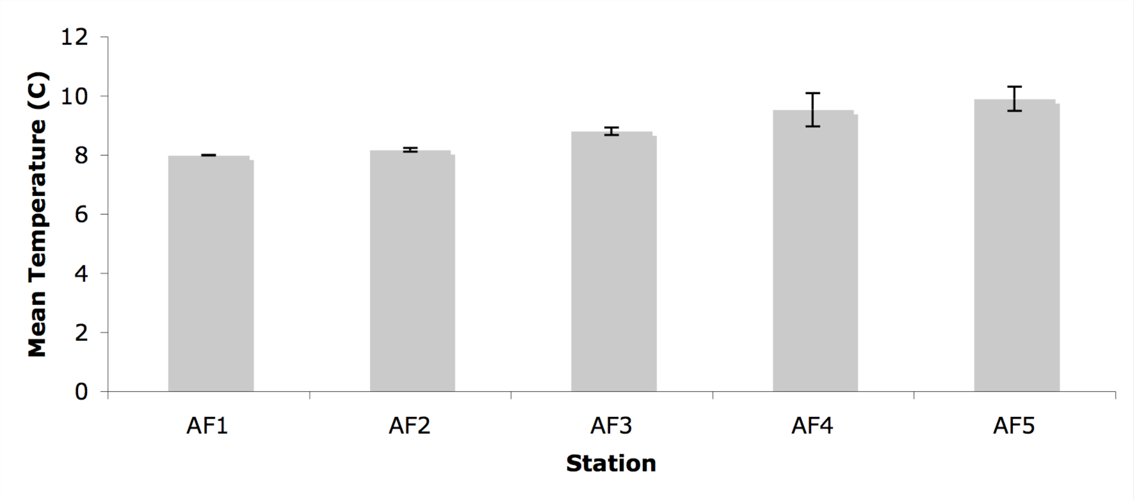


Figure 8b.

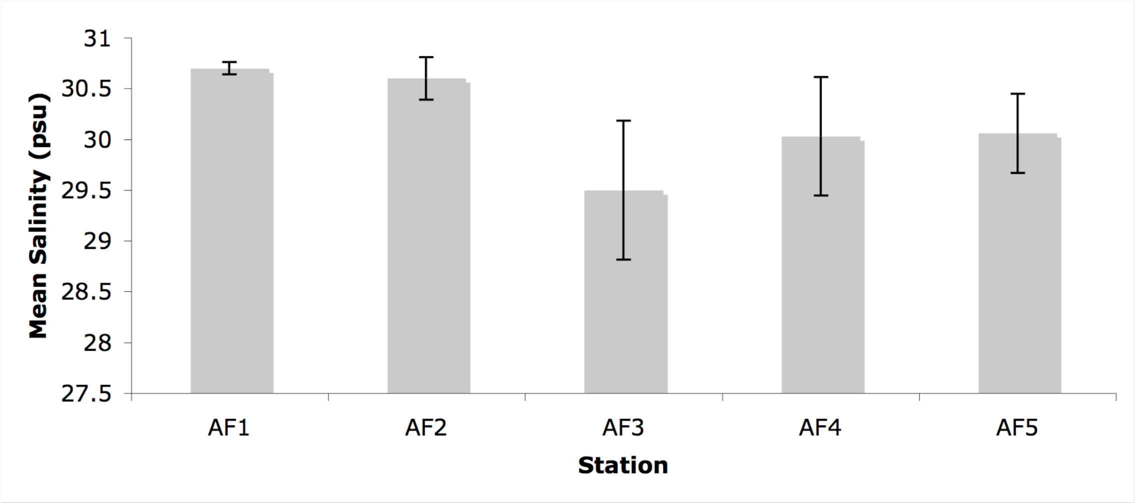


Figure 8c.

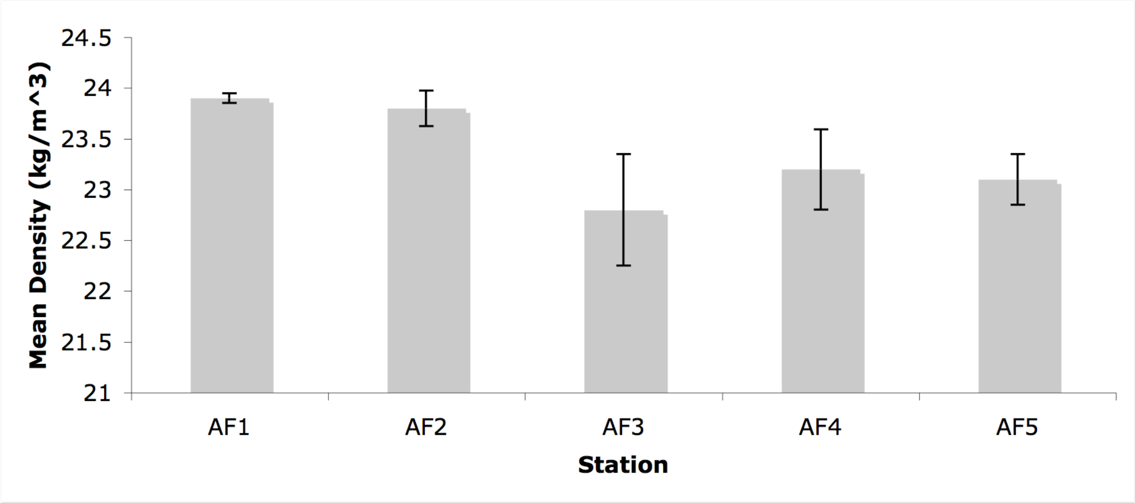


Figure 8d.

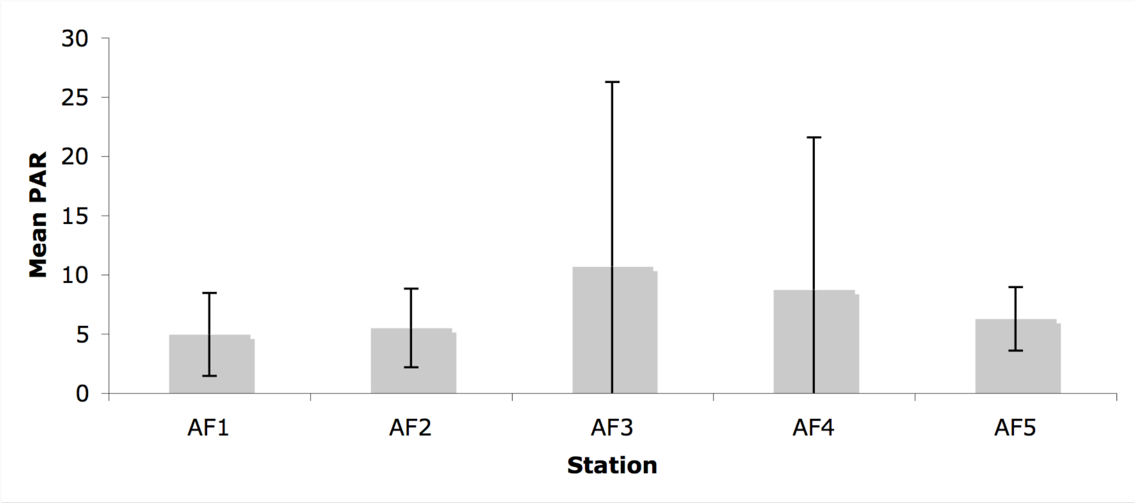


Figure 8e.

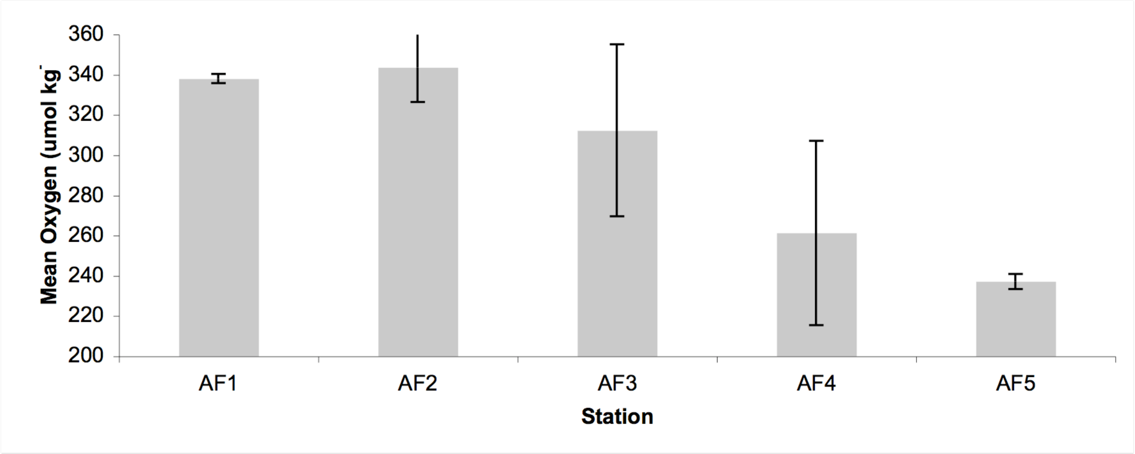


Figure 8f.

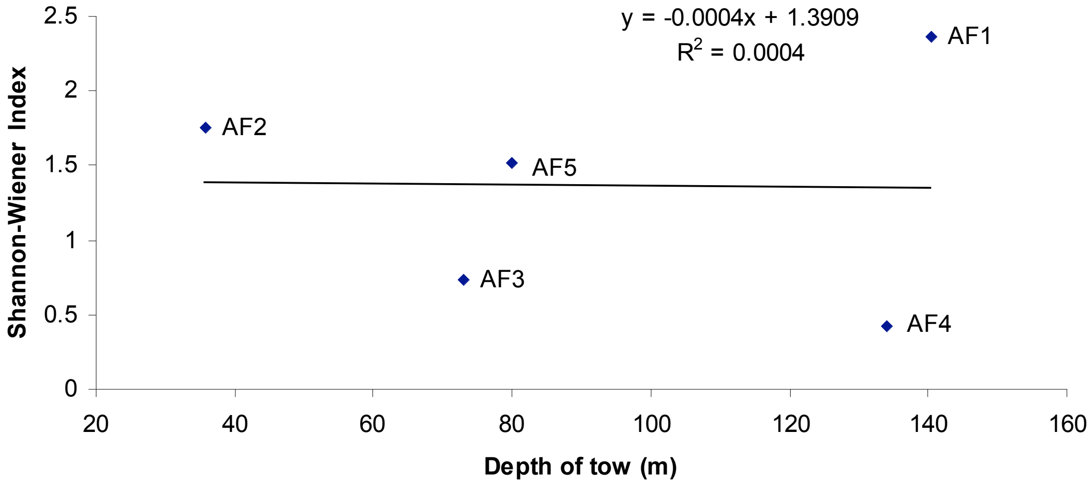


Figure 9a.

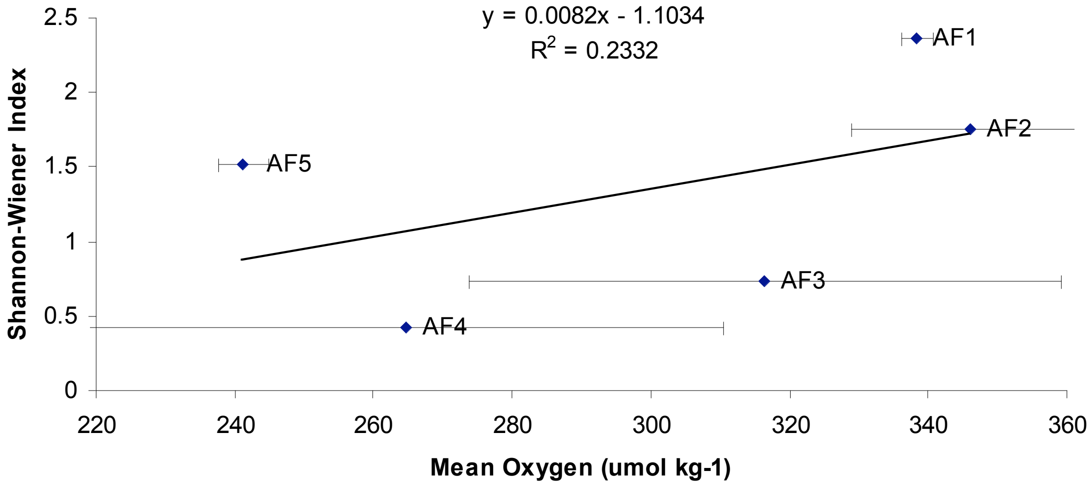


Figure 9b.

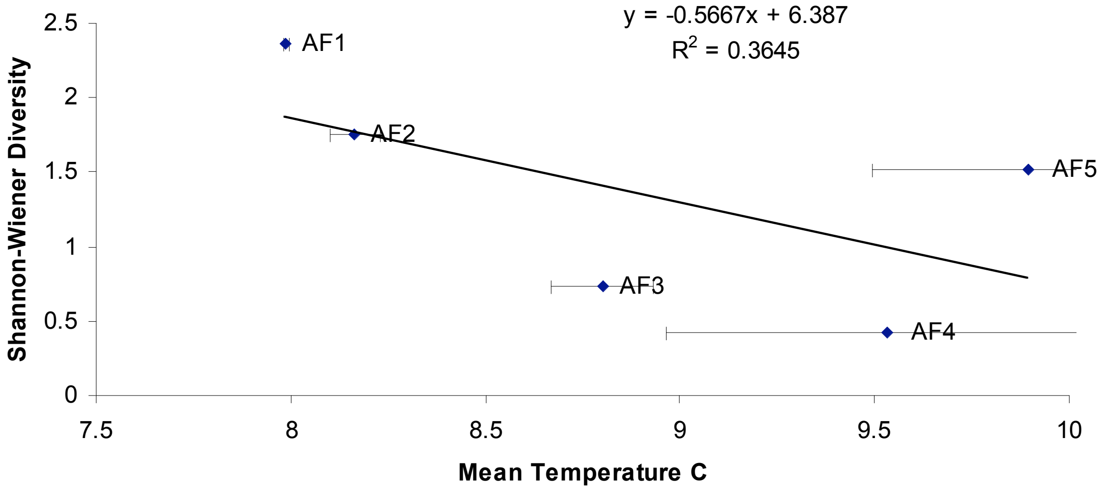


Figure 9c.

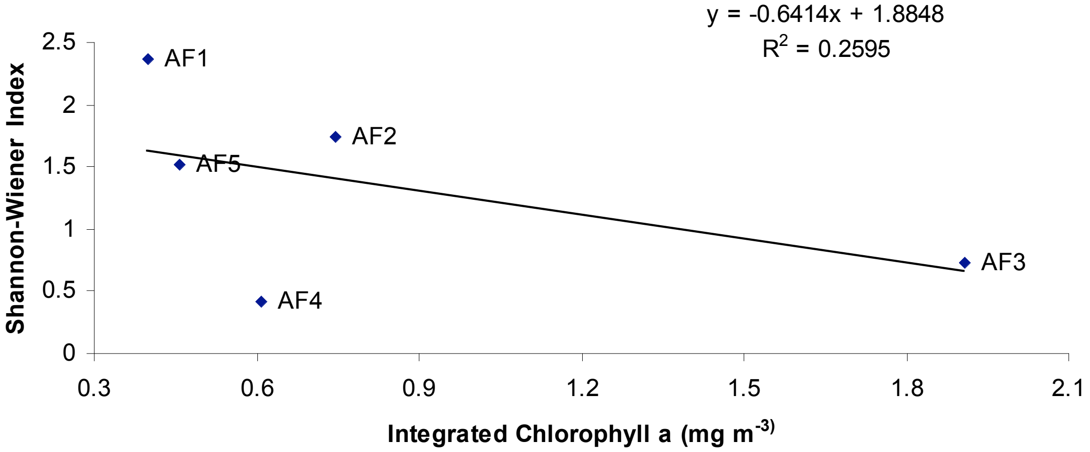


Figure 9d.