Temporal and spatial distribution and abundance of fish, crab, and zooplankton in the Hudson River Estuary from 1999-2015 using trawl and biological acoustic techniques.

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Maija Liisa Niemisto

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The aquatic biological community of the Hudson River Estuary (HRE) was examined using traditional and novel sampling techniques. A 16-year trawl, seine, and fish trap data set collected aboard the Hudson River Sloop *Clearwater* and Schooner *Mystic Whaler* from 1999-2015 was compiled and analyzed. Fish and crab species assemblages, geographic distributions, seasonal patterns, and abundance changes over the study period were analyzed and correlated to environmental conditions and climate variations. A biological acoustic survey of the HRE was conducted from 2013-2015 using a scientific echosounder hull-mounted to the Sloop *Clearwater*. Fish trawl and zooplankton tow data collected during this time period were used to ground-truth the bioacoustic records. Spatial and temporal patterns in biological scattering from pelagic fish and zooplankton were analyzed in relation to environmental conditions, trophic interactions, climate variability, and region.

Chapter 1 Abstract:

The temporal and spatial abundance and distribution of Hudson River Estuary fish and crab were examined using trawl, seine and trap data from 1999-2015. During this time period, fish abundance (as measured by catch per unit effort) was highest in 2003 and 2012. Patterns in organism abundance were investigated by examining the Hudson River Estuary regionally, seasonally, and by species. Each of the four geographic regions (Albany, Poughkeepsie, Piermont, and New York City) studied had different assemblages of dominant species. Seasonal abundance patterns between regions were found for blue claw crab (*Callinectes sapidus*), hogchoker (*Trinectes maculatus*), and white perch (*Morone americana*). Generalized linear models predicted a higher white perch presence in the downriver regions (Piermont and NYC) when water temperatures were lower and dissolved oxygen concentrations were higher. Lower white perch abundances were predicted for the upriver regions (Albany and Poughkeepsie) for the same environmental conditions. Higher catch per unit effort values for dominant species of fish and crab were associated with negative phase North Atlantic Oscillation index values in the upriver regions only (Albany and Poughkeepsie). Lower catch per unit effort values were observed during above average freshwater discharge rates, especially in the New York City Region.

Chapter 2 Abstract:

Pelagic fish and zooplankton abundance and distribution in the Hudson River Estuary (HRE) were quantified from August 2013 to September 2015 using a scientific echosounder mounted to the Hudson River Sloop Clearwater. Integrated acoustic backscatter from fish and zooplankton varied greatly within each day due to the patchy distribution of organisms. However, clear seasonal trends were evident each year with increases in the abundance of both fish and zooplankton occurring in the spring and fall. Freshwater discharge rates were associated with changes in the distribution of both fish and zooplankton in the estuary. High freshwater discharge decreased zooplankton abundance throughout the entire HRE and shifted the distribution of organisms downriver. These same conditions decreased fish abundance in the upper and lower estuary resulting in a more concentrated fish distribution centered near Poughkeepsie, NY. Acoustic surveys provide a non-invasive way to efficiently survey the distribution and abundance of pelagic organisms in a large estuarine system.

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Chapter 1:

"Seasonal and annual patterns in fish and crab abundance, assemblage, and distribution in the Hudson River Estuary from 1999 to 2015."

Introduction:

The Hudson River Estuary (HRE) is an important habitat for hundreds of fish species, and acts as a nursery for many migratory species (Levinton and Waldman, 2006). The estuarine portion of the Hudson is composed of a diverse community of fish favoring freshwater, estuarine, or marine habitats (O'Conner *et al.,* 2012). The HRE fish community has been extensively studied, with catch records dating back to the 1800s (Daniels *et al.,* 2005). Despite this long historical record, there remains much about Hudson River fish distribution, abundance, and species composition that is not well understood (Daniels *et al.,* 2005).

There is great spatial and temporal diversity in the distribution and abundance of fish in the Hudson due to the dynamic physical and biological conditions (Hagan and Able, 2003). The HRE fish community is influenced by many factors, including salinity, water residence times, water temperature, access to submerged aquatic vegetation, sediment type, prey availability, and spawning behavior, as well as anthropogenic disturbances (O'Conner, 2012). Salinity in the estuary varies with distance from the Atlantic Ocean, tidal cycle, depth, season, and rainfall events (Geyer and Chant, 2006). Freshwater from the surrounding watershed enters the estuary and disrupts the regular tidal oscillations with periods of relatively rapid advection of seaward and lower salinity levels throughout the HRE (Levinton and Waldman, 2006). Periods of high freshwater discharge into the estuary impact the distribution of zooplankton (a major food source for fish), resulting in a downstream flushing of the community and contraction of saline habitat regions (Pace and Lonsdale, 2006).

The greatest contribution of freshwater is the discharge of the Upper Hudson (from the Adirondack Mountains and the Mohawk River) which flows over the Troy Dam, and accounts for over 80% of the total input to the estuary (Abood *et al.,* 1995). Surface freshwater residence time of the Hudson River water ranges from 0.1 to 4 days, which makes it the fastest flushing estuary on the eastern seaboard (Howarth *et al.,* 2006). Water temperature in the estuary varies with season, depth, freshwater discharge, and thermal pollution (Ashizawa and Cole, 1994). O'Conner *et al. (*2012) found that periodic water temperature variations associated with the North Atlantic Oscillation (NAO) were correlated to freshwater discharge fluctuations and explained changes in some fish species abundances in the HRE.

The HRE has a long history of anthropogenic alterations to the biological community through industrialization, urbanization, pollution, dredging, commercial fishing, and the introduction of invasive species (Strayer *et al.,* 2014). Many fish species navigate this ever-changing ecological landscape throughout their life-cycle while others only populate the HRE during spawning and juvenile stages (Limburg *et al.,* 2010). There are many examples of fish species decline, population size fluctuations, and assemblage changes to the HRE community over the past century (Strayer *et al.,* 2014). For example, there has been a shift downriver in littoral species after the zebra mussel invasion (Strayer, 2006), declines in ten signature fish populations (Seaby and Henderson, 2006), and some recent population increases, such as in striped bass (*Morone saxatilis*), due to successful fishing regulations (Seaby and Henderson, 2006). Local climate variability has also been correlated to variations in abundance for some species of fish. For instance, larval striped bass abundance was positively correlated with high freshwater flow and larval shad abundance were negatively correlated with warmer sea surface temperatures in the HRE (O'Conner *et al.,* 2012). Similarly, winter water temperatures and freshwater discharge rates were found to impact abundances of striped bass, white perch, bay anchovy, and other species in the Chesapeake Bay (Wingate and Secor, 2008). Daniels *et al.* (2002) suggests that the best way to examine these patterns in the fish community is to consider trends in the entire fish assemblage, whereas Norris and Hawkins (2000) propose looking at individual species as a more accurate indicator of community response to natural and anthropogenic factors.

There is currently limited access to fish trawl collection on the Hudson River Estuary (HRE) with most published studies using a single data set, the Annual Year Class Report (Strayer *et al.,* 2014; Strayer *et al.,* 2013; and O'Conner *et al.,* 2013). These data are collected on behalf of several utility companies operating on the HRE and tasked with monitoring fish abundance and distribution in the river (ASA, 2010). Despite the regulations restricting extensive trawl surveying of the HRE, the Department of Environmental Conservation does allow limited trawling for educational purposes on vessels such as the Hudson River Sloop *Clearwater.* Through the Sailing Classroom Education Program, *Clearwater* has been trawling for fish almost daily within the estuary during their sailing season from early April until the end of October, with records dating from 1999 to 2015. This previously unanalyzed data set covers a relatively long temporal scale (16 years) and geographic range (the entire 240 km estuary) where trawling has been heavily restricted.

The purposes of this study are to use the Clearwater trawl data to examine the distribution, abundance, and assemblage changes in the Hudson River Estuary. Specifically, if there are changes in total fish community abundance, distribution, and assemblage temporally and geographically in the Hudson River Estuary; how fish distribution and abundance are impacted by salinity, water temperature, and changes in the freshwater discharge; if the fish community is impacted by local climate variability such as NAO index or winter water temperature variations; and if trends in distribution and abundance for individual fish species vary temporally and geographically in the Hudson River Estuary.

Materials and Methods:

Study Area – The Hudson River flows 507 kilometers from its headwaters in Lake Tear of the Clouds, high in the Adirondack Mountains (1,309 m elevation), to where it meets the Atlantic Ocean in New York Harbor. From Albany, NY to the Atlantic there is only a 1.5 meter change in elevation, allowing Atlantic tidal influence to reach all the way up to the Federal Dam in Troy, NY at river kilometer 247 (rkm 247), which results in the direction of the river current reversing twice each day (Helsinger and Friedman 1982). River kilometers (rkm) are measured from rkm 0 at the mouth of the estuary in New York Harbor up to rkm 507 at the headwaters of the Hudson River in the Adirondacks.

This study focuses on the navigable estuarine region of the Hudson River, with data coverage from the New York Harbor (rkm 0) up to the Dunn Memorial Bridge in Albany (rkm 240). This length of the HRE varies a great deal geographically, hydrologically, and in terms of human impacts to the shoreline. The Hudson narrows between Albany (rkm 240) and Poughkeepsie (rkm 113), and then opens into a series of wide shallow bays before becoming narrow once again near Manhattan (rkm 8). Haverstraw (rkm 56) and Newburgh Bays (rkm 97) are the widest points at 5.5 km and 3.2 km respectively. The depth in the estuary ranges from shallow, with an average of 8 m (between Albany and Poughkeepsie), to its deepest point at World's End (rkm 85) where the glacially-scoured river bottom at over 60 m deep, far upriver of its shallower outlet to the Atlantic which technically makes the Hudson a fjord (Daniels *et al.,* 2005) (Figure 1).

Figure 1. In eastern New York State, the Hudson River flows from the Adirondack Mountains to the Atlantic Ocean (tan area). The sampling region for this study is the Hudson River Estuary (within the orange box) extending from Albany, NY to the New York Harbor.

Salinity varies greatly with season, tidal cycle, vertical position in the water column, proximity to the Atlantic Ocean, and freshwater discharge into the HRE, from tidal freshwater (0.0 to 0.5 ppt), oligohaline (0.5 – 5ppt), mesohaline (5-18 ppt), polyhaline (18-27 ppt) and eurohaline (>27 ppt) waters (Geyer and Chant, 2006; Llanso, 2002). Trawling for this study was conducted in locations of the HRE where salinity ranges from 0 ppt (between 113 and 240 rkm) up to 30 ppt (between 0 and 113 rkm) (Ralston *et al.,* 2008). Freshwater discharge into the HRE varies seasonally and with rain events, primarily coming from the Mohawk River and the upper Hudson (measured by the US Geological Society at the Green Island, NY). The residence time of water in the Hudson is negatively correlated with discharge rates, that is, high discharge of freshwater into the estuary decreases the residence time of water in the system (Howarth *et al.,* 2006). Trawling occurred during a wide range of discharge rates.

The HRE has a navigation channel maintained by the US Army Corps of Engineers guaranteed to be at least 9 m deep, which necessitates regular dredging in some areas (USACE, 2015). The trawls included in this study were conducted outside the dredged channels. The shorelines and surrounding watershed have been altered historically by heavy industrialization, urban development and agricultural use (Stainbrook, 2006). Some trawling locations are impacted by industrial uses, for example the Albany trawl site is in a turning basin engineered to allow large ships to turn in the narrow river. These factors all contribute to an extremely diverse fish community with a wide range of environmental conditions.

Data Collection – Catches from trawls, beach seines, and fish traps were recorded from 1999 to 2015, between early April and the end of October onboard the Hudson River Sloop *Clearwater;* the Schooner *Mystic Whaler;* and at selected shore side locations in the Hudson River Estuary (HRE). These included 1540 trawl, 135 seine, and 77 fish trap deployment days during the 16 year sampling period. Trawl nets were deployed at 39 sites between the New York Harbor (rkm 0) and the Albany pool (rkm 240), with 85% of deployments occurring at eight geographic locations in the HRE (Figure 2 and Table 1).

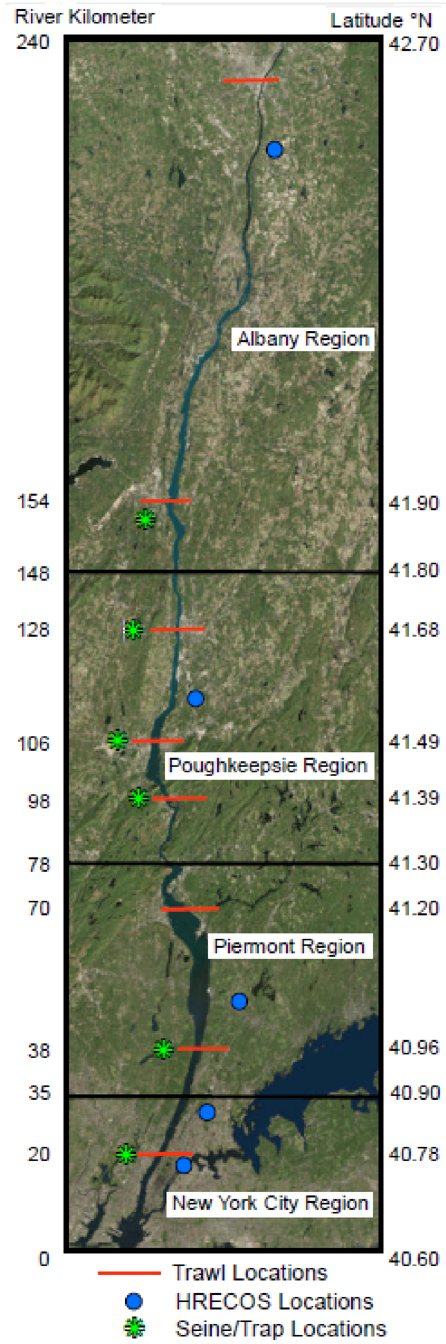


Figure 2. Sampling locations for fish and environmental data in the Hudson River Estuary were grouped into four distinct geographic regions (Albany, Poughkeepsie, Piermont, and New York City). Locations are shown for the eight most frequent trawl sites (red bars), the Hudson River Environmental Conditions Observing System (HRECOS) stations (blue circles), and the most frequent seine and fish trap locations (green stars).

Table 1. Trawl sampling abundance (trawling days) and locations on the Hudson River Estuary from 1999-2015 from both the Hudson River Sloop *Clearwater* and the Schooner *Mystic Whaler*.

Location Name	**River Kilometer**	**Latitude (ºN)**	**# of trawling days**
Albany	238	42.65	32
Kingston	154	41.9	59
Poughkeepsie	128	41.68	83
Beacon	106	41.49	86
Cold Spring	98	41.39	87
Haverstraw Bay	70	41.2	84
Yonkers	38	40.96	194
Manhattan	20	40.78	224

On any particular sampling day, trawl nets were deployed one to five times during that day. All trawl catches and deployment durations were summed into single daily values for each location. Seine and fish trap records were considered separately. The number of trawling days that occurred in a given month ranged from 3 to 26. This variation was dependent upon the location of the vessels, access to fishing grounds, and weather conditions- except when trawling was prohibited by the New York Department of Environmental Conservation (between August 2012 and November 2013), when the Atlantic sturgeon (*Acipenser oxyrhynchus oxyrhynchus*) was initially listed as an endangered species and before the vessel was granted an exemption to catch. Sampling locations and schedules were determined by sailing schedule of the vessel and generally included 3 to7 days of repeat sampling at a single location before transiting to another site on the river. During the months of April, May, and June, both vessels were trawling simultaneously at different locations on the HRE, whereas from July to November only the sloop *Clearwater* collected samples. The trawl nets used by both vessels include 7.64 m (from April 1999 - May 2005) and 4.9 m (from June 2005 - November 2015) head-rope length otter trawl nets (Sea Gear) all with 3.8 cm body mesh, 0.64 cm cod-end liners.

Deployment of trawl nets generally occurred under engine power at the same favored fishing grounds in each geographic location, in approximately 10 m of water on a shoal outside of the shipping channel. Tow times began when net was deployed and ended when the full net returned aboard. The length of line attaching the net to the vessel was three times the depth of water, unless heavy strain necessitated a longer line. Average vessel speed during tows was 3 knots (5.5 km hr^{-1}) determined from start/end times as recorded and referenced to corresponding GPS ship locations. Nets were generally towed against the prevailing currents, unless shipping traffic or proximity to shallows necessitated the opposite. Fishing techniques employed by the operators strived to "bounce" the net between the water column and benthos by maintaining a constant speed while deploying the net and then retrieving it by hand while stationary in the water; thus catches represent benthic and pelagic sampling.

Seine nets used in this study were 7.6 m head-rope length and 1.2 m depth with 3.8 cm mesh. These nets were deployed 135 times at 22 shoreline sites between Alpine, NJ (rkm 21) and Coxsackie, NY (rkm 180) with 76% occurring at 4 geographic locations; Esopus Meadows (147 rkm), Poughkeepsie (128 rkm) Beacon (106 rkm), and Alpine (38 rkm) (Figure 3). Fish were counted, identified, recorded, and returned immediately to the river, with select specimens temporarily kept in a tank aboard for educational purposes not related to this study. Fish traps used in this study consist of three different models of vinyl-coated traps (Frabill) (0.46 x 0.3 x 0.2 m, 2.5 cm opening, 0.64 cm mesh rectangular pinfish trap; 4.2 m length, 2.5 cm opening, 0.64 cm mesh round minnow trap;, and 0.8 x 0.5 x 0.3 m hoop crab traps). Traps were deployed 77 times at 17 dockside locations between

Manhattan (rkm 8) and Albany (rkm 240) with 73% occurring at 5 dock locations; Poughkeepsie (128), Beacon (106), West Point (93), Alpine (38), and Manhattan (20). Traps were baited, weighted to rest on the bottom, and deployed from the dock overnight. These records do not distinguish between the trap used in each deployment, thus, these data are included simply for daily presence or absence analysis at each location and are not included in catch per unit effort (CPUE) calculations. Catches were counted, identified, recorded and returned immediately to the river, with select specimens temporarily kept in a tank aboard for educational purposes not related to this study.

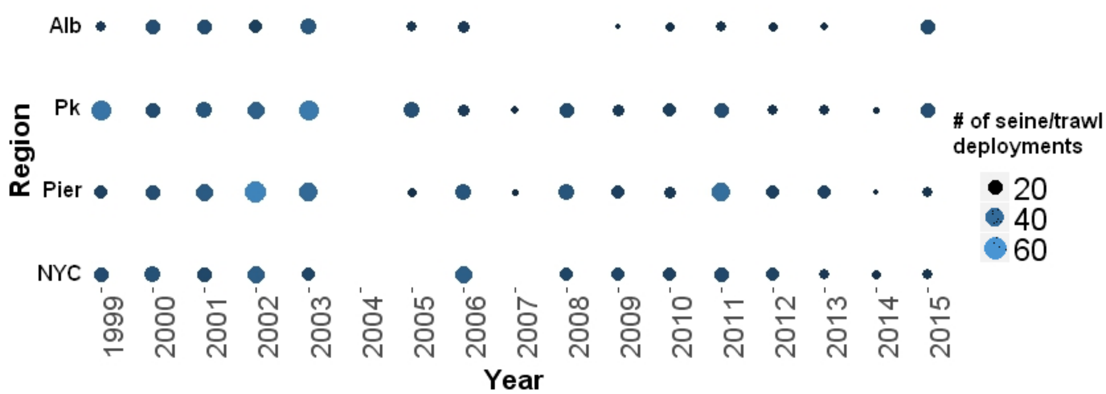


Figure 3. The spatial and temporal coverage of trawl and seine deployments from 1999-2015 in the four geographic regions (Alb = Albany, Pk = Poughkeepsie, Pier = Piermont, and NYC = New York City) on the Hudson River Estuary, show fairly even regional distribution of data collection over the study period. The Albany region has the fewest number of trawl and seine deployments, 2004 is missing all trawl and seine data, and 2013 is composed of only seine data due to restriction on trawling. Size and color of dots represent the total number of deployments from both methods.

Environmental data are from the Hudson River Environmental Conditions Observing System (HRECOS) shipboard and stationary data sets. Hudson River Environmental Conditions Observing System is a network of sondes collecting parameters including water temperature (degrees C), dissolved oxygen (mg l^{-1}), turbidity (NTU), and salinity (ppt) every 30 seconds to 15 minutes (depending upon station) from 2008 to 2015. These data were utilized from the mobile hull-mounded sonde aboard *Clearwater* and from 4 stationary sites located along the length of the estuary, corresponding geographically with the trawl locations (Table 2).

Table 2. Hudson River Environmental Conditions Observing System (HRECOS) site names, years of data coverage, locations (in river kilometers) with the closest corresponding Clearwater trawl site names and locations (in river kilometers).

HRECOS Station Location	Years of data set	River Kilometer	Clearwater Trawl location	River Kilometer
Schodack Island	2008-2015	225	Albany	240
Norrie Point Environmental Center	2008-2015	145	Kingston	154
Piermont Pier	2008-2015	51	Haverstraw Bay	70
George Washington Bridge	2009-2011	29	Manhattan	20
Pier 84, NYC	2012-2015	18	Manhattan	20

In addition to the HRECOS environmental data, water temperature (°C), dissolved oxygen (mg l^{-1}) and salinity (ppt) were measured at 1 m increments from the surface to 10 m depth with a calibrated YSI Model 85 hand-held meter lowered from the ship at 10 stations in 2015. These data provided information on the vertical water column structure.

Data Analysis - Trawl data were digitized from field logs and any records with unidentified species, and illegible trawl times or location information were excluded from further analysis. Tows where the net snagged on the bottom of the river, generally when trawl times were over 50 minutes, were excluded from analysis. Trawling generally occurred twice each day, however catch records did not consistently distinguish between species and counts caught in the morning and afternoon trawls, thus it was necessary to combine catches into a single daily value. Separate records were not kept for trawl attempts within a particular day when there were both zero and non-zero catch values, so these were combined in the daily trawl total times and species counts. There were no records kept for seine or trap deployments with zero catches, thus all recorded seine and fish trap records are for non-zero catches. Total number of fish caught were calculated by taking the sum of all individual fish and/or crab of a single species caught, and percent of total catch values were calculated by dividing the total number of individuals from one species caught by the total number of fish caught from all species combined.

Catch Per Unit Effort (CPUE, in number of fish per minute of trawl time) values were calculated by dividing total fish caught each day by the total trawl duration (i.e., pooling morning and afternoon trawls). In this manuscript, "CPUE of dominant fish" is defined as the species that make up over 80% of total CPUE in the HRE, or in the designated regions. Net gear change was taken into account by assuming a circular net opening with a radius of 2.42 meters (from April 1999 - May 2005) and 1.55 meters (from June 2005 - November 2015). Daily CPUE values were multiplied by the post-2005 net area, then divided by the net area used at deployment. For example, pre-2005 CPUE values were multiplied by $7.55\ m^2 / 18.40 m^2 = 0.41$ and post-2005 CPUE values were multiplied by $7.55\ m^2 / 7.55 m^2 = 1$.

HRECOS data from the shipboard records and four stationary locations were compiled from 2007 to 2015 and examined for data quality. Incomplete or inaccurate data due to instrument malfunctions were excluded. Missing values in this environmental time series were imputed, using the R package "impute TS" (Moritz, 2015) to ensure the most accurate and complete data possible were used for analysis (Carruthers, 2011). This process is a commonly used statistical method for substituting missing values in a time series with values following the same temporal or spatial pattern created by existing data (Schneider, 2001; Moritz, 2015). A cubic spline interpolation function was applied to water temperature and dissolved oxygen data because there was a clear periodic trend. A mean interpolation was applied to salinity and turbidity where there were no clear trends in the data. The mean and standard deviations did not change more than 5% for any of the four environmental parameters by the interpolation, except for the standard deviation of turbidity which changed by 15% (Table 3). Environmental data were averaged into daily values for salinity, turbidity, dissolved oxygen, and water temperature. Fish trawl and environmental data sets were combined by assigning stationary environmental data a geographic region within which trawling occurred. There were 340 days of environmental and trawl data available for further analysis, representing 34% of total trawl catch days and 99% of trawl catch days from 2007-2015.

Table 3. Imputation of missing environmental data changes to the mean and standard deviations for salinity, turbidity, water temperature, and dissolved oxygen were small. Data were imputed using cubic spline interpolation for water temperature and dissolved oxygen due to periodic trends in data, while mean interpolation was used for salinity and turbidity data due to lack of any clear trends in data.

Parameter	Mean		Standard Deviation		% of data present
	Before	After	Before	After	Before
Salinity (ppt)	4.19	4.52	6.18	6.34	78
Turbidity (NTU)	30.1	31.8	41.26	35.39	71
Water Temperature (C)	14.75	14.13	8.5	8.61	76
Dissolved Oxygen (mg/l)	9.3	9.43	2.57	2.59	74

The HRE was split into four regions (Albany, Poughkeepsie, Piermont, and New York City), based upon salinity regimes, geographical characteristics, and similarities between fish species distributions. The Albany region is defined latitudinally from 41.8 – 42.7 degrees N (148-240 rkm), with only tidal freshwater, relatively narrow riverbanks, and a fish assemblage dominated by freshwater or eurohaline species. The Poughkeepsie region is defined latitudinally from 41.3 – 41.8 degrees N (78-148 rkm), with tidal freshwater or oligohaline water, diverse geographic features including Newburgh

Bay (wide and shallow) and World's End (deep and narrow), and a fish assemblage dominated by freshwater and eurohaline species. The Piermont region (is defined latitudinally from 40.9 – 41.3 degrees N (35-78 rkm), with oligohaline, mesohaline, or eurohaline waters, a geographic stretch primarily made up of Haverstraw and Tapanzee Bays (extremely wide and shallow), and a fish assemblage made up of eurohaline and marine species. The New York City region is latitudinally defined between 40.6-40.9 degrees N (0-35 rkm), with oligohaline, mesohaline, or eurohaline waters, geographic features including narrow heavily engineered shorelines and relatively deeper bottom depths where the navigation channel extends almost bank to bank, and a greater diversity fish made up of eurohaline and marine species. Trawls occurring between the latitudinal boundaries of each region were correlated with the HRECOS stationary site data within that geographic region (Figure 2).

Generalized linear models (GLMs) were used to predict the presence and absence of the four most common species in the HRE (white perch, hogchoker, Atlantic tomcod, and blue crab) with the four environmental parameters (salinity, turbidity, dissolved oxygen, and water temperature). The logit function was used and the predictors were fit one at a time.

Freshwater discharge into the HRE, recorded in daily mean discharge rates by the United States Geological Survey at Green Island, NY, were utilized from 2000-2015 (USGS, 2015). Mean annual and mean monthly discharge rates were calculated. Mean discharge rates for this time period is 470 $m^3 s^{-1}$ and “high discharge rates” were defined as those greater than 740 $m^3 s^{-1}$, which was the 85th percentile for discharge rates, and is similar to peak discharge values used in previous analysis of these data (Geyer and Chant, 2006). Discharge rates were compared to trawl data to determine if the fish distribution or abundance were correlated with freshwater influx into the estuary. To determine if there were latitudinal distribution changes in CPUE (fish/min) during periods with different discharge rates, the CPUE values were multiplied by their corresponding latitudes (ºN). The CPUE-weighted latitudes were then used to measure if distributions of the dominant fish species shifted when discharge rates varied on monthly and annual resolutions.

Winter climate data, specifically the North Atlantic Oscillation (NAO) index from December, January, February, and March 1999-2015, were obtained from NOAA's National Center for Environmental Information database (http://www.cpc.ncep.noaa.gov/data/teledoc/nao.shtml). Winter water and air temperatures on the HRE were utilized from NOAA's National Estuarine Research Reserve System database from December, January, February, and March of 1999-2015. Yearly mean winter values were calculated for both the climate index and winter temperatures and combined with trawl records to determine if there were any correlations between winter climate conditions and subsequent fish distribution or abundance.

Results:

Sampling occurred 16.4 +/- 5.9 (mean +/- standard deviation) trawling days per month. Trawl deployment times were 10 +/- 9 minutes. There were 1,314 trawl days (including 311 days where the total daily trawl catch was zero) which captured a total of 47,423 organisms, composed of 52 fish and a single crab (*Calinus sapidus)* species (Table 4). The single most abundant species was the hogchoker (*Trinectes maculatus*) composing 32% of the total number of fish caught, and 28.2% of CPUE over the entire study site. White Perch (*Morone americana*), Atlantic tomcod (*Microgadus tomcod),* and blue crab *(Callinectes sapidus*) were the next-most abundant species, in the HRE (Table 4).

Table 4. Abundance (absolute and relative) of all marine organisms sampled by trawl methods on the Hudson River Estuary from 1999-2015. Species names (scientific and common), total number of each species caught, percent of each species caught, and percent of catch per unit effort (CPUE) in fish min^{-1} of trawling are listed in order of most to least abundant species.

Species	**Total Number Caught**	**% of Total Catch**	**% of CPUE**
*Trinectes maculatus (*Hogchoker)	15410	32.3	28.2
*Morone americana (*White Perch)	7511	15.7	15.1
*Microgadus tomcod (*Atlantic Tomcod)	7374	15.5	10.0
*Callinectes sapidus (*Blue crab)	3880	8.1	10.7
*Ictalurus punctatus (*Channel catfish)	2203	4.6	5.3
*Cynoscion regalis (*Weakfish)	2026	4.3	4.3
*Urophycis regia (*Spotted hake)	1771	3.7	4.1
Anchoa mitchilli (Bay anchovy)	1609	3.4	4.3
Ameiurus nebulosus (Brown bullhead)	1113	2.3	2.0
Notropis hudsonius (Spottail Shiner)	889	1.9	2.0
Menidia menidia (Atlantic silverside)	702	1.5	1.2
Alosa sapidissima, *Alosa pseudoharengus* (Herring)	525	1.1	1.6
Morone saxatilis (Striped bass)	456	1	0.7
Triglidae (Sea Robin)	356	0.8	1.4
Anguilla rostrata (American eel)	311	0.7	1.3
Ameiurus catus (White catfish)	212	0.4	0.7
Pseudopleuronectes americanus (Winter flounder)	174	0.4	0.5
Opsanus tau (Oyster toadfish)	121	0.3	0.8
Etheostoma olmstedi (Tessellated darter)	114	0.2	0.2
Scophthalmus aquosus (Windowpane flounder)	107	0.2	0.5
Paralichthys dentatus (Summer Flounder)	107	0.2	0.7
Perca flavescens (Yellow perch)	90	0.2	0.1
Peprilus triacanthus (Butterfish)	89	0.2	0.5
Urophycis chuss (Red Hake)	56	0.1	0.2
*Selene vomer (*Lookdown)	50	0.1	0.2
Stenotomus chrysops (Porgy)	47	0.1	0.2
*Hippocampus erectus (*Seahorse)	42	0.1	0.3
Cyprinus carpio (Carp)	41	0.1	0.1
Fundulus diaphanus (Banded killifish)	41	0.1	1.1
Pomatomus saltatrix (Bluefish)	38	0.1	0.3
Syngnathus fuscus (Pipefish)	36	0.1	0.6
Acipenser oxyrhynchus (Atlantic Sturgeon)	33	0.1	0.2
Gobiidae (Goby)	22	0.1	0.1
Aplodinotus grunniens (Freshwater drum)	20	<0.1	0.1

Tetraodontidae (Pufferfish)	20	<0.1	0.1
Stenotomus chrysops (Scup)	19	<0.1	<0.1
Lepomis gibbosus (Pumpkin seed sunfish)	17	<0.1	<0.1
Osmerus mordax (Rainbow smelt)	17	<0.1	<0.1
Cottoidea (Sculpin)	17	<0.1	<0.1
Fundulus heteroclitus (Mummichog)	14	<0.1	<0.1
Lepomis auritus (Red breasted sunfish)	7	<0.1	<0.1
Menticirrhus saxatilis (Northern kingfish)	6	<0.1	<0.1
Lepomis macrochirus (Bluegill sunfish)	5	<0.1	<0.1
Carassius auratus (Goldfish)	5	<0.1	<0.1
Notemigonus crysoleucas (Golden Shiner)	4	<0.1	<0.1
Catostomus (Sucker)	3	<0.1	<0.1
Lagodon rhomboides (Pinfish)	3	<0.1	<0.1
Phoxinus phoxinus (Minnow)	2	<0.1	<0.1
Gasterosteidae (Stickleback)	2	<0.1	<0.1
Micropterus salmoides (Largemouth Bass)	2	<0.1	<0.1
Congridae (Conger eel)	2	<0.1	<0.1
Squalus acanthias (Dogfish)	2	<0.1	<0.1

There were a total 135 seine and 76 fish trap deployments which caught 2,115 fish and crabs, composed of 40 fish and one crab species. The most abundant species captured was the spottail shiner (*Notropis hudsonius*) composing 26.7% of fish caught with these methods. Banded killifish (*Fundulus diaphanus),* White Perch (*Morone americana),* herring (*Alosa sapidissima, Alosa pseudoharengus),* and American Eel (*Anguilla rostrata)* were the next most abundant species of fish caught using the seine and trap methods (Table 5).

Table 5. Abundance (absolute and relative) of all marine organisms sampled by seine and trap methods on the Hudson River Estuary from 1999-2015. Species names (scientific and common), total number of each species caught, and percent of each species caught with seine and trap methods only are listed in order of most to least abundant species.

Species	Total Number Caught	% of Catch (from seine/trap)
Notropis hudsonius (Spottail Shiner)	565	26.7
Fundulus diaphanus (Banded killifish)	287	13.6
*Morone americana (*White Perch)	189	8.9
Alosa sapidissima, *Alosa pseudoharengus* (Herring)	181	8.6
Anguilla rostrata (American eel)	177	8.4
Morone saxatilis (Striped bass)	118	5.6
Etheostoma olmstedi (Tessellated darter)	93	4.4
Lepomis gibbosus (Pumpkin seed sunfish)	77	3.6
Fundulus heteroclitus (Mummichog)	76	3.6
Menidia menidia (Atlantic silverside)	70	3.3
*Callinectes sapidus (*Blue claw crab)	49	2.3
Anchoa mitchilli (Bay anchovy)	47	2.2
*Trinectes maculatus (*Hogchoker)	44	2.1
Gasterosteidae (Stickleback)	28	1.3
Lepomis auritus (Red breasted sunfish)	22	1.0
Notemigonus crysoleucas (Golden Shiner)	14	0.7
Lepomis macrochirus (Bluegill sunfish)	12	0.6
*Ictalurus punctatus (*Channel catfish)	9	0.4
*Cynoscion regalis (*Weakfish)	8	0.4
Alosa sapidissima (Shad)	7	0.3
Ameiurus nebulosus (Brown bullhead)	6	0.3
Catostomus (Sucker)	4	0.2
Syngnathus fuscus (Pipefish)	4	0.2
Pomoxis nigromaculatus (Black crapie)	4	0.2
Perca flavescens (Yellow perch)	2	0.1
Scophthalmus aquosus (Windowpane flounder)	2	0.1
Lagodon rhomboides (Pinfish)	2	0.1
Gobiidae (Goby)	2	0.1
Notropis atherinoides (Emerald Shiner)	2	0.1
Squalius cephalus (Chub)	2	0.1
Cyprinus carpio (Carp)	2	0.1
*Alosa pseudoharengus (*Alewife)	2	0.1
Scophthalmus aquosus (Windowpane flounder)	1	<0.1
*Microgadus tomcod (*Atlantic Tomcod)	1	<0.1

Paralichthys dentatus (Summer Flounder)	1	<0.1
Acipenser oxyrhynchus (Atlantic Sturgeon)	1	<0.1
Stenotomus chrysops (Porgy)	1	<0.1
Opsanus tau (Oyster toadfish)	1	<0.1
Micropterus salmoides (Largemouth Bass)	1	<0.1
Pomatomus saltatrix (Bluefish)	1	<0.1

Fish abundance (as measured by CPUE of dominant species in the entire HRE) varies with time and location on the HRE with a mean CPUE of 2.32 +/- 2.62 fish min^{-1}. CPUE had a bimodal distribution over the 16 year time period with the highest CPUE values in 2003 and 2012 in all regions. There were also high CPUE values in 2001 for the northern two regions (Albany and Poughkeepsie), and 2009 in the Poughkeepsie and NYC regions. (Figure 3).

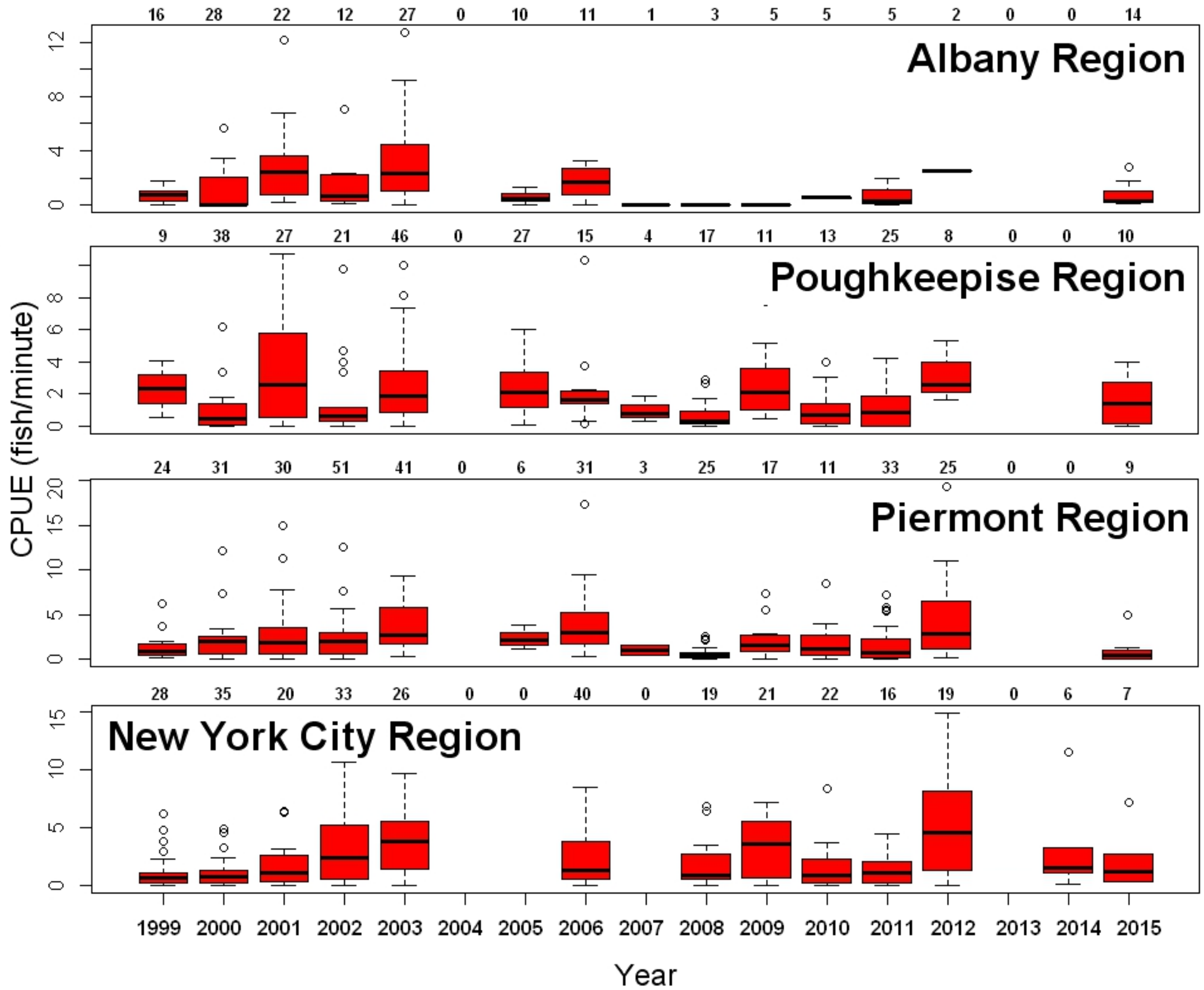


Figure 3. Temporal trends in fish and crab abundance over 16 years in catch per unit effort (CPUE) of dominant fish in each region of Hudson River Estuary from 1999-2015, showing peaks in abundance for all regions in 2003 and 2012. Zero catch trawl days are excluded from plot for clarity, the number of trawl days for each year are 1999=59/122 (non-zero/total trawl days), 2000= 98/128, 2001=114/126, 2002=112/127, 2003=133/140, 2004=0/0, 2005= 40/52, 2006=91/106, 2007=6/25, 2008=61/113, 2009=40/74, 2010=58/94, 2011=67/82, 2012=44/44, 2013=0/0, 2014=15/16, and 2015=39/66. Above each subplot are the number of trawl deployments in each year corresponding to the region plotted below. Note there are no data in 2004 or 2013. The black horizontal line represents the yearly median CPUE value, bottom and top of the boxes represent the 1st and 3rd quantiles, whiskers represent the 1st and 3rd quantiles +/- 1.5 times interquartile range.

Regional Fish and Crab Abundance- There were unique species assemblages in the four geographic regions of the HRE. In each of the three upriver regions (Albany, Poughkeepsie, and Piermont), community assemblages were dominated by six different species, comprising over 80% of the respective CPUE totals, with some overlapping species between regions. In the NYC region, the eight most abundant species comprise just over 60% of CPUE, so the addition of the next nine most abundant species were included (to reach 80% of CPUE) to make the assemblage comparable to the other regions. All analysis of regional CPUE use these dominant species assemblages for CPUE calculations (Figure 4, Table 6)

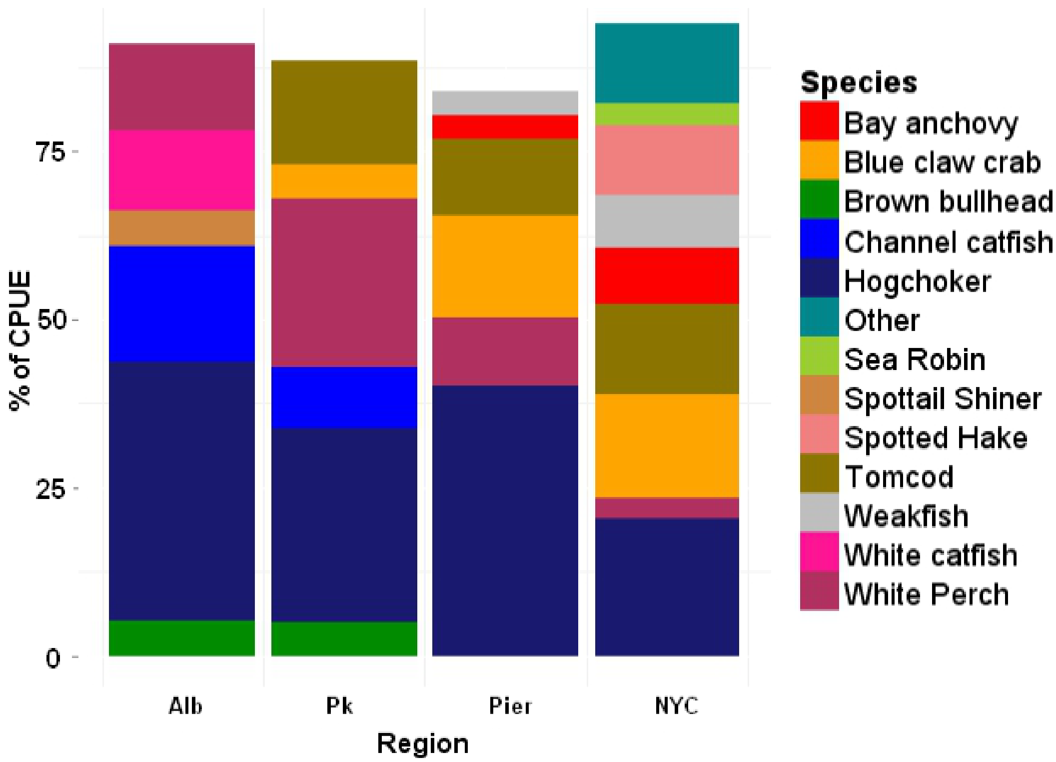


Figure 4. Dominant fish and crab species for each of four geographic regions on the Hudson River Estuary and the percent of total catch per unit effort (CPUE) each species represents. Dominant species in each region compose majority of total CPUE, specifically in the Albany region(Alb) 91%, in the Poughkeepsie region (Pk) 88.5%, in the Piermont region (Pier) 84%, and New York City region(NYC) 94.1%.Colors correspond to different crab and fish species.

Table 6. The relative abundance of only the dominant species, those which comprise >84% of the total catch per unit effort (CPUE in fish min^{-1}), for each of four Hudson River Estuary regions (Albany, Piermont, Poughkeepsie, and New York City) from 1999-2015.

Region	Species	% of CPUE
Albany	Hogchoker	38.4
	Channel catfish	17.3
	White Perch	13.0
	White catfish	11.7
	Brown bullhead	5.3
	Spottail Shiner	5.3
	Total	91
Poughkeepsie	Hogchoker	28.7
	White Perch	25.2
	Tomcod	15.4
	Channel catfish	9.2
	Brown bullhead	5.0
	Blue claw crab	5.0
	Total	88.5
Piermont	Hogchoker	40.2
	Blue claw crab	15.2
	Tomcod	11.5
	White Perch	10.0
	Bay anchovy	3.6
	Weakfish	3.5
	Total	84
New York City	Hogchoker	20.3
	Blue claw crab	15.4
	Tomcod	13.6
	Spotted Hake	10.4
	Bay anchovy	8.3
	Weakfish	7.8
	Sea Robin	3.2
	White Perch	3.1
	Summer Flounder	1.6
	Banded killifish	1.6
	Spottail Shiner	1.4
	Herring	1.4
	Winter flounder	1.3

	Butterfish Windowpane flounder Atlantic silverside American eel	1.3 1.2 1.1 1.1
	Total	94.1

The temporal trends in the CPUE varied with geographic location in the HRE. In the Albany Region, CPUE was highest in 2003 (3.5 +/- 3.1 fish min^{-1}), but dropped during the remainder of the study period from 2004-2015 (1.1 +/- 1.2 fish min^{-1}). In the Poughkeepsie Region, CPUE was relatively stable from 2001-2006 (2.7+/- 2.7 fish min^{-1}), then declined after 2006 to 1.7 +/- 1.8 fish min^{-1}. The down-river regions (Piermont and NYC), had much higher CPUE than the upriver regions throughout the study period, with mean CPUE of 1.1+/- 1.9 fish min^{-1} for the upriver regions and 2.2 +/- 3.3 fish min^{-1} for the downriver regions. The Piermont Region CPUE trend reflects the bimodal distribution of CPUE temporally as seen in the estuary wide pattern, with the highest CPUE in 2003 (3.5 +/- 2.8 fish min^{-1}) and 2012 (4.6 +/-5.3 fish min^{-1}). The NYC region had a unique pattern in CPUE over the study period compared to the other three regions. There is a peak in CPUE in 2003 (8.3 +/- 9.7 fish min^{-1}), and an increase in CPUE after 2009 with the highest values in 2012 (5.6 +/- 4.6 fish min^{-1}) and 2015 (5.4 +/- 8.9 fish min^{-1}), and relatively consistent CPUE for all intervening years for which data is available (2.3 +/-2.5 fish min^{-1} for all remaining years) (Figure 5).

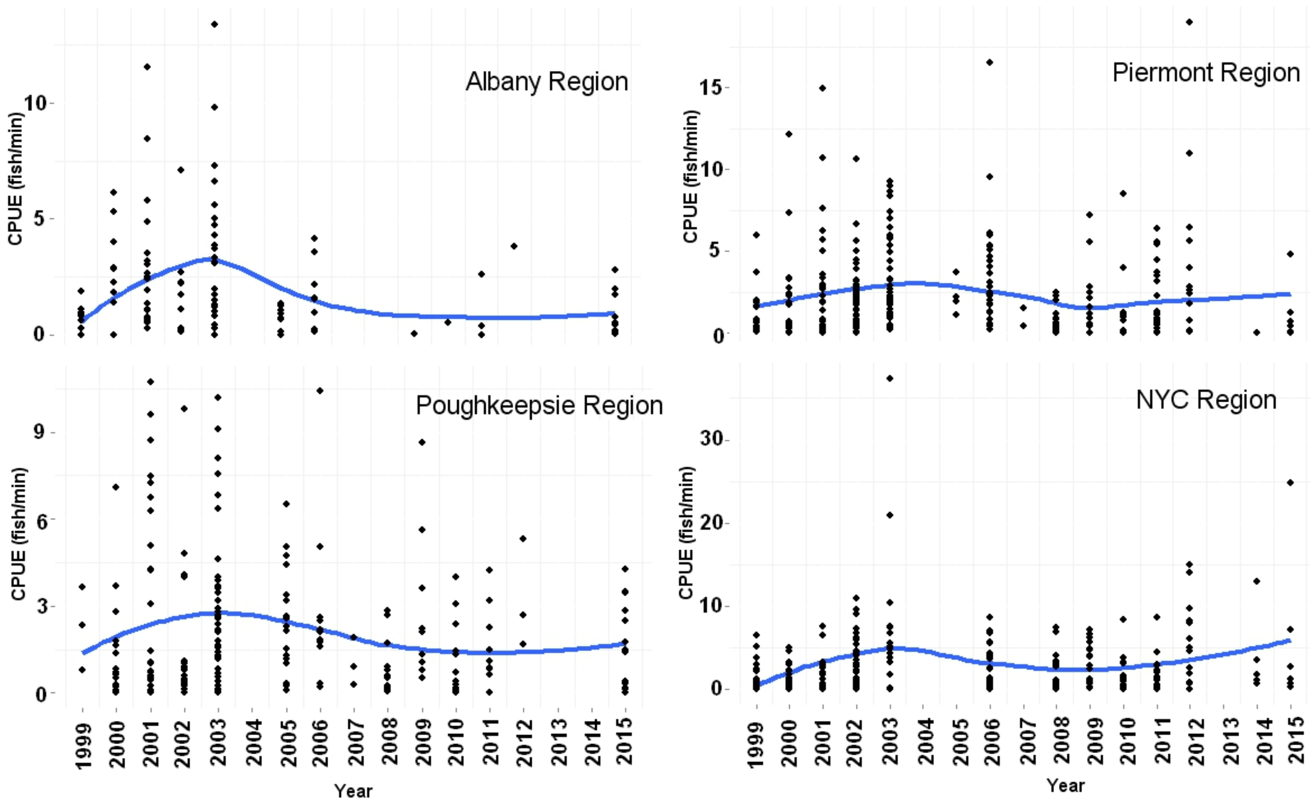


Figure 5. Temporal trends of dominant fish abundance differ in the four different regions (Albany, Poughkeepsie, Piermont, and New York City) on the Hudson River Estuary from 1999-2015. The blue line is a locally weighted polynomial regression (LOESS) curve fit to the CPUE values for each year within each region. The Piermont and NYC have overall higher CPUE throughout the entire survey period. The Albany and Poughkeepsie regions have similar patterns with peak CPUE in 2003 and much lower CPUE after 2006. The Piermont region has two peaks in abundance in 2003 and 2012, while the NYC region has peak abundances in 2003, 2012, and 2015. Note that the y-axis scales in each of the regional subplots are different in order to better illustrate the temporal trends.

The abundances of dominant fish and crab species in each geographic region exhibited distinct patterns. White perch abundance (as measured by mean annual CPUE) was highest in different years regionally (2000 in Albany, 2006 in Poughkeepsie, 2003 in Piermont, and 2002 in NYC). After 2006, white perch abundance declined in all four regions, with the partial exception of the Albany and Piermont regions, where it showed a small increase in 2015. Hogchokers had moderately high abundances in NYC and Poughkeepsie in 2003, but showed an increase in abundance in all four regions after 2008. Atlantic tomcod began and ended the time series with relatively high CPUE values (in 1999 and 2015), but showed a decrease in CPUE between 2005 and 2009 in all four geographic regions. Weakfish followed similar patterns to the Atlantic tomcod in both the NYC and Piermont Regions for the entire time series. All other common species peaked in abundance between 2003 and 2005 and thereafter declined for the remaining years, with the exception of bullheads and white catfish in the Albany Region in 2011 and 2012, which each had a single year of modestly higher CPUE (Figure 6). Bay anchovy exhibited a temporal abundance pattern different than all other species in the NYC region, and exactly opposite that of the Atlantic tomcod and weakfish, with relatively low abundance at the beginning and end of the study period, and relatively high abundance in 2009 when all other species except hogchokers had low relative abundances. Hogchokers, Atlantic tomcod, and weakfish were responsible for the second peak in total CPUE between 2011-2013. All other species were responsible for the first peak between 2001 and 2003 (Figure 7).

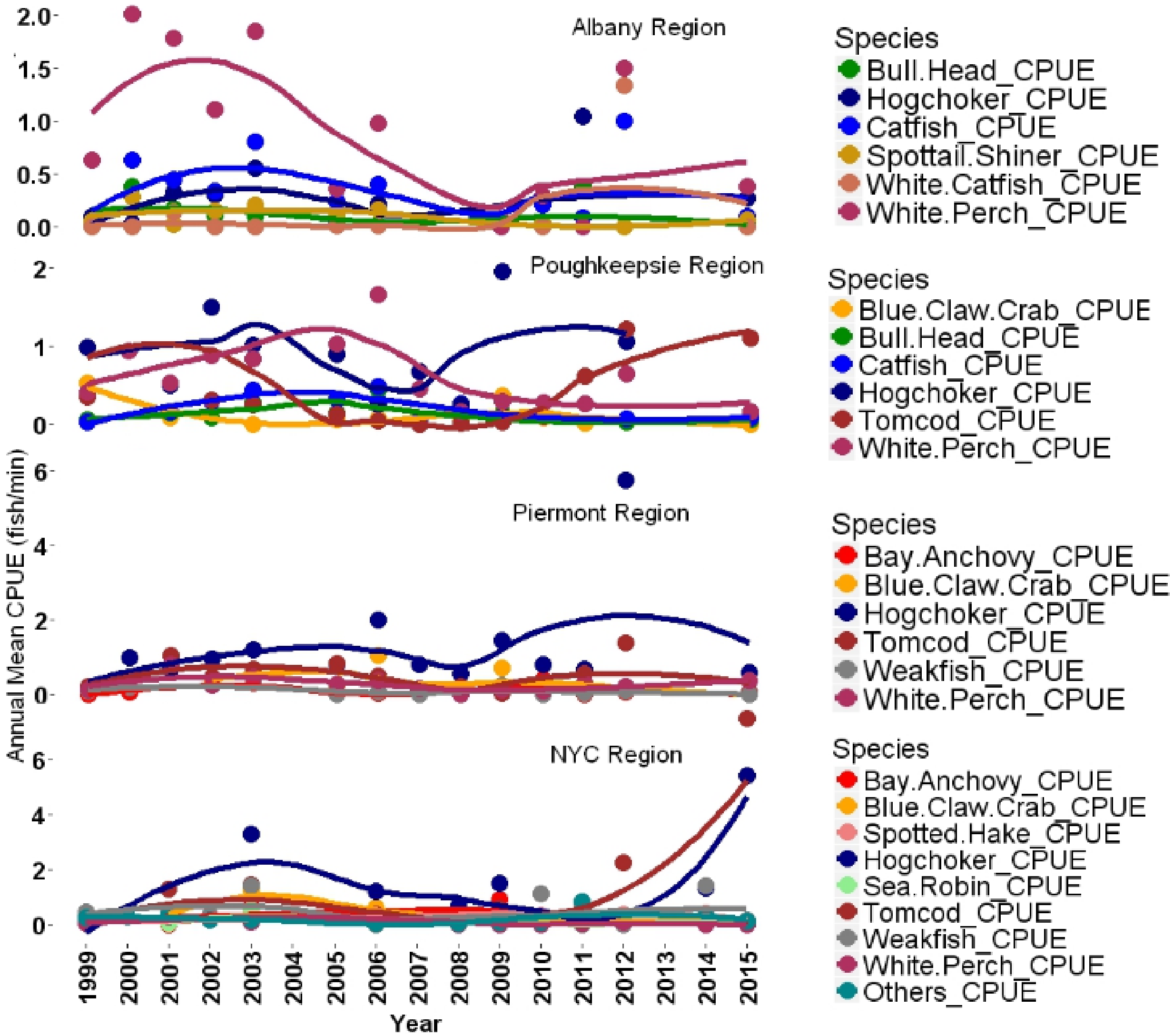


Figure 7. Temporal trends in the dominant fish and crab species abundance exhibit different patterns in four regions (Albany, Poughkeepsie, Piermont, and New York City) on the Hudson River Estuary from 1999-2015. Atlantic tomcod, hogchoker, weakfish, and channel catfish increase in abundance after 2009 in all regions, whereas all other species decline after 2003, with the exception of white perch in the Poughkeepsie region which peaks in 2006. Note, species change in each region but colors representing species are are consistent throughout all sub-panels, the y-axes ranges on each subplot are different to maintain clear temporal patterns, dots represent the annual mean value, and lines are a LOESS model for each species.

Seasonal Variations in Fish and Crab Abundance - There were no clear seasonal patterns in the abundance of the dominant species for the estuary as a whole. However, there were distinct variations between months in the Poughkeepsie region (Figure 8), with highest mean CPUE in April (2.4+/- 2.4 fish min^{-1}) and October (2.5 +/- 2.4 fish min^{-1}), and the lowest in July (1.2 +/- 1.2 fish min^{-1}).

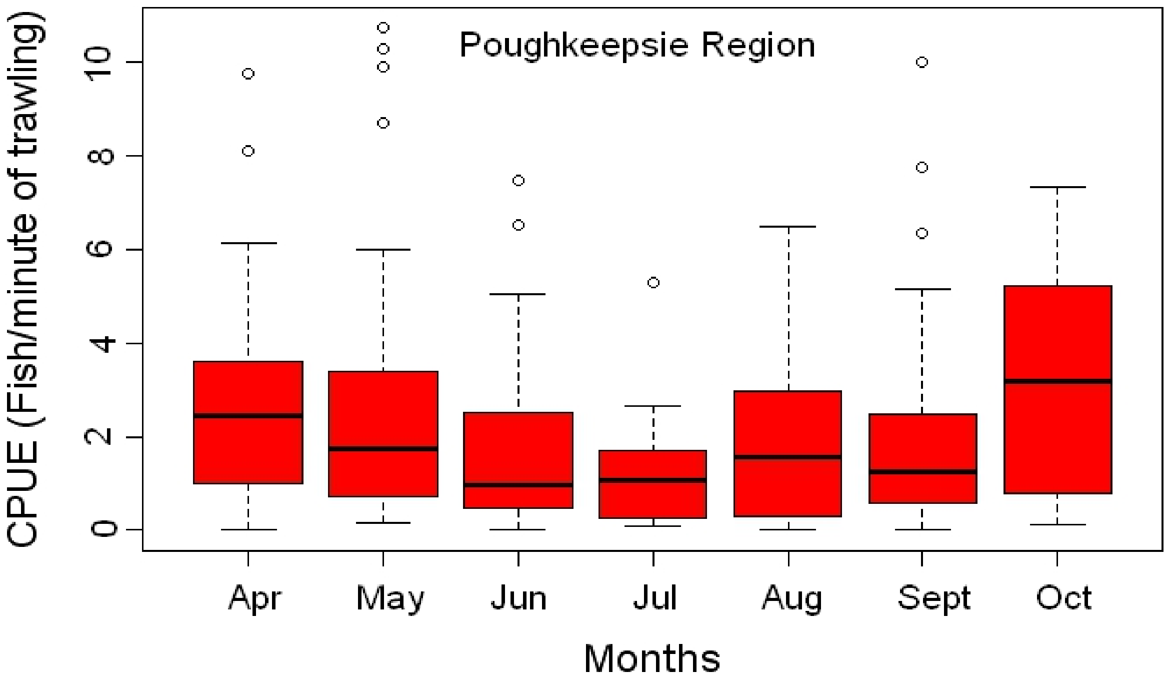


Figure 8. Seasonal patterns in fish abundance of dominant species in the Poughkeepsie region of the Hudson River Estuary from 1999-2015 show higher catch per unit effort (CPUE) in April and October, and lowest CPUE in July. Black horizontal line represents the yearly median CPUE value, bottom and top of the boxes represent the 1st and 3rd quantiles, whiskers represent the 1st and 3rd quantiles +/- 1.5 times the interquartile range.

There some observable seasonal trends in the abundance of individual species within the estuary as a whole and in each of the four regions. Abundances were higher in spring (April, May, and June) than in summer or fall for white perch, Atlantic tomcod, and spotted hake. Hogchokers maintained a relatively stable abundance throughout the year. Bay anchovy, blue claw crab, and weakfish increased in the fall months (September and October) with peaks in October for all three of these species (Figure 9).

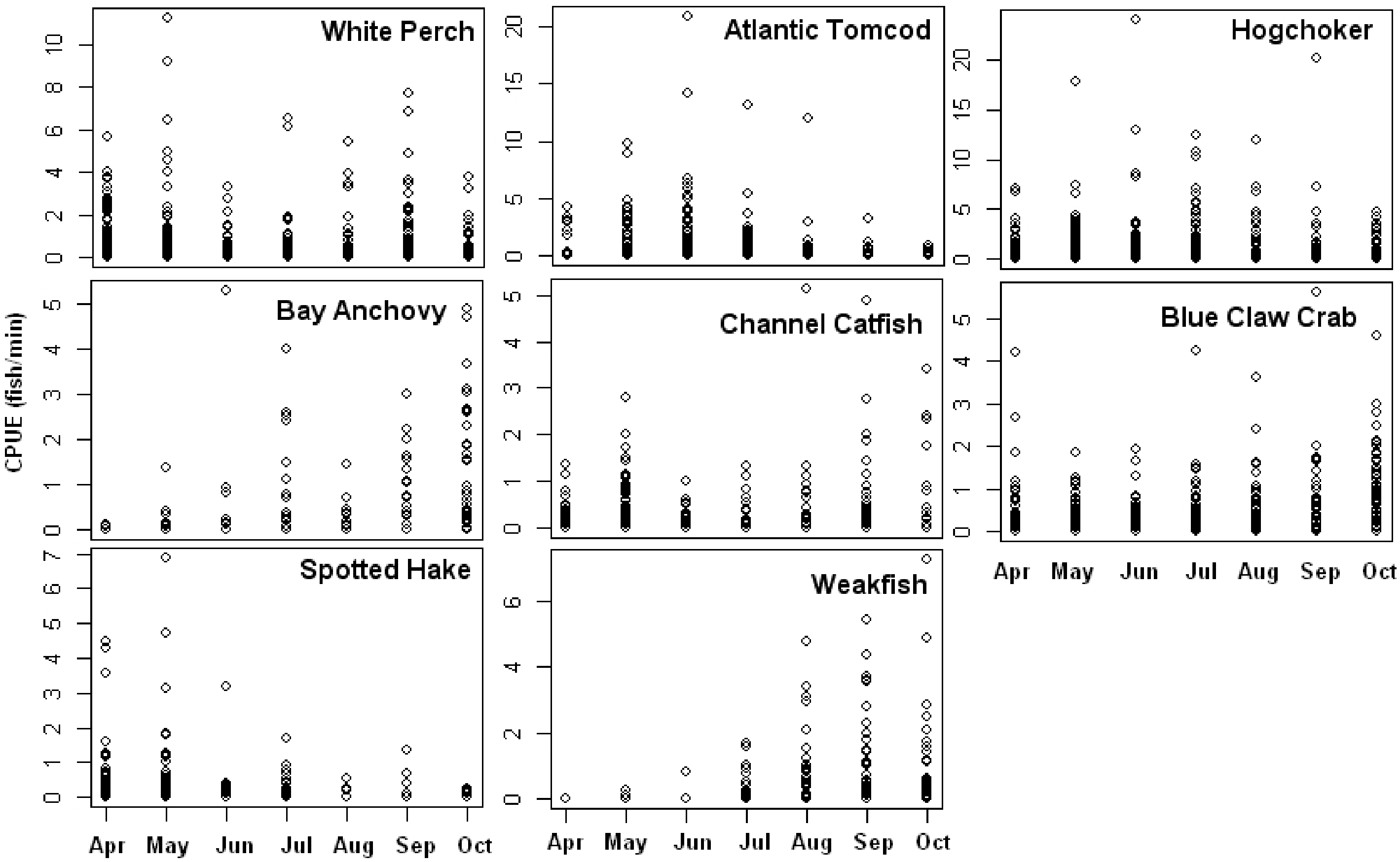


Figure 9. The seasonal variations in fish abundance of eight species in the Hudson River Estuary from 1999-2015, show different seasonal trends in each species. Bay anchovy, channel catfish, and weakfish increase in catch per unit effort (CPUE) throughout the year. Atlantic tomcod decrease in abundance throughout the year. White perch, blue claw crab, hogchoker, and spotted hake exhibit variability in the spring and fall versus summer months. The axis ranges vary in subplots to better show temporal trends in each species.

Seasonal abundance patterns (as measured by the differences among the four regional abundances) are observable in blue claw crab, hogchoker, Atlantic tomcod, and white perch populations. Blue crabs are present throughout the year in the Albany Region, but compose less than 1% of the total CPUE for the area. In the other three regions (Poughkeepsie, Piermont, and NYC), blue crabs are present in every month of the year but peak in CPUE in a fall month (September or October) depending on the region. They are always more abundant downriver than upriver, however, they are not always more abundant in the Piermont or NYC Regions. Specifically, in the spring (April, May, June), they are more abundant in Piermont (0.4 +/- 0.6 fish min^{-1}) than in NYC (0.2 +/- 0.4 fish min^{-1}). In the summer (July and August), they are equally distributed in the NYC Region (0.38 +/- 0.5 fish min^{-1}) and the Piermont Region (0.4 +/- 0.7 fish min^{-1}). And in the fall, they increase in abundance in the NYC Region (0.7 +/- 1.0 fish min^{-1}) when compared to the Piermont Region (0.6 +/- 0.8 fish min^{-1}) (Figure 10).

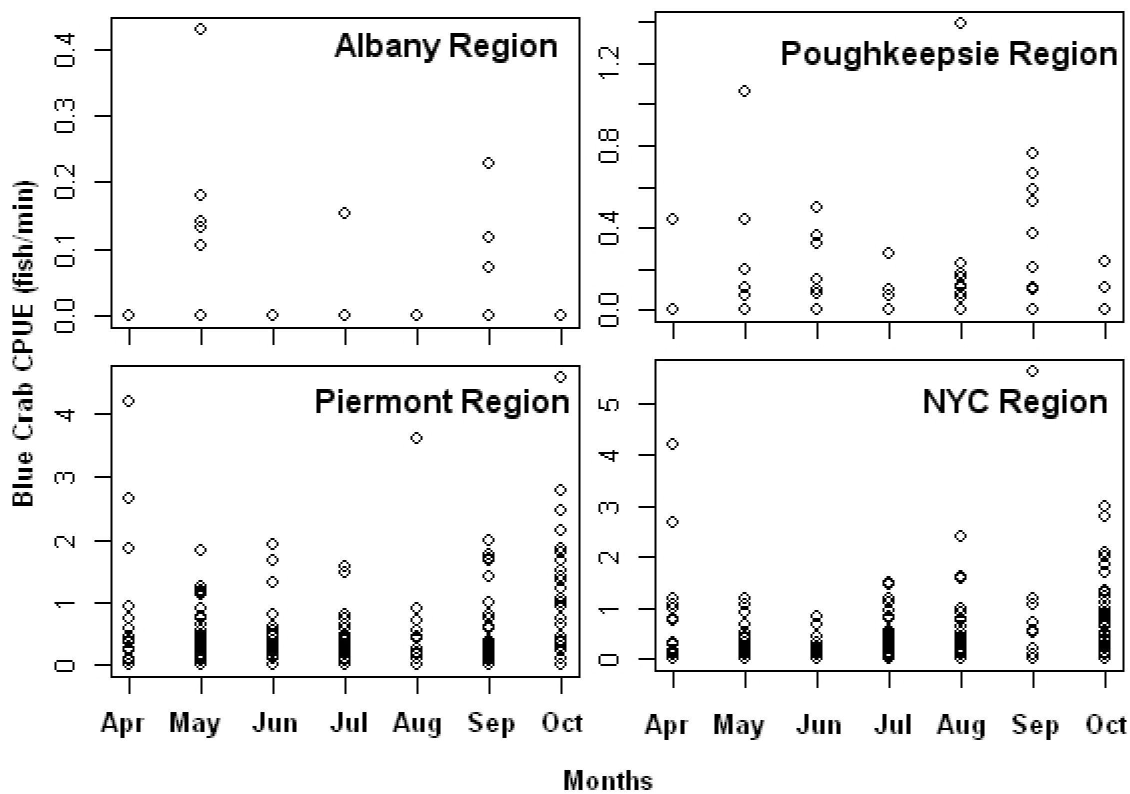


Figure 10. Blue claw crab (*Callinus sapidus)* abundance varies seasonally in four different regions (Albany, Poughkeepsie, Piermont, and New York City (NYC) of the Hudson River Estuary from 1999-2015, with different trends in each region, but an overall higher CPUE in Piermont and NYC regions than Albany and Poughkeepsie regions. The y axis in each subplot are different to more clearly show temporal trends.

Hogchokers were also present in all months of the year in all regions on the HRE, and exhibited seasonal migration patterns between regions. Their abundance was much higher in the spring (0.8 +/- 1.1 fish min^{-1}) and fall (1.1 +/- 1.7 fish min^{-1}) in the Poughkeepsie Region, and declined in the summer months (0.4 +/- 0.8 fish min^{-1}). In the down river regions, however, the opposite was true, with greater abundances in the summer in both the Piermont (1.5 +/- 2.5 fish min^{-1}) and NYC Regions (1.1 +/- 2.3 fish min^{-1}), than spring in Piermont (1.0 +/-2.0 fish min^{-1}) and NYC (0.9+/- 2.1 fish min^{-1}) or fall months in Piermont (0.7 +/- 0.9 fish min^{-1}) and NYC Regions (0.7 +/-2.7 fish min^{-1}) (Figure 11).

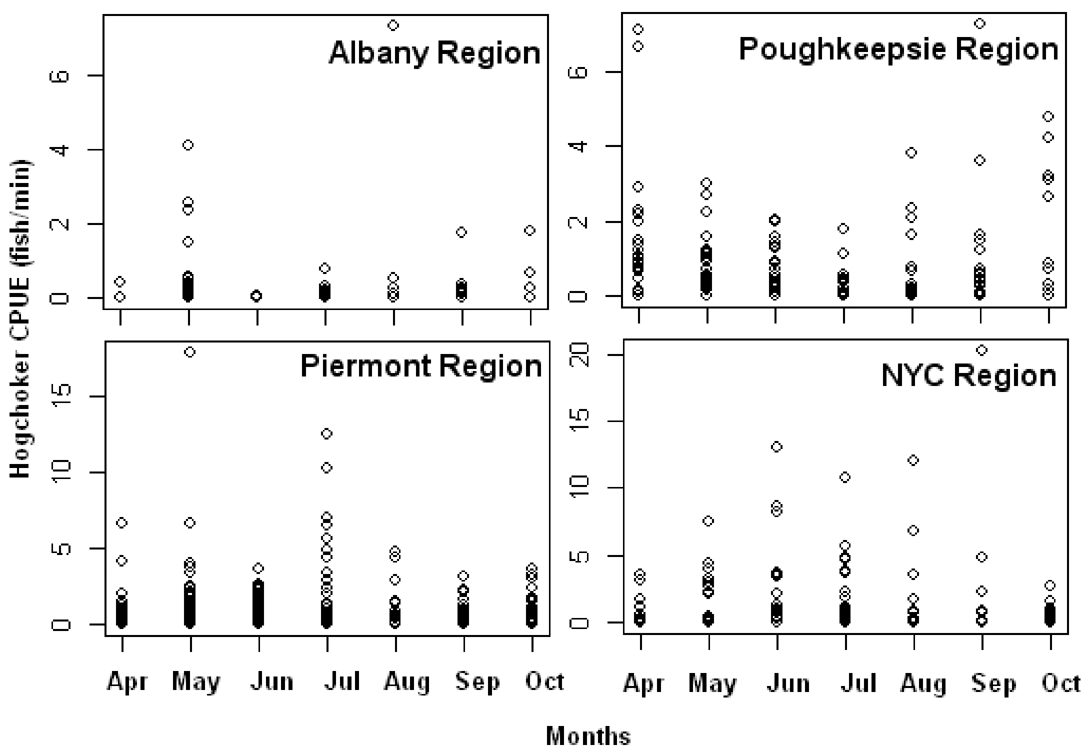


Figure 11. Seasonal abundance of hogchokers (*Trinectes maculatus)* in four different regions (Albany, Poughkeepsie, Piermont, and New York City (NYC) of the Hudson River Estuary from 1999-2015 show different seasonal trends in each region. Hogchokers are abundant in the upper estuary (Albany and Poughkeepsie regions) in the spring and fall, with a summer migration to the lower estuary (Piermont and NYC regions). The y axis in each subplot are on a different scale to best demonstrate temporal trends.

Atlantic tomcod exhibited the same abundance patterns in every region where they are found. They were not frequently found in the Albany Region, although they did appear there occasionally in spring and summer. They were found abundantly in late spring and early summer throughout the other three regions (Poughkeepsie, Piermont, and NYC), with peak CPUE values in June, and lower CPUE in late summer and fall (Figure 12).

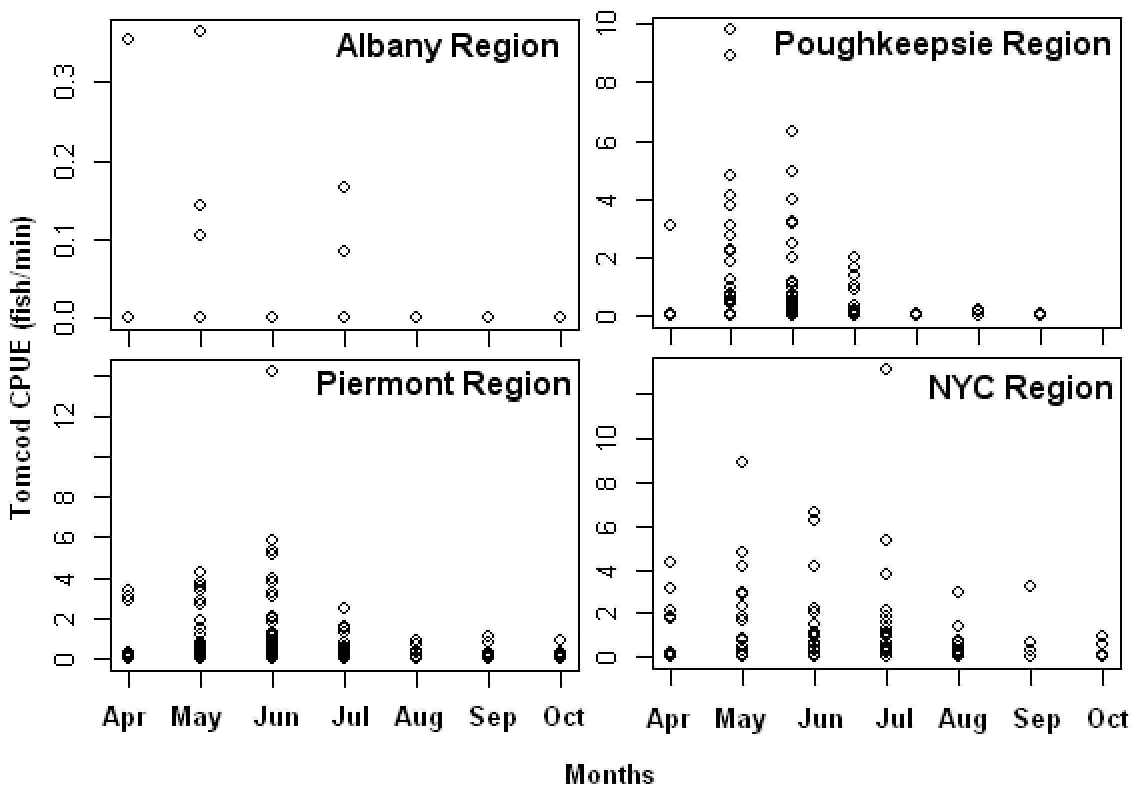


Figure 12. Seasonal abundance of Atlantic tomcod (*Trinectes maculatus)* in four different regions (Albany, Poughkeepsie, Piermont, and New York City (NYC) of the Hudson River Estuary from 1999-2015 show different trends in each region. Tomcod catch per unit effort (CPUE) is highest in the late spring and summer months in all four regions. The y axis in each subplot are on a different scale to best illustrate temporal trends.

White perch were found in all four regions of the HRE, throughout the year. They exhibited different seasonal patterns of abundance in each region, but had consistently higher CPUE in April (1.4 +/- 1.4 fish min^{-1} for all four regions combined) than any other month of the year. The abundance of white perch in Albany and Piermont was variable in the other seasons, with no clear patterns. However, near Poughkeepsie and NYC, they declined in CPUE after the April maximum and remained relatively low for the remainder of the year (Figure 13).

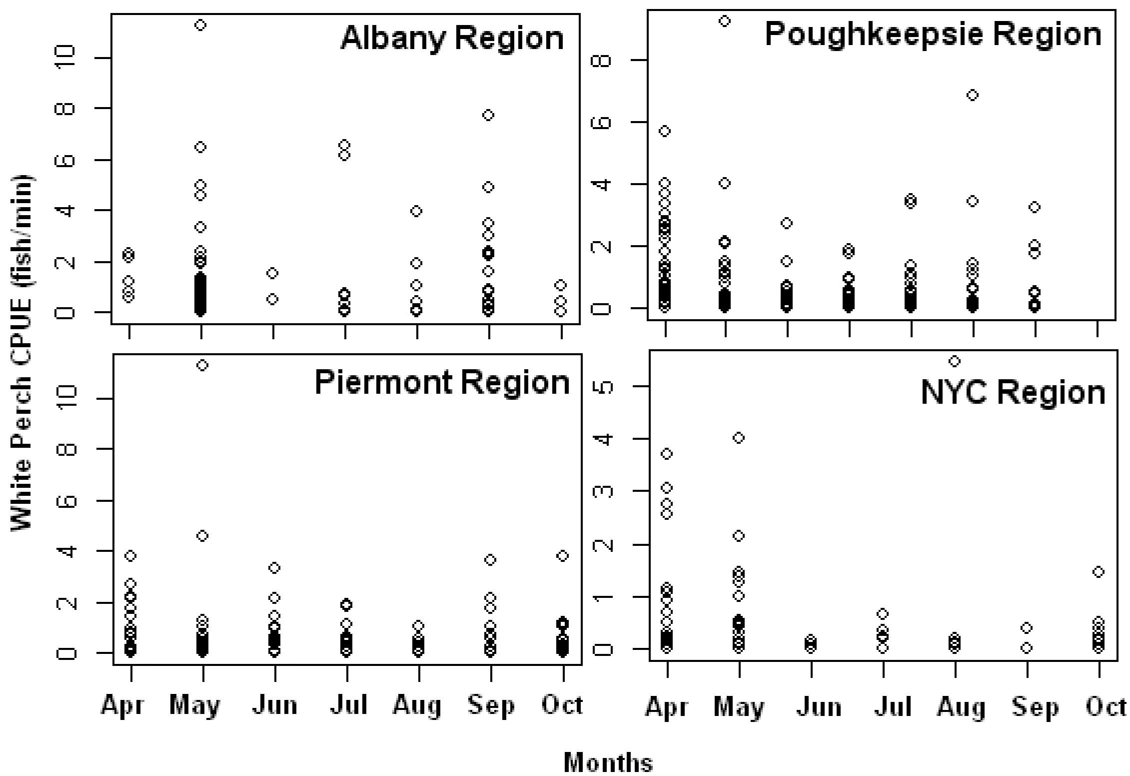


Figure 13. Seasonal abundance of white perch (*Morone americana)* in four different regions (Albany, Poughkeepsie, Piermont, and New York City (NYC) of the Hudson River Estuary from 1999-2015 exhibit different trends in each region. White perch abundance is highest in April in all regions and variable throughout the other months. The y axis in each subplot are on a different scale to best demonstrate temporal trends.

Variations in Fish and Crab abundance with Environmental Variables - When considering the HRE as a whole, local environmental parameters, such as dissolved oxygen, salinity, turbidity, and water temperature had some observable patterns with abundance of the dominant species (Figure 14). The highest abundances (as measured by CPUE in fish min^{-1}) were between 6-8 mg l^{-1} dissolved oxygen, however, fish and crab were still caught at relatively high CPUE within the entire range of dissolved oxygen levels measured in the HRE (3-14 mg l^{-1}). The highest abundance of fish were caught between 8-13 ppt salinity, however, there were relatively high CPUE values at the full range of salinity values recorded on the HRE in this data series (0-24 ppt). Turbidity values ranged from 0.17 to 449.5 NTU in this data series, with 95% of CPUE values falling below 106.9 NTU. Fish abundance varied with water temperatures, with the highest CPUE values between 19-22 degrees C, but relatively high CPUE values recorded throughout the entire water temperature range (4-28 degrees C) (Figure 14).

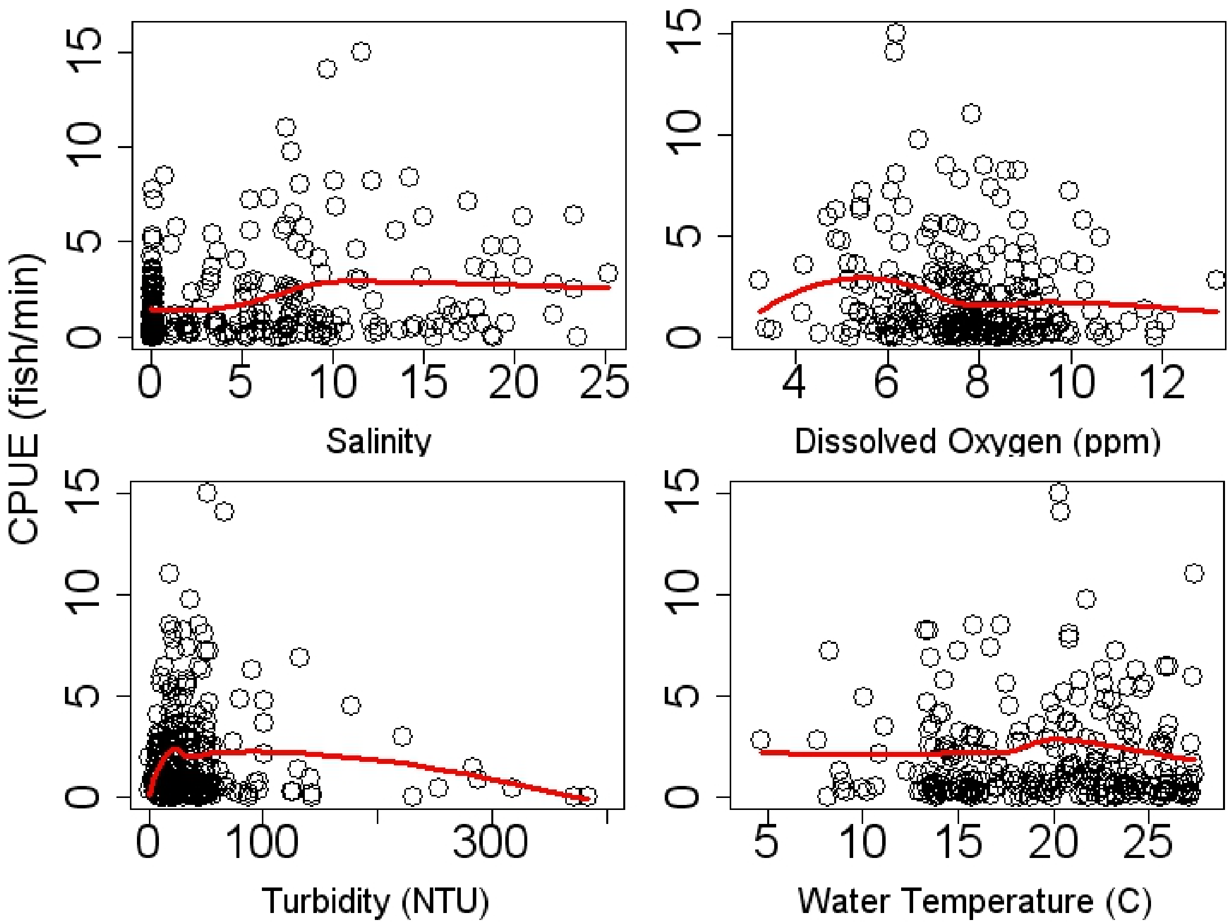


Figure 14. Dominant fish and crab species abundance vary with dissolved oxygen (mg l^{-1}), salinity (ppt), turbidity (NTU), and water temperature (ºC) in the Hudson River Estuary from 1999-2015, however catch per unit effort (CPUE) remains relatively high across a very wide range of each environmental parameter.. Red lines are the locally weighted polynomial regression (LOESS) model for daily CPUE and each daily mean environmental parameter.

There were only four species caught in all regions of the HRE (Albany, Poughkeepsie, Piermont, and NYC). The white perch, hogchoker, Atlantic tomcod, and blue crab were the most ubiquitous species on the HRE and were present in a wide range of environmental conditions (salinity, turbidity, water temperature, and dissolved oxygen). These four species were unique to the HRE fish and crab community assemblage because they were found along the entire length of the estuary in an extremely wide variety of environmental conditions. There were some interesting similarities and differences between these species and their regional presence or absence as environmental conditions vary (presence and analysis includes trawl, seine, and fish trap data). The white perch inhabit the most restricted salinity range of the four species (2.3 +/- 3.8 ppt). Even though salinities can reach above 30 ppt in the NYC region, the maximum salinity where this species were present in that region was only 17.0 ppt. Similarly, while water temperatures ranged from 4.2 to 33.6 ºC in the NYC Region, white perch were only present in the NYC region between 9.2 and 20.8 ºC. White perch were also present in water with higher dissolved oxygen (8.3 +/-1.8 mg l^{-1}) compared to Atlantic tomcod (7.7 +/- 1.7 mg l^{-1}), blue crab (7.8 +/- 1.3 mg l^{-1}), or hogchokers (7.9 +/- 1.8 mg l^{-1}). White perch were present in water with the lowest mean turbidity compared to the four other species (29.2 +/- 32.1 NTU), but were present with much greater frequency in the Albany region at higher turbidity values (> 45 NTU).

Hogchoker were the most robust of these four species, inhabiting the widest range of salinity values (0-29.3 ppt), the highest mean temperature (17.6 +/- 5.8 ºC), and lowest dissolved oxygen levels (7.2 +/- 1.7 mg l^{-1}) in the NYC region compared to the other species. Atlantic tomcod and blue crab exhibited very similar presence and absence patterns in relation to the four environmental parameters in each region, with the exception that blue crab were generally more abundant in the Albany Region in all conditions than Atlantic tomcod. Both species were present in the NYC Region when temperatures ranged from 4.8 to 26.0 ºC, dissolved oxygen ranged from 4.9 to 10.9 mg l^{-1} and the salinity range was greater than white perch but less than hogchokers. Both inhabited the NYC Region with lower mean water temperature values (tomcod = 15.8 +/- 6.0 ºC and crab = 16.2 +/- 5.4 ºC) when compared to their presence in the other four regions. Both Atlantic tomcod and blue claw crab were present with increasing turbidity mean values and ranges when considered regionally from north to south.

Dissolved oxygen, temperature, and turbidity predicted white perch, Atlantic tomcod, blue crab, and hogchoker presence and absence differently by species(as determined by a generalized linear model). For Atlantic tomcod, hogchoker, and blue crab the probability of presence increased with higher salinity values, warmer water temperatures, and decreased dissolved oxygen levels over the entire estuary. For white perch, the opposite trends were predicted, with higher probability of presence with lower salinity, cooler water temperatures, and increased dissolved oxygen levels when looking at the entire estuary (Figure 15 and Table 7). However, when the HRE was split by region there were differences for presence predicted (by generalized linear model) for only the white perch, In the Albany and Pougheepsie regions, increasing dissolved oxygen levels were predictors of lower white perch presence, conversely in the Piermont and NYC Regions the probability of white perch presence increased with increasing dissolved oxygen. Higher temperatures in the Albany and Poughkeepsie Regions were predictors of higher white perch presence, whereas higher temperatures in the Piermont and NYC Regions were predictors of lower white perch presence. Higher turbidity values were predictors of lower white perch presence in all regions except for Albany (Figure 16). It is possible that environmental predictors are interacting, for example dissolved oxygen and water temperature values are likely to impact each other.

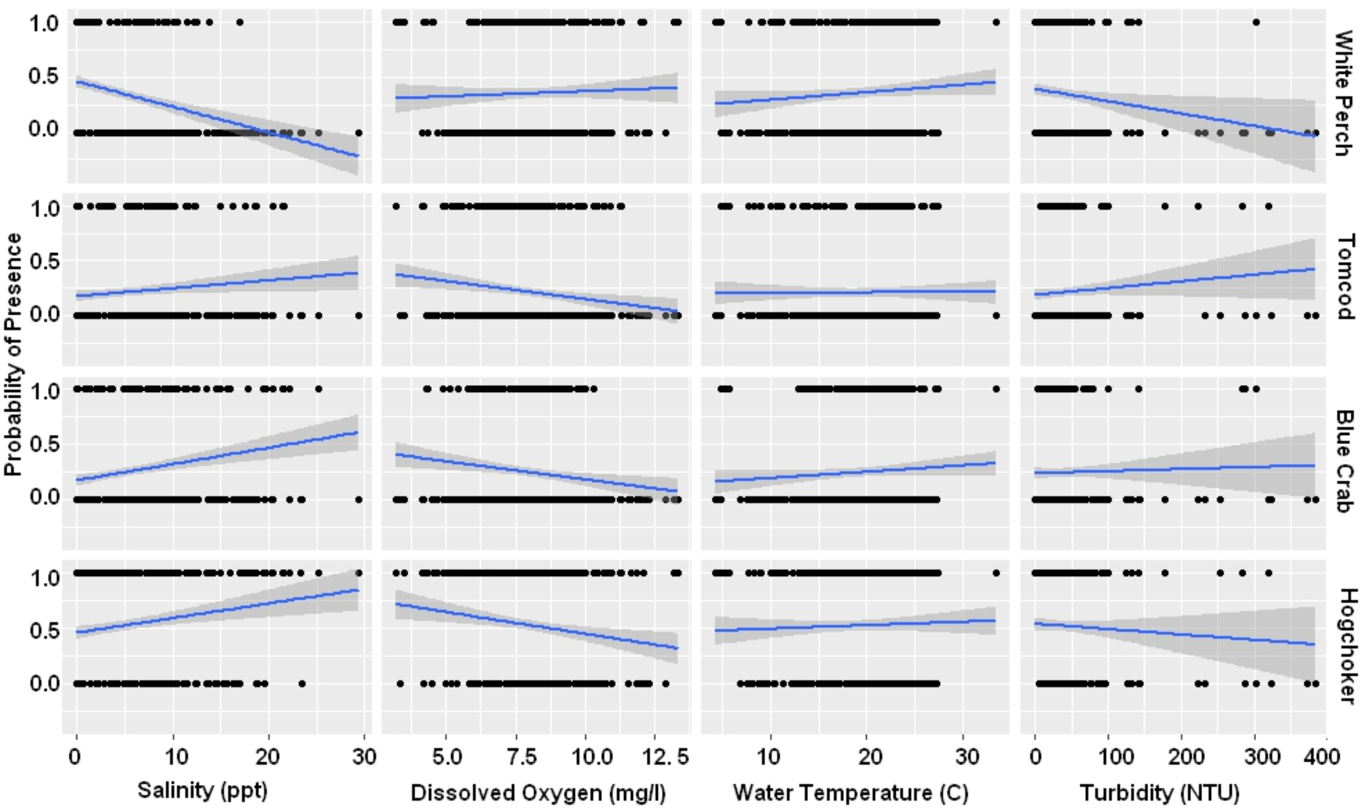
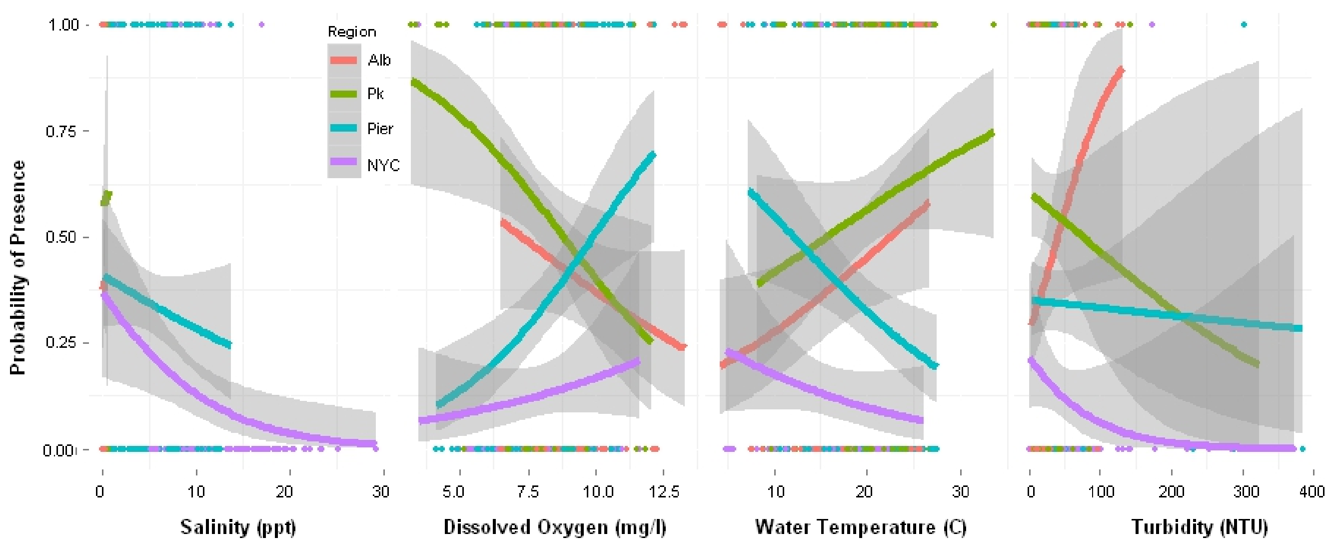


Figure 15. Environmental conditions predict the probability of white perch, Atlantic tomcod, blue crab, and hogchker presence differently by species in the Hudson River Estuary from 1999-2015. Generalized linear model predict presence of these four species in response to salinity in ppt, dissolved oxygen in mg l^{-1}, temperature in ºC, and turbidity in NTU with tomcod, blue crab, and hogchoker exhibiting similar patterns while white perch contrast with all variables except water temperature. The blue lines are the probability of presence of each species at different environmental parameter values, and the gray bands are the standard error.



Species	Environmental Parameter	Coefficients: intercept	Coefficients: value	Deviance	Degrees of Freedom	AIC

White perch	Salinity	-0.01897	-0.14685	663.7	508	610.3
	Turbidity	-0.330678	-0.007623	663.7	508	659.4
	D.O.	-0.98664	0.04893	663.7	508	666.9
	Water Temp.	-1.10630	0.02785	663.7	508	664.9
Hogchoker	Salinity	-0.03587	0.04188	698.3	505	694.8
	Turbidity	0.26939	-0.00307	698.3	505	700
	D.O.	1.2857	-0.1377	698.3	505	694.9
	Water Temp.	0.01440	0.00777	698.3	505	702.1
Blue Crab	Salinity	-1.51232	0.07864	574.1	508	555
	Turbidity	-1.145906	0.001492	574.1	508	577.6
	D.O.	0.3373	-0.1860	574.1	508	555.3
	Water Temp.	-1.1653455	0.0005895	574.1	508	564.6
Tomcod	Salinity	-1.33065	0.03484	560.6	508	560.3
	Turbidity	-1.230140	0.002032	560.6	508	563.7
	D.O.	0.3373	-0.1860	560.6	508	555.3
	Water Temp.	-1.1653455	0.0005895	560.6	508	564.6

Climate indices, specifically the North Atlantic Oscillation (NAO) from December-March and winter water temperatures, show some observable patterns with CPUE of the dominant species. In the upriver regions (Albany and Poughkeepsie), higher CPUE was associated with negative NAO values, whereas in the Piermont and NYC regions high CPUE was associated with both positive and negative NAO values. Winter water temperatures did not show any patterns associated with CPUE values when considered regionally (Figure 17).

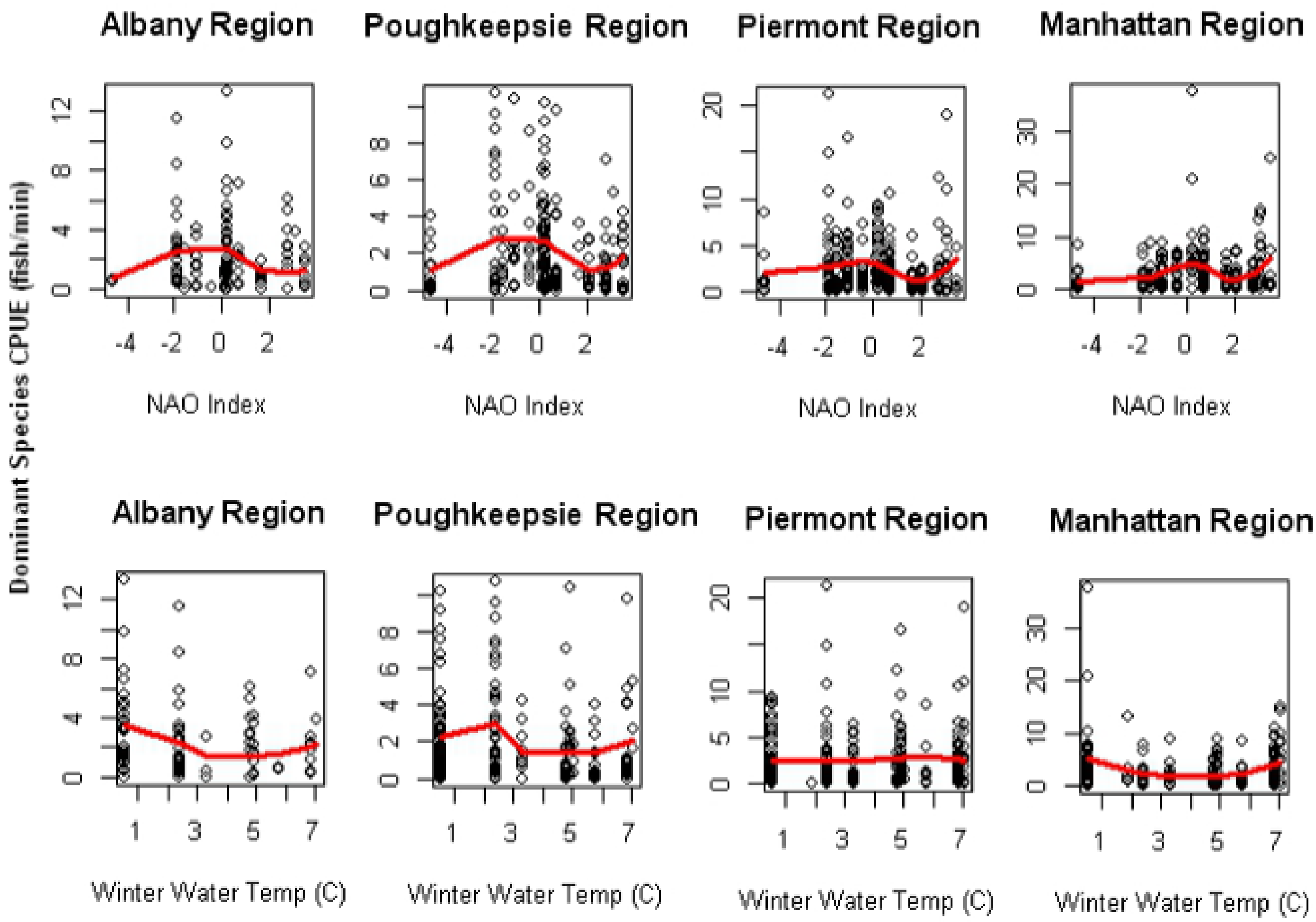


Figure 17. Abundance of dominant fish and crab species in each of four geographic regions on the Hudson River Estuary (Albany, Poughkeepsie, Piermont, and New York City) vary with mean winter North Atlantic Oscillation (NAO) Index and mean winter water temperatures in degrees Celcius from 1999-2015. Higher catch per unit effort (CPUE) occur during negative NAO values than positive in Albany and Poughkeepsie regions, but not Piermont or New York City regions. CPUE is variable across winter water temperatures with no clear trends in any of the four regions. Red lines are the locally weighted polynomial regression (LOESS) model curves. Note the y-axes varies between sub-panels to better illustrate CPUE values in each region.

Trawling occurred during a wide range of discharge rates, from 71 $m^3 s^{-1}$ to 2832 $m^3 s^{-1}$ with 84.6% of trawls occurring below 1133 $m^3 s^{-1}$. During periods of mean monthly discharge rates above the “high discharge” value of 740 $m^3 s^{-1}$, there was a lower mean CPUE compared with periods of mean monthly discharge rates below the “high discharge” value. The abundance of fish during low discharge periods had a mean CPUE of 1.7 fish min^{-1} and 3 fish min^{-1} during high discharge times in this region. In all other regions, the highest CPUE values were recorded during low discharge periods but the difference in mean CPUE values were close (Figure 18). However, the weighted latitude during high discharge months was higher (41.28 °N) than during low discharge months (40.85 °N), indicating there was not a downriver shift of fish during months with high discharge rates. On an annual time scale, there was very little difference in weighted latitudes during high discharge years (40.86 °N) and low discharge years (40.83 °N).

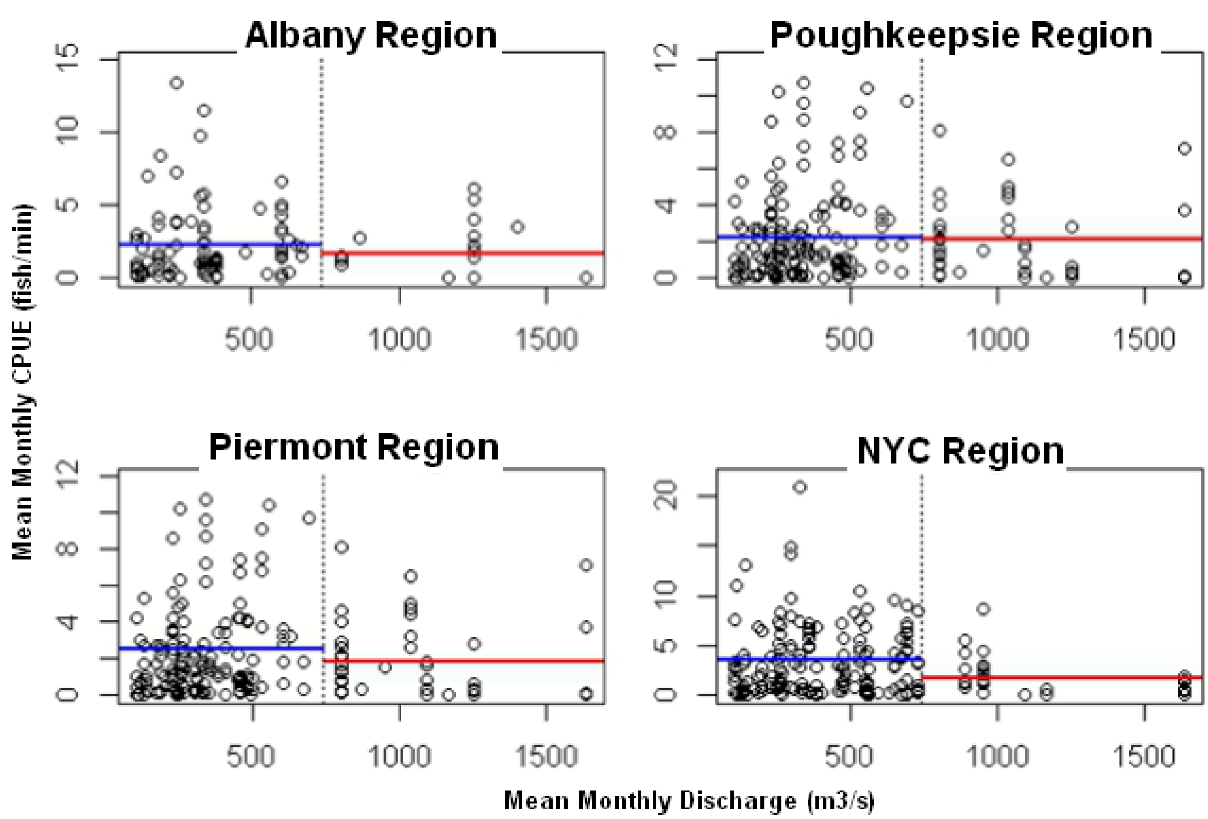


Figure 18. Abundance of dominant fish species in each of four regions (Albany, Poughkeepsie, Piermont, and New York City (NYC) vary with mean monthly discharge rates in $m^3 s^{-1}$ of freshwater into the Hudson River Estuary from 1999-2015. Catch per unit effort (CPUE) is lower during high discharge times for all regions but most observable in the NYC region. Vertical dotted line at 740 m^3/s discharge delineates low and high discharge rates, blue and red horizontal lines represent mean CPUE during low and high discharge months respectively. The number of monthly mean trawls in each regional subplot are Albany = 111, Poughkeepsie = 202, Piermont = 267, and NYC = 220.

Discussion:

Fish abundance and composition in the Hudson River Estuary (HRE) varied over the 16 year time period, from 1999- 2015. Past studies on the HRE have also found that the species composition of the fish community and the abundances of individual species have changed over past decades and also in response to different environmental and biological conditions (O'Conner *et al.,* 2012; Strayer *et al.,* 2014). Most other studies of fish abundance and distribution on the HRE utilize a single dataset, the Annual Year Class Report compiled by a number of utilities companies (ASA, 2010).

Seaby and Henderson (2006) found that ten species of Hudson River fish declined from 1985 to 2005. This study also found that three of these same species (white perch, spottail shiner, and bay anchovy) were in decline until 2005, and then continued to decrease in abundance until 2015. However, four of these species (hogchoker, Atlantic tomcod, weakfish, and white catfish) declined until 2005, but then increased in abundance after 2009 and peaked between 2012-2015.

Patterns in the HRE fish community have been examined by looking at individual species (Norris and Hawkins, 2000) and at the entire fish assemblage (Daniels *et al.,* 2002). This study found that examining the total HRE fish assemblage was not a reliable indicator of the underlying changes in the biological community. Individual species had different abundance patterns over the entire study period, both seasonally, and regionally. For example the two peaks in fish abundance seen in the CPUE of all dominant species were the result of two distinct trends between hogchokers, Atlantic tomcod, and weakfish versus all other species, which contributed to the two peaks in CPUE very differently during each of those years. Hogchokers had a relatively high and stable CPUE across all months, and because this species dominates trawl catches both temporally and spatially, they are responsible for insulating the seasonal trends against differences when examining the fish community as a whole. In addition, there are two groups of fish and crab which respond asynchronously with the seasons (peaking in the spring vs fall) in terms of abundance which mask the overall seasonal pattern. White perch, Atlantic tomcod, spotted hake, and channel catfish exhibit higher abundances in the spring whereas, bay anchovy, weakfish, and blue claw crab exhibit higher abundances in the fall months.

The HRE fish community have been found to respond to both environmental and biological conditions differently in upriver (freshwater) versus downriver (saltwater) regions of the HRE. Hurst and Conover (2002) demonstrated this difference in responses to fresh vs saltwater portions of the estuary in larval striped bass survival with the interactions between salinity ranges and overwintering temperatures. They found that during low winter temperatures (below 1ºC), striped bass had better rates of survival at mid salinity ranges (15 ppt) than either fresh (0ppt) or saline waters (25ppt). Similarly, a regional fish response to the introduction of the freshwater zebra mussel (*Dreissena polymorpha*), in the HRE has been well documented (Strayer *et al.,* 2004; Strayer, 2006; and Strayer *et al.,* 2014). Some fish species declined in number and shifted downriver after the invasion, where as other species increased in number and their population center shifted upriver as a result of the bivalve (Strayer *et al.,* 2004). This study also found that there were regional differences in both the whole fish community abundance and in individual species, which may be related to the complex interactions between environmental conditions (such as salinity and temperature), or as a response to biological conditions that were not measured.

The seasonal trends apparent among blue crab, hogchoker, Atlantic tomcod, and white perch are evidence of the timing of life history events associated with particular habitat preferences, such as mating and spawning migrations, common among many estuarine species (Hagan and Able, 2003). In this study blue crab abundances in different regions of the HRE seasonally suggested a migration pattern upriver from the Piermont region in the spring down to NYC for the summer, and then an increase in abundance in Piermont and Poughkeepsie regions in the fall again. This supports other findings on blue crabs with the female population migrating to warmer more saline waters for spawning in July and August (Churchill, 1919; Stehlik, 2004). Hogchoker migration patterns observed in this study (from freshwater upriver regions in spring and fall to downriver saline regions in the summer) are consistent with other published literature (Curti, 2005; Dovel, 1969; Peterson, 1996). This migration pattern may be related to salinity limiting juvenile hogchoker activity and decreasing metabolic rates during extremely cold temperatures in the winter (Peterson-Curtis, 1997).

Unlike with the other species, the Atlantic tomcod's spawning behavior is not evident in this study because it primarily occurs during the winter to early spring months (December to March) when trawling was not conducted (Dew, 1994). Atlantic tomcod are residents of the HRE year-round (Dew, 1994) so, this could either be an actual increase in abundance between the months of May-July in all regions of the HRE or may be evidence of when this short-lived species (primarily less than 1 year) are large enough to be caught in the trawl's mesh, but not yet fast enough to avoid being caught in the net.

Higher white perch abundance in the spring throughout the estuary is consistent with previous findings (Kraus and Secor, 2004) showing a preference for lower salinity waters during spawning season. Variability throughout the rest of the seasons may be a function of this species being partial migrators, meaning that individual white perch exhibit differential migratory behaviors within a single population (Kerr, 2009).

It has been shown in other studies that fish abundance on the HRE is correlated with climatic conditions, specifically freshwater discharge into the estuary and winter North Atlantic Oscillation (NAO) index (O'Conner *et al.,* 2012; Wingate and Secor, 2008). This study also found that these two factors may be associated with higher abundance of fish, however, we found that these climatic conditions have specific regional impacts on the HRE. Freshwater discharge rates were found to influence CPUE only in the NYC region and in none of the other upriver regions. This is consistent with the findings of Wingate and Secor (2008) that the fish community in only the lower Patuxent River of the Chesapeake Bay were impacted by freshwater flow rates. However, freshwater discharge rates that precede sampling by a three to twelve months (rather than at the time of sampling) may have a greater impact on CPUE in the HRE upriver regions (Hurst *et al.*, 2004). Strayer *et al.* (2004) found that consideration of high freshwater flow on an annual scale were correlated with downriver shifts in the population centers of many HRE fish species. However, this study did not find that the center of mass shifted downriver during high freshwater flow periods on the monthly or annual time resolution. This suggests that the time window considered for freshwater discharge rates (prior vs. concurrent with fish sampling) and correlation to fish abundance may be an important factor, warranting further analysis. In this study, there was a pattern of higher fish abundance in the upriver regions (Albany and Poughkeepsie) during winters with negative North Atlantic Oscillation (NAO) index, but not the downriver regions (Piermont and NYC). This suggests that changes in local climate conditions may have different impacts on fish abundances on a regional basis, with upriver areas more susceptible to warming winter temperatures.

When considering the dominant HRE fish and crab species together they exhibit high CPUE values across wide ranges of the four measured environmental variables (salinity, turbidity, dissolved oxygen, and water temperature) which reflects the biological community's resilience or adaptations to the extreme variability of an estuarine habitat. There are clearly regional differences among the species present in the four regions (Albany, Poughkeepsie, Piermont, and NYC) of the HRE, as evident by the different dominant species in each of these four regions. However, even among the four most ubiquitous species (white perch, Atlantic tomcod, hogchokers, blue claw crab), found everywhere in the HRE and present over the widest range of environmental conditions, there are still some interesting patterns. For example the temperature, dissolved oxygen, and salinity preference of the white perch by region may leave even this fish, one of the most common and adaptable species in the HRE, susceptible to the impacts of changing climate conditions, as has been shown with other species of the HRE (Limburg and Waldman, 2009; O'Conner, 2010; and Strayer *et al.,* 2014)

Limitations of this study include a small (mouth opening of 7.55 or18.40 m^2) trawl net deployed at slow (5.5 km/hr) speeds which under-samples larger adult fish and faster swimming species which can better avoid capture. The relatively large mesh size (3.8 cm) of the trawl net may also bias away from young-of-the-year or smaller species of fish as they more easily pass through the net and avoid capture. While there is fairly good geographic coverage of the entire HRE over the 16-year study period, there are fewer trawl days in the Albany Region than the other three regions (Poughkeepsie, Piermont, or NYC) which may lead to underestimates of the less common freshwater species. There are differences in the fish species assemblages and percent contributions from each species between the trawl and seine or trap data. This may reflect a bias in the equipment for some species (such as hogchokers with the otter trawl) and habitat preference by some species, such as killifish and sunfish preferring near-shore habitats (Yozzo and Ottman, 2003; McCairns and Fox, 2004)

Examination of the individual fish and crab species and their responses to environmental factors, as well as spatial and temporal trends, was more informative than examining the biological community as a whole. Regional analysis of the biological community and individual species was more instructive than examining the HRE as one larger system, where underlying trends such as seasonal migration patterns, were not evident. Fish and crab species exhibited different abundance patterns seasonally and regionally throughout the HRE from each other. Even among the four most abundant and widely distributed species, there were distinct patterns in their presence/absence responses to environmental parameters. In addition, the biological community responded to local climate conditions, specifically NAO, winter water temperatures, and freshwater discharge, differently in the upper regions (Albany and Poughkeepsie) compared to the lower regions (Piermont and NYC). These findings highlight the complexity and dynamic nature of the entire Hudson River Estuary ecological system over decadal scales.

Chapter 2:

"Spatial and temporal variation in acoustic backscatter from pelagic fish and zooplankton in the Hudson River Estuary from 2013-2015"

Introduction:

The Hudson River watershed is roughly 33,670 square kilometers with a topographical diversity ranging from the Adirondack Mountains to New York City. The river is 507 kilometers long from its headwaters at Lake Tear of the Clouds to the Verrazano Narrows at the Atlantic Ocean, and flows past agricultural, industrial, and urban lands along its path from the mountains to the sea. The watershed supports an incredibly productive ecological system with terrestrial nutrient inputs supporting the base of the riparian food web. The most unique feature of the Hudson is its long estuarine arm with tidal influences reaching 247 kilometers inland to the Federal Dam near Albany (Levinton and Waldman, 2006). Due to the large salinity gradient latitudinally in the estuary, there is great biological diversity over the entire estuarine system.

The Hudson River Estuary (HRE) is a critical habitat for over 200 species of fish and many freshwater and marine zooplankton (O'Conner, 2012). Hudson River fish and zooplankton are part of a complex food web that includes migratory, invasive, endangered, and poorly understood aquatic species. This community is influenced by physical factors such as water temperature, the salinity gradient along the estuary, the alternating direction of water currents, and seasonal shifts in these elements. Different life history strategies among fish and zooplankton result in varying responses to these environmental conditions across the biological assemblage (Pace and Lonsdale, 2006, Limburg *et al.*, 2006). Spatial and temporal patterns in distribution and abundance between Hudson species are important for understanding predator-prey relationships that support the stability of this ecological system (Strayer *et. al,* 2004).

Zooplankton are thought to be a key link between primary production and higher trophic levels in the HRE. The most common zooplankton in the Hudson are cyclopoid, calanoid, and harpacticoid copepods and *Bosmina* cladocerans (Cole, 2012). They are an important food source for young-of-the-year and larval fish (Pace and Lonsdale, 2006). There is large seasonal and geographic variability of zooplankton biomass due to the varying residence time of the Hudson River water (Pace *et al*. 1992; Basu 1996) and predation pressure from fish. Freshwater discharge and the tidal influence from the Atlantic Ocean impact the residence time of water differentially along the HRE (Howarth, 1996).

Zooplankton abundance in the HRE is primarily regulated by advection out of the estuary, with higher freshwater discharge rates resulting in lower overall zooplankton abundance (Pace *et al.* 1992). Late winter and early spring peaks in copepod abundance are seen earliest in low salinity sites in the estuary and proceed seaward as the year progresses (Stepien, 1981). Predation pressure on zooplankton is not well understood in the HRE due to the limited number of studies on the food web dynamics of this area (Pace and Lonsdale, 2006).

The most significant trophic link between zooplankton and the rest of the pelagic food web are small planktivorous fish. Striped bass (*Morone saxatilis)*, bluefish (*Pomatomus saltatrix),* and Atlantic tomcod (*Microgadus tomcod*) are predators that during their juvenile stages exploit zooplankton (Pace and Lonsdale, 2006). Lifelong planktivorous species in the HRE include bay anchovies *(Anchoa mitchilli)*, American shad (*Alosa sapidissima)*, alewife *(Alosa pseudoharengus*), blueback herring *(Alosa aestivalis)*, gizzard shad (*Dorosoma cepedianum*), and Atlantic silversides (*Menidia menidia*) (Grabe, 1996). Bay anchovies have been identified as the primary consumer of copepods and the most important prey item to adult striped bass, bluefish and weakfish in the HRE (Tipton, 2003).

Many fish species change their distribution within the HRE on a seasonal basis or in response to environmental changes. These migration patterns vary greatly between species; for example, the catadromous American eel *(Anguilla rostrata)* arrives from the Sargasso Sea between March and April and then resides in the HRE for 30 years. Most of the anadromous adult striped bass arrive in the Hudson between May and June to spawn before returning to the Atlantic waters, however, many juvenile, yearling, and some adult striped bass overwinter in the lower estuary (Waldman, 2006). Some alewife remain in the estuary year-round, but migrate up tributaries to spawn, while others migrate out of the estuarine system entirely after spawning season (Lake, 1998; Waldman, 2006); and bay anchovies follow pre-spawning, spawning, and post-spawning migration patterns along the length of the estuary (Tipton, 2003).

While some migration paths follow seasonal patterns, there have been dramatic changes in fish distribution due to environmental disruptions in the HRE. There have been many significant changes to the HRE ecosystem over the past 400 years due to anthropogenic alterations including channel dredging, industrial waste dumping, invasive species introduction, species-targeted overfishing, shoreline habitat destruction, watershed urbanization, and climate change impacts (Strayer *et al*. 2014; Daniels, 2004). Recent declines in many signature Hudson River fish populations (Seaby and Henderson, 2008) show that the community is variable. Low dissolved oxygen levels, invasive species, water temperature increases and habitat alteration have had an impact on the abundance and distribution of many species (Seaby and Henderson, 2008). For example, the introduction of zebra mussels to the freshwater reaches of the Hudson has had an enormous impact on fish distribution. Open water pelagic fish species shifted down river from the freshwater areas impacted by the zebra mussel invasion, conversely some, fish species, preferring shallow or shoreline habitats, have moved upriver into the freshwater areas (Strayer *et al.,* 2004). American shad (*Alosa sapidissima)* and striped bass populations have changed over the past 30 years with new fishing regulations, local hydrology change, and climate variability favoring bass but not shad recovery (O'Conner, 2012). Increasing variability in annual freshwater flow has contributed to a detectable downriver shift in fish population centers during wet years (Strayer *et al.,* 2014). These physical and biological factors are leading to declines in fish and zooplankton abundance or changes in their distribution, and are predicted to increase in the future with climate change, watershed alterations, and new conduits for invasive species (Strayer *et al.,* 2014). Fish and zooplankton responses to these changing conditions should be examined for a better understanding of the stability of the HRE food web and management purposes.

The sampling methods used to examine the pelagic community consist primarily of trawls, seines, individual fish tagging, or electrofishing. These invasive methods are often limited in their geographic and seasonal coverage, result in stress or death to the fish, and do not provide insight into how the fish are assembled in the water column before being caught. Traditional sampling methods also do not take into account distribution patchiness and net avoidance behavior, and thus may provide inaccurate estimates of fish abundance. Predictive models for fish abundance and distribution in the HRE that rely upon trawl and seine data are being developed for management purposes (Singkran and Bain, 2008, O'Conner *et al.* 2012). These models which correlate habitat and water conditions to fish presence are presently unable to account for net avoidance behavior of fish, vertical distribution patterns, or trophic interactions. For example, when fish presence is predicted by the model, but measurements show that fish are actually not present for those conditions, predation is tentatively hypothesized to explain this difference, however it may also be due to model errors (O'Conner *et al*. 2012). To improve their accuracy, predictive models should include other physical and biological factors that affect fish distribution (Singkran and Bain, 2008). Fisheries surveys can benefit by the use of additional methods, such as biological acoustics, that do not have the same limitations as traditional sampling methods for stock assessments, predictive models, and scientific inquiry.

Biological surveys using acoustic echosounders have been conducted in estuaries throughout the world (Duncan and Kubecka, 1996; Guillard and Vergest, 2007; Kubecka *et al.*, 2000; Samedy *et al.,*2013; Taylor and Rand, 2003; Tipton, 2013; Zahn, 1993). Scientific echosounders are a non-invasive technology that can measure the spatial distribution and quantity of fish or zooplankton at high spatial and temporal resolution. While acoustic-scattering generally cannot identify animals to a species level, acoustic survey methods use ground-truthing with direct sampling methods including trawls, beach seines, and video to provide more information at the species level.

Bioacoustics are used to quantify the stock size of fish in both oceanic and estuarine environments for fishery management purposes (MacLennan and Simmonds, 2008). A hydroacoustic study of fish on the Elbe River in the Czech Republic (Kubecka et al. 2000) positively linked habitat disruption with fish patchiness. Echo integration of fish biomass showed a more evenly distributed fish population where backwaters, tributaries, and other habitat features were intact. Conversely, where dredging, backfilling, shoreline hardening, and damming occurred, available habitat became limited and fish patchiness increased. An acoustic survey of the Neuse River mouth in the Pamlico Sound (Taylor and Rand, 2003) showed a positive spatial correlation, under normal conditions, between copepods and their bay anchovy predators. Acoustic backscatter from the overall pelagic community suggested that, when strong stratification of the estuarine water column occurs, copepod densities increased as the fish were unable to cross hypoxic barriers to feed on the zooplankton. An acoustic survey of the Gironde Estuary, France was conducted to evaluate two sampling pattern strategies: zig-zag pattern versus repeat cross river transect approach. The study compared fish biomass estimates made during flood and ebb tides, and concluded that survey design did not have an impact on fish estimates and hydroacoustic sampling was a valid methodology for assessing fish biomass in an estuarine system (Samedy *et al.* 2007).

There have been few bioacoustic studies of zooplankton and fish distributions of the HRE, and all previous studies are limited in temporal resolution, geographic coverage, or both. Fish distribution and swimming behavior at the Verrazano Narrows were measured acoustically (Zahn, 1993), but because data were collected over a small time period (a single 12 hour tidal cycle), its conclusions that fish orientations become more regularly distributed and face into the current during max current may not be applicable to other time-periods. Fish distribution and abundance were measured hydroacoustically over two winters in the lower Hudson River (Hartman and Nagy, 2006), and found that fish distributions were significantly different between two winters (1995 and 1997) and were correlated with salinity. Zooplankton were not measured in these studies, so it is unknown whether these patterns were related to prey distribution. There were also no diel patterns of vertical distribution or abundance found by Hartman and Nagy (2006). Diel vertical changes in pelagic organisms are frequently detected in bioacoustic surveys, but not in studies using traditional catch methods (Beamish, 1966; Guillard and Vergès, 2007).

Differences in abundance estimates from traditional and acoustic surveys are often attributed to net avoidance of fish during daylight hours in traditional methods (Hartman and Nagy, 2006). A hydroacoustic survey of bay anchovies in the HRE between May 1996 and September 1998 (Tipton, 2003) showed strong distribution changes during spawning migration periods within brackish water reaches of the HRE. There were unexplained peaks in abundance at a number of locations during the study period, especially near the Indian Point Power Plant and at Yonkers, NY. These distribution differences were attributed to possible variation in zooplankton availability (Tipton, 2003), however zooplankton samples were not collected so conclusive evidence of a geographic correlation between predators and prey is lacking.

Acoustic sampling methods have accurately estimated fish distribution and abundance, especially when supported by ground truthing data, such as trawling. Samedy *et al.* (2015) showed that fish density estimates from hydroacoustic and direct sampling methods have a highly significant correlation, specifically in estuaries, with both methods measuring the same seasonal peaks in fish abundance. Hydroacoustic estimates of fish abundance in the Ohio River system were highly correlated with estimates from rotenone surveys (a method by which fish are killed using a chemical compound to ensure extremely high accuracy in abundance estimates) and accurately estimated the size range of the most abundant fish (Hartman *et al.* 2000). Acoustic methods have also been shown to distinguish between scattering from biological and non-biological sources, such as bubbles and suspended sediment, due to spectral differences in their acoustic scattering characteristics (MacLennan and Simmonds 2008, Bezerra-Neto 2013).

In this study, abundance and distribution of fish and zooplankton at high spatial and temporal resolution were measured throughout the HRE using ground-truthed bioacoustic surveys at high spatial and temporal resolution. Near-daily sampling (from August 2013 to November 2013, April 2014 to November 2014, and April 2015 to September 2015) covered the entire navigable portion of the HRE multiple times and provided a unique dataset for examination. Specific geographic regions within the estuary were analyzed for trends related to seasonal variability, patchiness, vertical water column distribution, and possible trophic interactions between fish and zooplankton.

The objectives of this study were to examine fish and zooplankton distribution and abundance in the HRE using biological acoustic survey methods and to determine environmental factors related to changes in their distribution and abundance. I examined whether fish and zooplankton abundance on the HRE were correlated with latitude, season, water depth, freshwater discharge rates, abundance of other pelagic organisms, and other environmental conditions. The three specific hypotheses tested were that fish and zooplankton abundance (as measured by acoustic backscatter) were correlated with each other due to predator-prey interactions; that fish and zooplankton abundance (as measured by acoustic backscatter) were positively correlated with salinity; and that the abundance of fish and zooplankton (as measured by acoustic backscatter) shifted downriver during periods of high freshwater discharge into the Hudson.

Methods:

Ship-based data were collected from the Hudson River Sloop *Clearwater*. The 106-foot wooden sailing vessel travels daily from various ports on the HRE from April until November with slight variations in daily schedules. The geographic coverage of the vessel includes the entire navigable, estuarine portion of the Hudson River, between the New York Harbor (rkm0) and the port of Albany (rkm 240). Every navigable kilometer of the approximately 240 km estuary was sampled at least once each year with more frequent sampling occurring between 25 and 30 separate days each year near seven cities (NYC, Yonkers, Verplanck, Cold Spring, Beacon, Poughkeepsie, and Kingston) where the ship docks (Figure 2). Sampling occurred almost daily between August to November 2013, April to November 2014, and April to September 2015, with a total of 209 days over the entire study period (Figure 19).

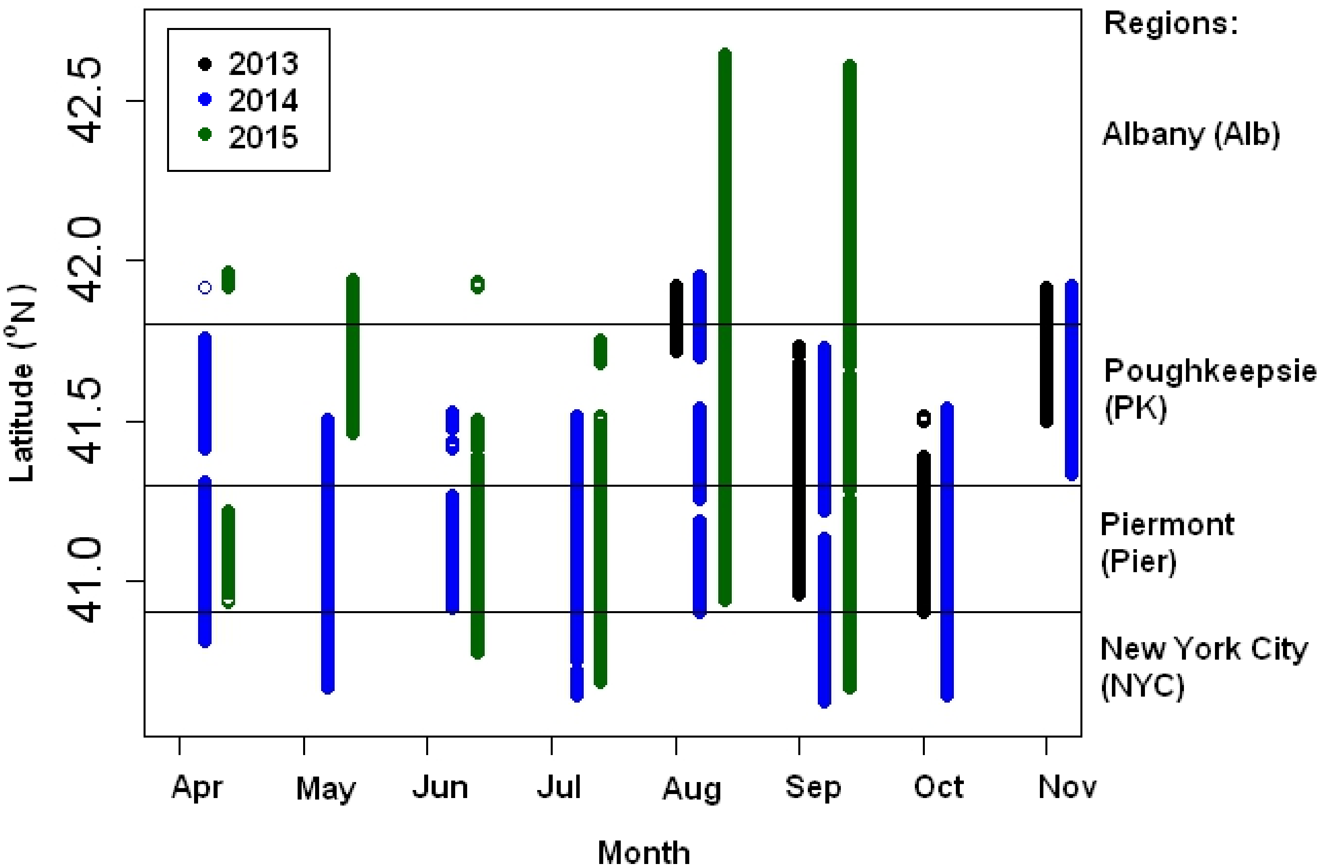


Figure 19. Spatial and temporal coverage of acoustic data includes all four regions (Albany, Poughkeepsie, Piermont and New York City) of the Hudson River Estuary in all three years of data collection (2013-2015). The greatest coverage throughout the year and over the widest latitudinal range occurred in 2014. The Albany and Poughkeepse regions had the least and most coverage respectively.

Environmental Sampling - Environmental data were collected aboard the Clearwater and at stationary recording sites of the Hudson River Environmental Conditions Observing System (HRECOS) (www.hrecos.org). HRECOS is a network of sondes measuring parameters including water temperature (ºC), dissolved oxygen (mg/l) and salinity (ppt) every 30 seconds to 15 minutes (depending upon station) from 2008 to 2015. Data from the mobile hull-mounded sonde aboard *Clearwater* and from 4 stationary sites located along the length of the estuary were analyzed. When hull-mounted HRECOS sonde data were not available due to instrument malfunction, the HRECOS stationary sonde data closest to the boat were used.

Freshwater discharge into the HRE varies seasonally and with rain events, primarily coming from the Mohawk River and the upper Hudson. HRE freshwater discharge (daily mean discharge) rates were recorded by the United States Geological Survey at Green Island, NY, (USGS 2015). The mean discharge rate from 2013 to 2015 was 315 $m^3 s^{-1}$ and this value delineates between "high" and "low" discharge regimes in this study.

In situ water column measurements of water temperature (ºC), dissolved oxygen (mg/l) and salinity (ppt) were sampled periodically, in conjunction with zooplankton tows or fish trawl collections, during the 2015 sailing season from the ship with a calibrated hand-held T-85 (YSI) water quality meter at 1 meter increments from the surface to 10 meters deep. These data provide information on the vertical water column structure.

Geographic Regions - The HRE was divided into four regions (Albany, Poughkeepsie, Piermont, and New York City), based upon salinity regimes, geographical characteristics, vertical water column structure, and similarities between fish species distributions (Figure 2). The Albany Region (Alb) has only tidal freshwater, relatively narrow riverbanks, an unstratified or well-mixed water column, and a fish assemblage dominated by freshwater or eurohaline species. Poughkeepsie Region (Pk) has tidal freshwater or oligohaline water, diverse geographic features including Newburgh Bay (wide and shallow) and World's End (deep and narrow), a well mixed water column, and a fish assemblage dominated by freshwater and eurohaline species. Piermont Region (Pier) has partially stratified oligohaline, mesohaline, or eurohaline waters, a geography primarily made up of Haverstraw and Tapanzee Bays (extremely wide and shallow), and a fish assemblage made up of eurohaline and marine species. New York City Region (NYC) has stratified oligohaline, mesohaline, or eurohaline waters, geographic features including narrow heavily engineered shorelines and realtively deeper bottom depths where the navigation channel extends almost bank to bank, and a greater diversity fish made up of eurohaline and marine species (Figure 2).

Organism Collection and Categorization - Biological data were collected to provide ground-truth information about the species and size of marine organism detected acoustically. Fish and zooplankton specimens were collected underway and at the shorelines using several methods. A 16-ft SeaGear otter trawl with 1.5” body mesh and 1/4” cod-end liner was deployed from the Hudson River Sloop *Clearwater*. All fish were counted and identified, Fork Length (FL) measurements were taken for five fish from the most abundant species caught. Seine nets, pop nets and fish traps were set from docks or nearby shorelines for additional fish collection (Niemisto and Warren, in review). A 150 micron mesh, 45 cm diameter zooplankton tow was deployed during cruises two times per month in 2015 from April to September. Samples were preserved in a 10% buffered formalin solution and zooplankton were identified to the species level and enumerated microscopically.

To more accurately interpret the acoustic data, organisms were categorized based on their size and acoustic scattering characteristics as follows: fish (fork length > 10 cm and swimbladder present), small fish (fork length < 10 cm and/or swimbladder absent), or zooplankton. Some species of fish may be represented in multiple categories at different life stages, with juveniles in the “small fish” and adults in the “fish” categories. Fish trawl and zooplankton tow data were analyzed to determine the most abundant species and the sizes present. Species abundance, geographic distribution, and size were supplemented using published literature when available. Trawl data were negatively biased for small or larval fish due to mesh sizes used, thus literature values for their distribution and abundance were used in place of *in situ* data for fish smaller than 10 cm. All pelagic fish species caught in the trawl net have swimbladders, thus their scattering characteristics will be roughly similar. Juveniles of some species of fish with swimbladders (as adults) were categorized as small fish as their swimbladders, while present, were not inflated due to their stage of development (Brown *et al.* 1988). These small fish and zooplankton were considered as fluid-like scatterers acoustically.

Acoustic Data Collection and Analysis - A multiple-frequency scientific echosounder (38 and 200 kHz, SIMRAD ES60) was mounted to the hull of *Clearwater* to measure real-time, high-resolution water column backscatter continuously while the boat transited the HRE. Backscatter data (volume backscattering strength, S_v) were collected from one to two hours before and after the ship got underway each day with a vertical resolution of 0.05 m, a ping rate of 1 Hz, a transmitted pulse length of 0.256 ms, and transmission power of 1000 W for the 38 and 200 kHz frequencies. The acoustic system was calibrated using a standard target (38.1 mm TC sphere) on 14 September, 2015.

Acoustic data were processed using Echoview 6.1 (Echoview Software Pty. Ltd, 2015). All echograms were individually scrutinized for any surface bubble intrusions or irregular bathymetry to exclude all non-biological scattering (ie. ship wakes) from analysis. There were three days in late June each year that were excluded from the analysis due to the boat being located in extremely shallow (< 2.5 m) water during an annual music festival. An Sv threshold of -70 dB at both 38 and 200 kHz was applied to best compromise between the removal of background noise and inclusion of scattering from small aggregations of zooplankton and fish.

Using information on the size of organisms present, the acoustic scattering characteristics of the organisms based on acoustic scattering models (Love, 1971; Stanton *et al.*, 1998, Urmy, 2016), and the differences in measured backscatter at both 38 and 200 kHz; backscatter data were classified as to the likely biological source of scattering (Brierley et al., 1998; Warren et al., 2003; D'Elia et al, 2016). This method is commonly applied in biological acoustic data processing to differentiate between size classes or taxonomic groups of scatterers (Watkins and Brierley, 1998). Spectral differences in backscatter (ΔS_v

= Sv at 200 kHz – Sv at 38 kHz) were sorted on a voxel by voxel basis according to the following classification method: ΔS_v <= 0 were fish and ΔS_v > 0 were either small fish or zooplankton. Echograms containing small fish or zooplankton were visually scrutinized for clear aggregates of zooplankton versus small individual fish or schools of small fish. The division between these two taxonomic groups were best categorized using the volume backscattering strength at 200 kHz with Sv > -61 dB considered small fish and Sv <= -61 dB classified as zooplankton. These groups are referred to as "fish", "small fish", and "zooplankton" in all further analysis and figures.

These classification methods were then applied within Echoview to generate volume backscatter data for each category. Due to differences in the scattering characteristics between different organisms, backscatter at different frequencies (38 kHz for fish, 200 kHz for small fish and zooplankton) were then further analyzed. Volume backscatter data were vertically integrated between a bottom exclusion line 0.5 meters above the bottom and a surface exclusion line 2 meters (38 kHz) and 1.5 meters (200 kHz) from the surface horizontally over 100 meter latitudinal bins. These integrations were done for the three categorized backscattering parameters and then converted to Nautical Area Scattering Coefficient (NASC, m^2 nmi^{-2}), an acoustic measure related to fish and zooplankton biomass (MacLennan and Simmonds 2008). It should be noted however that NASC values based on different frequencies can not be directly compared in terms of relative biomass. The largest twenty-five NASC values for each frequency were visually inspected to verify scattering were from biological targets.

Mean daily NASC values for each scattering category were calculated. Whenever daily mean backscatter were calculated for days when the vessel transited between two or more geographic regions, a mean value was calculated for each region within the same day and are referred to as "backscatter". Due to the path of the vessel, this results in some days having multiple daily mean backscatter values. Given the large range of values present in a linear measure of backscatter (such as

NASC), the data are often log10-transformed for visualization purposes; however all mathematical operations (e.g. averaging) were calculated in the linear domain.

Biological scattering values were analyzed in relation to water temperature, salinity, turbidity, dissolved oxygen, and freshwater discharge. Temporal relationships (daily, seasonal, and annual) and spatial changes (in depth, latitude, and region) of biological scattering were also analyzed. Linear correlations between zooplankton and turbidity were performed to assess whether biological scattering from zooplankton could be including non-biological suspended sediments. Geometric mean regression models were used to determine spatial relationships between scattering groups (zooplankton, small fish, and fish) on short (daily) and larger (three year) time scales (Sprent and Doby, 1980). To examine if the latitudinal distribution of biological scatters varies during periods with different discharge rates, the NASC values for fish, small fish, and zooplankton (in the linear domain) was multiplied by their corresponding latitude. NASC- weighted Latitude (ºN) = sum (Latitude (ºN) x NASC (m^2/nmi^2))/sum(NASC m^2/nmi^2). The NASC-weighted distribution of acoustic backscatter was then used to measure if distributions of organisms shifted when discharge rates varied.

Results:

Organisms Present - There were a total of 10,356 individual zooplankton, from 34 distinct species or life stages collected in plankton tows on the HRE between April and November 2015 (Table 8). Biological scattering from zooplankton were assumed to be primarily from copepods, crab larvae and barnacle nauplii due to the percent composition of zooplankton collected. Calanoid copepods *(Acartia tonsa)* were the most abundant species numerically, making up 43.8% zooplankton collected. Crab nauplii, barnacle nauplii, and Calanoid copepods *(Pseudocalanus newmani)* constitute 11.3, 7.1, 6.8% of individual zooplanktan collected respectively. Cyclopoid copepods (*Halicyclops fosteri),* unidentified copepod nauplii, Calanoid copepods *(Acartia species)*, and Calanoid copepods *(Paracalanus parvus)* each make up between 4-5% of the total individuals collected (Table 8).

Table 8. Species of zooplankton were collected aboard the Hudson River Sloop *Clearwater* between April – November 2015 and considered to be the dominant biological scatters in the zooplankton acoustic category. The total number counted, the percent contribution of each species, and the mean and standard deviation (SD) of animal lengths (in mm) of each species found are presented here. The first 100 individual animals counted in each sample were measured, thus some mean lengths and standard deviations are missing when that species did not occur in the first 100 counted.

Species	Total Number	% of Total	Mean Length (mm)	SD (mm)
Copepoda Calanoida Acartia tonsa Adult	4538	43.8	0.74	0.23
Crab Zoea Larvae	1167	11.3	1.49	0.28
Cirripedia Naplius (barnacle)	739	7.1		
Copepoda Calanoida Pseudocalanus newmani Adult	701	6.8	0.80	0.23
Copepoda Cyclopoida Halicyclops fosteri Adult	484	4.7	0.63	0.11
Copepoda unidentified Nauplius	429	4.1	0.32	0.09
Copepoda Calanoida Acartia unidentified Adult	420	4.1	0.79	0.18
Copepoda Calanoida Paracalanus parvus Adult	418	4.0	0.75	0.17
Copepoda Cyclopoida Oithona Unidentified Adult	296	2.9	0.59	0.12
Copepoda unidentified Adult	229	2.2		
Copepoda Calanoida unidentified Adult	206	2.0	0.72	0.19
Copepoda Cyclopoida Mesocyclops unidentified Adult	106	1.0	0.76	0.22
Copepoda Calanoida Eurytemora affinis Adult	92	0.9		
Copepoda Calanoida Acartia hudsonica Adult	89	0.9	0.84	0.11
Branchiopoda Cladocera Bosminidae Bosmina freyi Adult	88	0.9	0.41	0.01
Copepoda Calanoida Parvocalanus crassirostris Adult	69	0.7	0.75	0.35
Branchiopoda Cladocera Daphniidae Daphnia Adult	47	0.5	0.45	0.14
Decapoda caridean Larvae (shrimp)	47	0.5		
Zooplankton Unidentified	46	0.4		
*Copepoda Harpacticoida Microstella norvegic*a Adult	39	0.4	0.90	0.14

Copepoda Calanoida Pseudodiaptomus coronatus Adult	31	0.3	0.75	0.11
Copepoda Cyclopoida Oithona atlantica Adult	13	0.1	0.55	0.16
Copepoda Calanoida Eurytemora unidentified Adult	13	0.1		
Unidientified Aquatic Insect	13	0.1		
Copepoda Calanoida Metrida unidetified Adult	6	<0.1	0.63	0.18
Copepoda Cyclopoida Cyclops unidentified Adult	6	<0.1	0.74	0.09
Copepoda Calanoida Acartia longiremis Adult	5	<0.1		
Copepoda Cyclopodia Diacyclops bicusidatus Adult	5	<0.1		
Polychaeta Larvae	4	<0.1		
Copepoda Cyclopoida Oithona colcarva Adult	3	<0.1		
Cladocera Chydorinae unidientified Adult	3	<0.1		
Decapoda caridean Adult (shrimp)	2	<0.1		
Copepoda Calanoida Metrida lucens Adult	1	<0.1		
Copepoda Cyclopoida unidientified Adult	1	<0.1		

The most abundant fish species caught during acoustic sampling period was the Atlantic tomcod, representing 41.7% of the catch and ranging from 90 to 225 mm in length. The second most abundance species caught was the hogchoker, representing 31.7% of the trawl catch, however, hogchokers were not likely to contribute significantly to biological scattering due to their flat body shape and benthic habitat preference which is within the 0.5 meters of the river bottom that is excluded from analysis. Thus, the white perch and Atlantic silverside represent the next most abundance fish species captured during acoustic sampling comprising 11.6 and 7.6 % of total catch (Table 9).

Table 9. Species collected by trawl net aboard the Hudson River Sloop *Clearwater* concurrently with acoustic data collection in 2014-2015 and categorized as "fish" acoustically. All fish included have swimbladders with the exception of hogchokers. Fish lengths and regional (Albany = Alb, Poughkeepsie = Pk, Piermont = Pier, New York City = NYC) distributions were determined from trawl collections and published literature.*(Singkran 2008, Daniels 2005, Strayer 2006, Waldman 2006,

Tipton 2003, O'Conner 2010, Kelley 2003, and Schwartz 1965), ***Callinectes sapidus* carapace width reported (Stehlik *et al.* 2004).

Fish Species	**Present in Regions**	**literature lengths (mm)***	**measured lengths (mm)**		**% of total catch**
		min-max	**mean +/- sd**	**min-max**	
Microgadus tomcod (Atlantic tomcod)	Pk, Pier, NYC	90-300	185 +/-64.4	90-225	41.7
Trinectes maculatus (Hogchoker)	Alb, Pk, Pier, NYC	70-200	108.5 +/-17.4	70-170	31.7
Morone americana (White perch)	Alb, Pk, Pier, NYC	203-254	215.0 +/-12.4	200-230	11.6
Menidia menidia (Atlantic silverside)	NYC	100-130	NA	NA	7.6
Ictalurus punctatus (Channel catfish)	Alb, Pk	280-420	116.4 +/-57.4	40-200	2.5
Ameiurus nebulosus (Brown bullhead)	Alb, Pk	200-355	230.0 +/-16.3	210-250	>1
Notropis hudsonius (Spottail shiner)	Alb	51-76	66.9 +/-16.0	50-100	>1
Anguilla rostrata (American eel)	Pk, NYC	270-457	222 +/- 0	222	>1
Cynoscion regalis (Weakfish)	Pier, NYC	203-355	200 +/- 0	200	>1
Urophycis regia (Spotted hake)	NYC	130-250	170.0 +/-52.0	135-230	>1
Callinectes sapidus (Blue claw crab)	Pk, Pier, NYC	21-185**	NA	NA	>1
Ameiurus catus (White catfish)	Alb	150-360	NA	NA	>1
Anchoa mitchilli (Bay anchovy)	Pier, NYC	100-125	NA	NA	>1

Table 10. Species of fish categorized as "small fish" due to their size, scattering characteristics, and presence in seine and trawl collections. Many of the "small fish" are juveniles while the adults of those species occur in the "fish" category as their size and morphology changes as they grow. *Size measurements and regional distribution (Alb – Albany, Pk – Poughkeepsie, Pier – Piermont, NYC –

New York City) are from the Longitudinal River Ichthyoplankton Survey and Fall Juvenile Survey data (ASA, 2012), as biological collection aboard the Hudson River Sloop *Clearwater* had a negative gear bias to fish in this size range.

Small Fish Species	**Present in Regions**	**literature lengths (mm)***	
		mean +/- sd	**min-max**
juvenile *Morone saxatilis* (striped bass)	Pier, NYC	26.4 +/- 29.0	20-140
juvenile *Morone americana* (White perch)	Alb, Pk, Pier, NYC	20.5 +/- 26.7	18-100
juvenile *Microgadus tomcod* (Atlantic tomcod)	Pk, Pier, NYC	46.5 +/- 23.4	25-140
juvenile *Anchoa mitchilli* (Bay anchovy)	Pier, NYC	21.8 +/- 11.7	12-70
juvenile *Alosa sapidissima* (American shad)	Alb, Pk	74.0 +/- 13.2	9-108
juvenile *Alosa pseudoharengus* (Alewife)	Alb, Pk, Pier, NYC	30.0 +/- 32.4	40-118
juvenile *Notropis hudsonius* (Spottail shiner)	Alb, Pk, Pier	64.4 +/- 20.1	10-85
juvenile *Ameiurus catus* (White catfish)	Alb, Pk, Pier, NYC	73.4 +/- 35.0	20-118
juvenile *Cynoscion regalis* (Weakfish)	Pier, NYC	82.9 +/- 32.4	10-140

Acoustic Backscatter - Individual fish, fish schools, and aggregations of zooplankton were observed on small spatial scales (1 to 100 m) through visual inspection of the acoustic data in the form of echograms, which helped to confirm that scattering sources were biological. Biological scattering from zooplankton was not linearly correlated ($r = 0.006$, $n = 344$, p-value = 0.072) with turbidity, supporting the theory that suspended sediments were not large contributors to the acoustic backscatter measured in this study. Visual correspondences between fish and zooplankton scattering were observed both vertically within the water column and horizontally along the track distance of the vessel. (Figure 20).

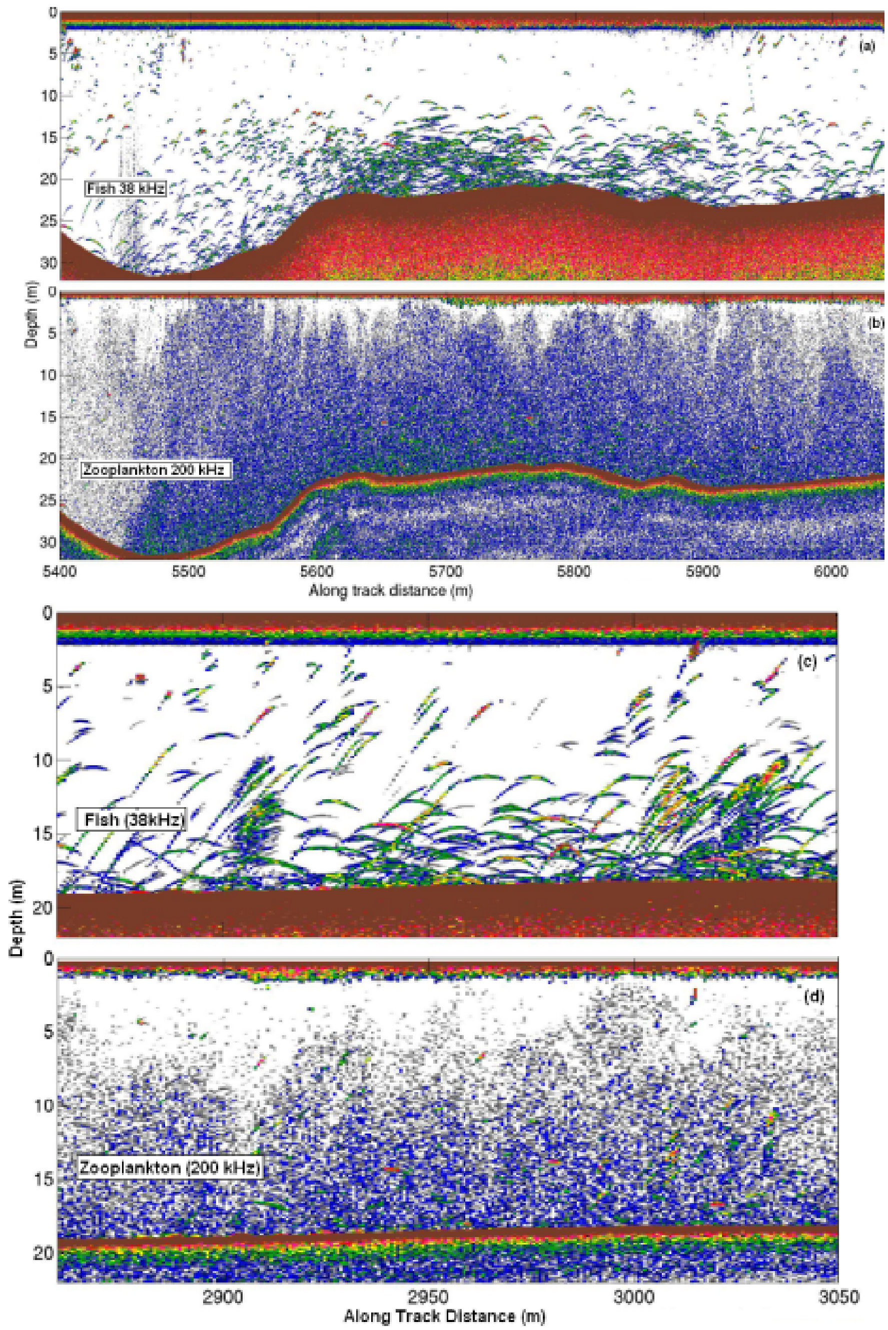


Figure 20. Echograms of acoustic backscatter from fish and zooplankton collected on 08 August (a and b) and August 01 (c and d) 2014 near Beacon, NY. Colors represent volume backscatter strength ranging from red (-34 dB) to blue (-70 dB). Arcs in the 38 kHz echograms (a and c) are individual fish and blue clouds in the 200 kHz echograms (b and d) are aggregates of zooplankton. Red bands at the top and bottom of the echograms represent the surface and river bottom which were excluded from analysis.

There were a total of 209 days of acoustic sampling (20 days in 2013, 102 day in 2014, and 87 days in 2015), between August 2013 and September 2015, with 88.7% of acoustic data collected between 0800 and 2000 hrs local time. On days where the vessel surveyed acoustically in more than one geographic region, daily mean regional backscatter (referred to as backscatter) were calculated (see Methods). There were 259 backscatter values calculated. Spatial coverage of the four geographic regions include 35 days in the Albany region, 97 in the Poughkeepsie region, 84 in the Piermont region, and 43 in the NYC region. There was coverage in every region in every month of the collection season except for July and October in the Albany region and November in the NYC regions over the course of the three year acoustic survey (Figure 19).

During short time periods (i.e., within a single day), the patchiness of fish, small fish, and zooplankton are apparent. The conditions driving the distribution patterns and their spatial correlations (such as environmental conditions or predation pressure) may be different on the shorter time scale than on the longer scale. Fish and small fish are less strongly correlated at this scale (geometric mean regression, $r = 0.66$). Whereas geometric mean regression model values between zooplankton and the two fish groups are much higher at this small scale (with small fish $r = 0.38$) and (with fish $r = 0.42$) than when compared to the entire study period (Figure 21 and Figure 22).

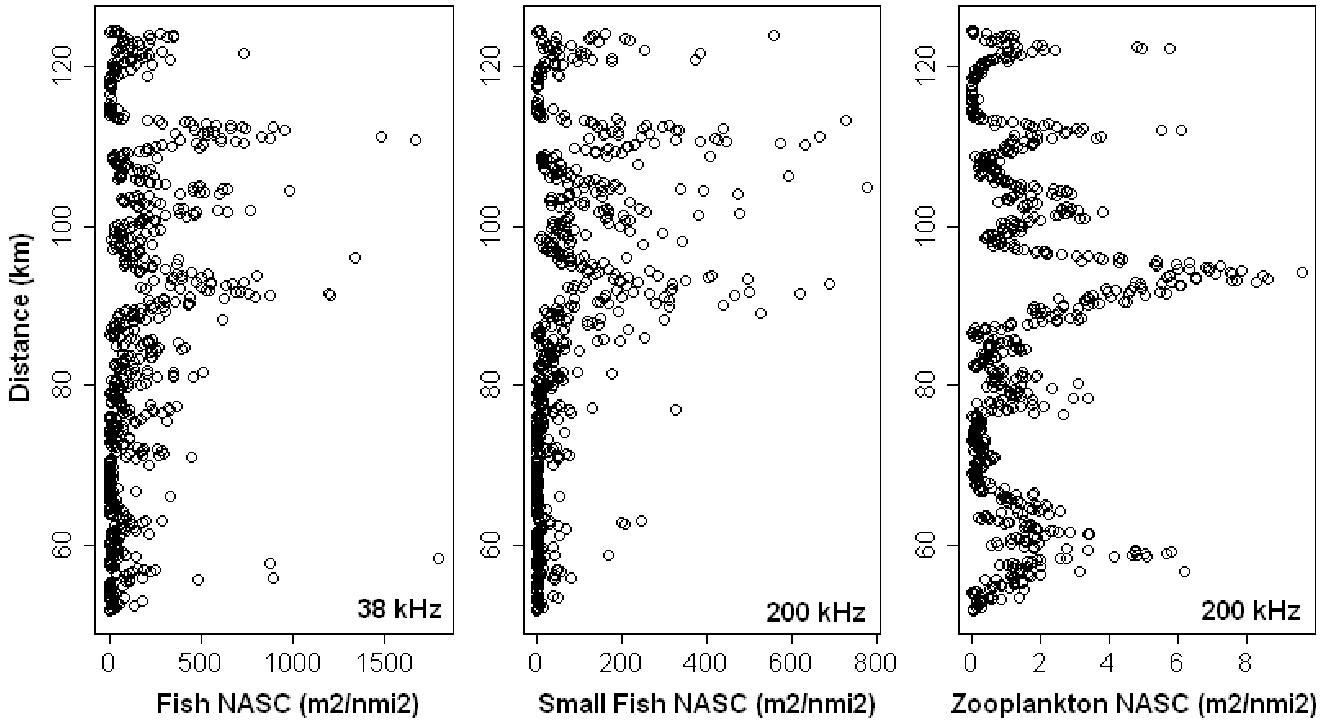


Figure 21. Patchiness of fish, small fish, and zooplankton backscatter is shown in the variability in Nautical Area Scattering Coefficient (NASC) values collected as the boat sailed on 29 September, 2015

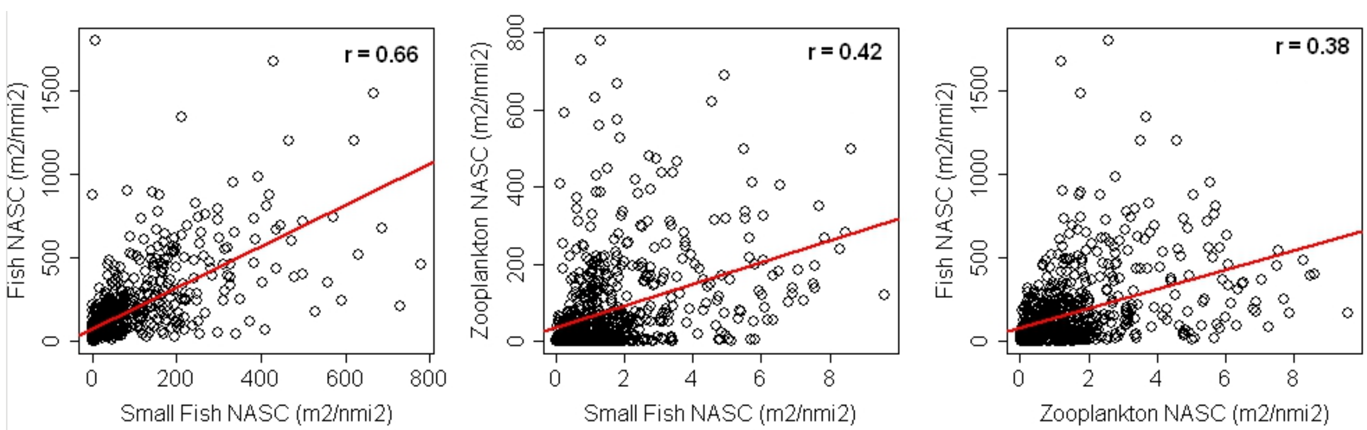


Figure 22. Backscatter (proportional to biological abundance) as measured by Nautical Area Scattering Coefficient (NASC) for a single day (29 September 2015) was most highest geometric mean regression value between the fish and small fish groups ($r = 0.66$, $n = 692$, p-value = 3.97e-86), geometric mean regression between zooplankton and small fish groups ($r = 0.38$, $n = 687$, p-value = 4.57e-26) and zooplankton and fish groups ($r = 0.42$, $n = 696$, p-value = 8.02e-31) were smaller. Dots represent all NASC (m^2 nmi^{-2}) for zooplankton, small fish (both 200 kHz), and Fish (38 kHz) for a single day, and red lines are geometric mean regression models for each subplot. Note that the axes are on different scales for each subpanel.

Biological scattering from fish, small fish, and zooplankton (as measured by daily NASC) were spatially and temporally correlated with each other to different degrees when considered on a daily regional scale over the entire three year study period. Scatter from fish and small fish had the highest geometric mean regression value (r = 0.72), while there was little (if any) relationship between either fish and zooplankton (r = 0.30) or small fish and zooplankton (r = 0.22) (Figure 23).

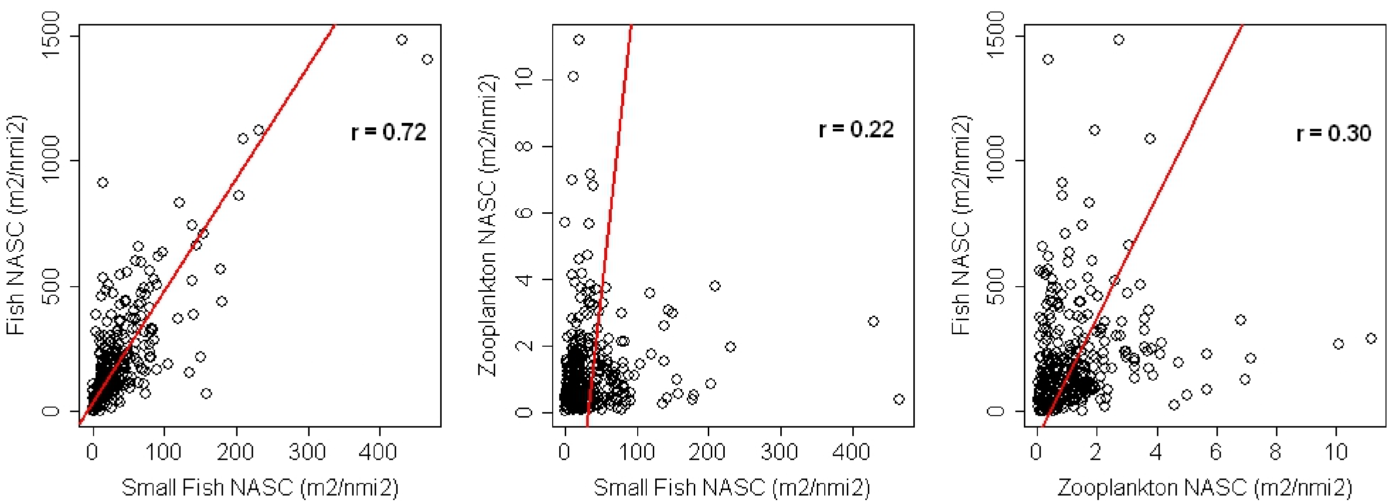


Figure 23. Daily mean regional backscatter (proportional to biological abundance) as measured by Nautical Area Scattering Coefficient (NASC) was most strongly geometric mean regression model value (r = 0.72, n = 318, p-value = 5.76e-51) between the fish and small fish groups, while the other pairings of the three scattering groups had smaller geometric mean regression values with fish and zooplankton (r = 0.30, n = 318, p-value = 5.35e-08) and small fish and zooplankton (r = 0.22, n = 313, p-value = 7.6e-05). Dots represent the daily mean NASC (m^2 nmi^{-2}) for zooplankton, small fish (both 200 kHz), and Fish (38 kHz) and red lines are geometric mean regression models for each subplot. Note that the axes are on different scales for each subpanel

Over the entire three year sampling period, backscatter from fish as measured by NASC (240+/-1000 m^2 nmi^{-2}) was always the highest, small fish backscatter (43 +/- 220 m^2 nmi^{-2}) was always much lower, and zooplankton backscatter (1.2 +/- 2.1 m^2 nmi^{-2}) was always the lowest. This pattern is due to the distinct size differences and presence or absence of swim bladders, and is supported by the biological acoustic premise that larger animals scatter more energy than smaller animals, and fish with gas filled swim-bladders scatter more energy than fluid-like scatterers like zooplankton. Due to spectral scattering differences, abundances based on NASC values from different acoustic frequencies can not be directly compared to each other. The large variability in backscatter within a given day was a function of the patchiness in fish and zooplankton distribution spatially (Figures 21 and 24). There are observable seasonal patterns where the daily backscatter increases and variability decreases, for example in June for fish and zooplankton (Figure 24).

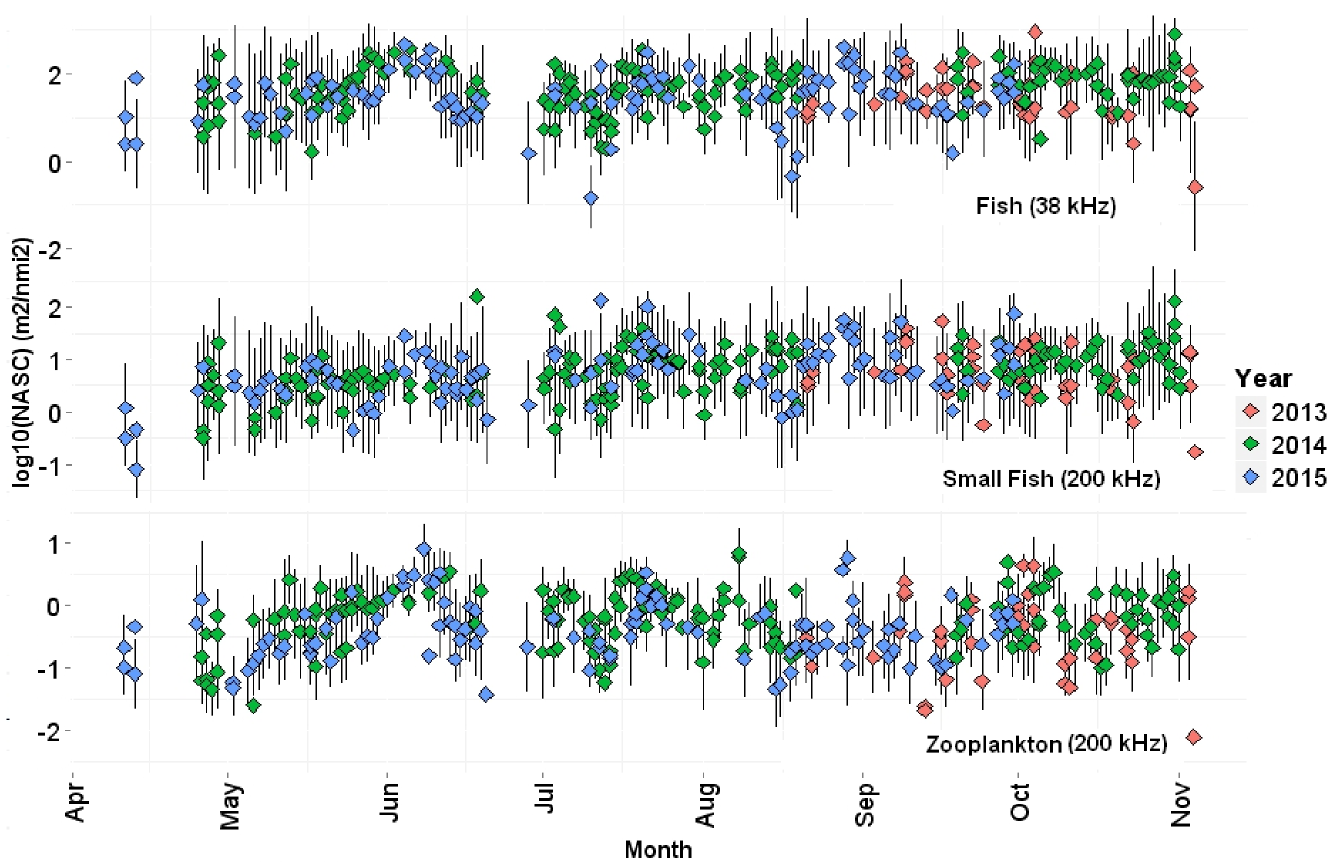


Figure 24. High variability in daily backscatter (log 10 (NASC)m^2 nmi^{-2}) values from fish, small fish and zooplankton is due to the patchiness of biological scatterers in the Hudson River Estuary although some seasonal trends are evident such as blooms occurring in June and October. Diamonds are the mean daily backscatter, colors represent year of data collection (red =2013, blue = 2014, and green = 2015), black lines represent daily standard deviation. The y-axes for each subpanel have different scales.

There were annual differences in mean daily backscatter within all three groups. For fish and small fish, the median backscatter values increased from 2013-2015, whereas for zooplankton, 2014 had the highest median backscatter value (Figure 25). Backcatter for the fish group was significantly different between years (p=0.028), but not for the other two groups (small fish p = 0.10, and zooplankton p = 0.99).

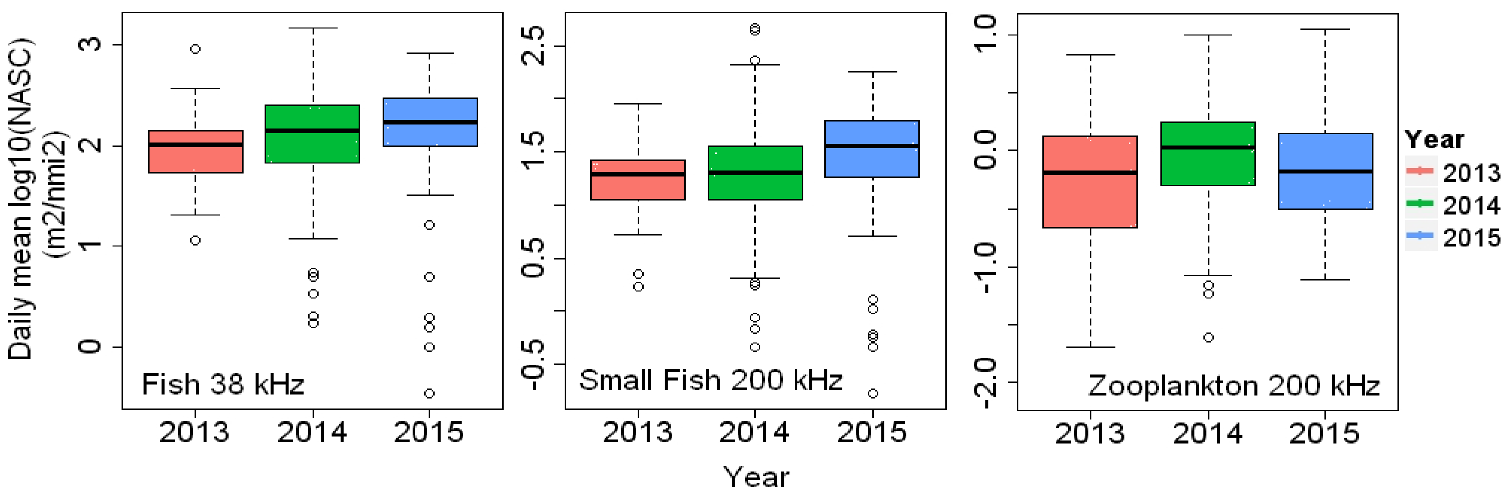


Figure 25. Daily biological backscatter from fish and small fish was increased from 2013 to 2015. Daily biological backscatter from zooplankton was highest in 2014 and lowest in 2013. Only fish backscatter is significantly different between the three years (t-test, p = 0.028). Black band represents the median backscatter value, boxes encompass the first and third quantiles, whiskers represent the first and third quantiles +/- 1.5 times the interquartile range.

There were observable seasonal patterns in daily mean backscatter for all three scattering categories (fish, small fish, and zooplankton). Throughout the spring months (April, May, and June) of 2014 and 2015, there were increases in backscatter in fish, small fish, and zooplankton, with the exception of fish in 2014 when scattering remained relatively stable. In the summer months (July and August) backscatter continues to increase for small fish in 2014 and 2015, however, for fish and zooplankton the summer months show a decline in scattering. Both fish and small fish increase in scattering in the fall months for 2014 and 2015, however 2013 shows a relatively stable level for fish and a decrease in small fish and zooplankton abundance during the fall months of September and October (Figure 26). There was no variation in backscatter with time of day, for any of the three groups.

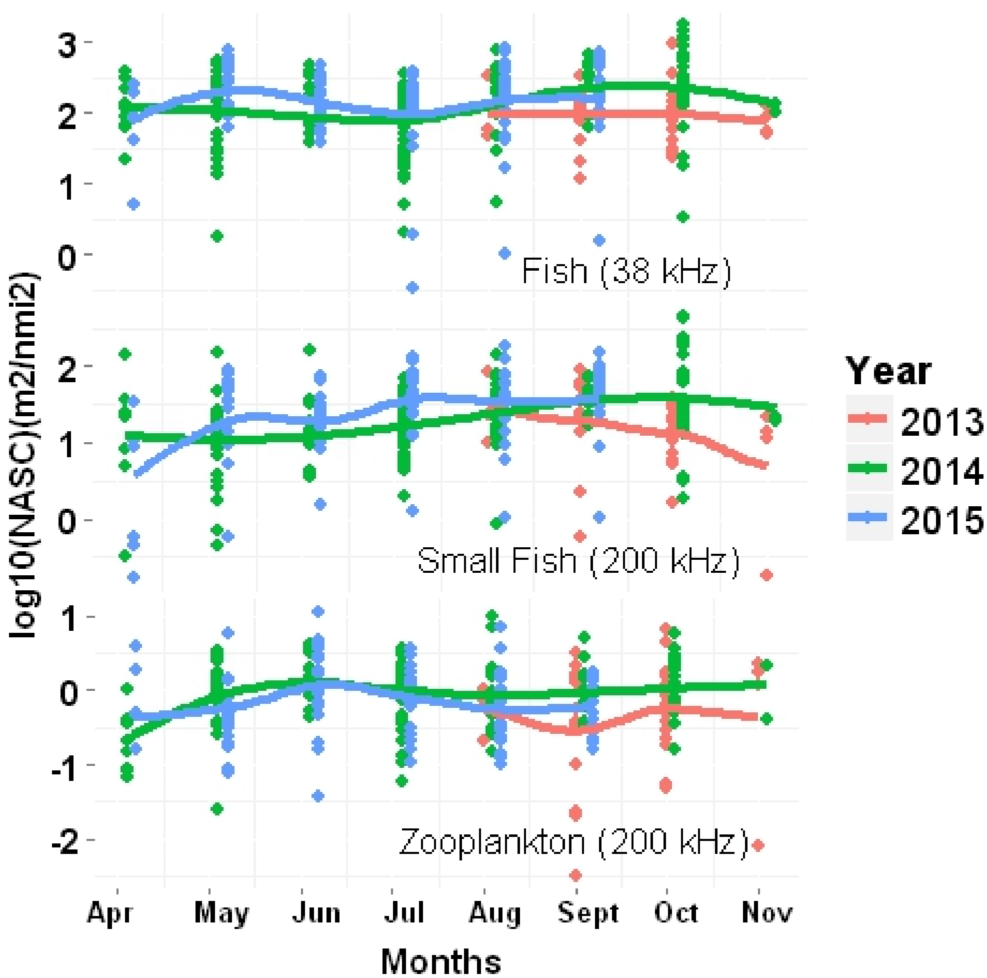


Figure 26. All three years of fish, small fish, and zooplankton backscatter show seasonal patterns and variations between the different organisms. Dots represent mean daily backscatter values in m^2 nmi^{-1}, colors represent different years from 2013-2015, and lines are a locally weighted polynomial regression (LOESS) curve fit.

When analyzed by region, there were some distinct patterns in backscatter among fish, small fish, and zooplankton (Figure 27). Fish have the highest scattering in the Albany region (300 +/- 220 m^2 nmi^{-2}) followed by the NYC region (280 +/- 330 m^2 nmi^{-2}). Small fish had the highest scattering in the NYC region (68 +/- m^2 nmi^{-2}) followed by the Albany region (52 +/- 38 m^2 nmi^{-2}). Zooplankton have the highest backscatter in the Poughkeepsie region (1.7 +/- 1.6 m^2 nmi^{-2}) followed by the NYC region (1.5 +/- 1.0 m^2 nmi^{-2}).

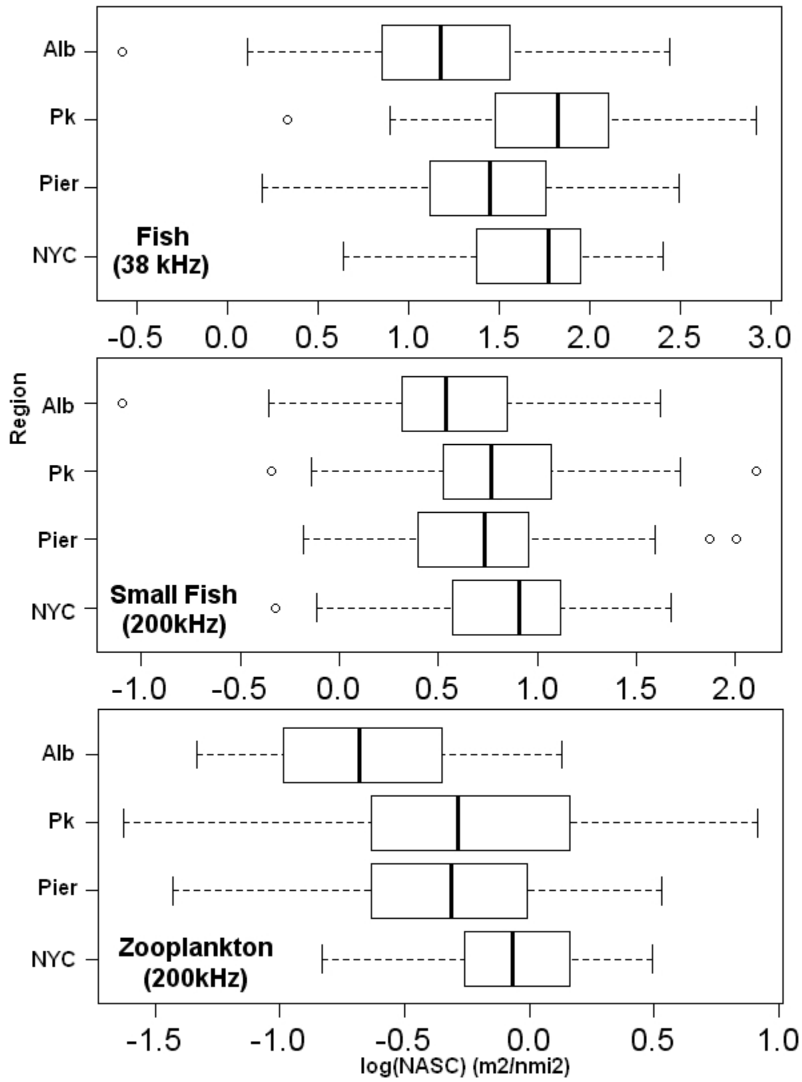


Figure 27. Regional patterns in biological scattering from fish, small fish, and zooplankton in four geographic regions of the Hudson River Estuary (Albany = Alb, Poughkeepsie = Pk, Piermont = Pier, and New York City = NYC) from 2013 – 2015 show increases in abundance for all three groups in order of Albany, Piermont, Poughkeepsie, and NYC regions. Black band represents the median backscatter value, boxes encompass the first and third quantiles, whiskers represent the first and third quantiles +/- 1.5 time the interquartile range. Note the x-axes ranges are different for fish, small fish, and zooplankton sub-panels.

When these regional patterns were further analyzed by season, again there were clear similarities between the spring, summer, and fall distributions of fish and small fish, while zooplankton had their own seasonal distribution patterns across the HRE. Scattering from fish and small fish was higher in the upriver regions (Albany and Poughkeepsie) during the spring months (April, May, and June) than the downriver regions (Piermont and NYC). Fish and small fish scattering in the summer months remained high in the Albany region, dropped slightly in the Poughkeepsie region, and increased in the downriver regions. In the fall months, fish and small fish scattering increased in the NYC region and was lower in all other regions. Zooplankton scattering was lowest in the Albany region compared to the other regions in all seasons. In the spring, the Poughkeepsie region had the highest scattering, whereas in the summer and fall the highest scattering from zooplankton was in the NYC region (Figure 28).

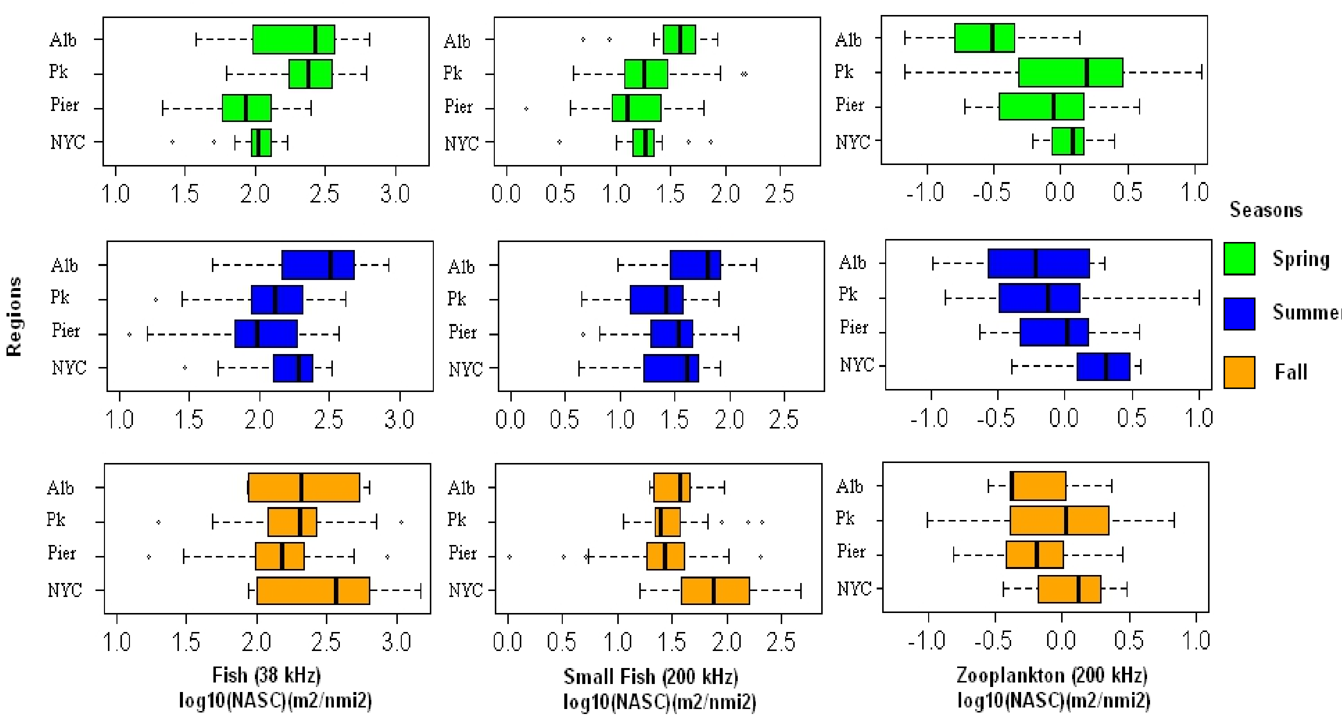


Figure 28. Seasonal distributions of biological scattering in the four regions (Albany = Alb, Poughkeepsie = Pk, Piermont = Pier, and New York City = NYC) on the Hudson River Estuary were similar for fish and small fish, but varied for zooplankton. Seasons are represented by color. Black band represents the median backscatter value, boxes encompass the first and third quantiles, whiskers represent the first and third quantiles +/- 1.5 times the interquartile range. Note the x-axes ranges are different between fish, small fish and zooplankton panels.

There were some observable patterns between backscatter and environmental conditions, specifically dissolved oxygen and water temperature, in the HRE. Turbidity and salinity values did not show any interesting trends with acoustic scattering in this study. For fish, small fish, and zooplankton there were higher daily mean backscatter values when dissolved oxygen was between 7-8 mg/l. Fish were present at a wider range of DO levels (down to 4 mg/l) than small fish or zooplankton, however all three groups had less backscatter at extremely high (> 12 mg/l) DO values. Small fish daily mean backscatter increased with increasing temperature, however the linear regression was strong ($r = 0.12$, $n = 340$, p-value = 1.94e-11). Fish daily mean backscatter also increased with increasing temperature with the exception of some lower scattering between 25 and 27 °C. Zooplankton backscatter was higher between 19-23 °C (mean backscatter = 1.22 +/- 2.11 m2/nmi2), but did not increase with temperature as with the other two groups (Figure 29).

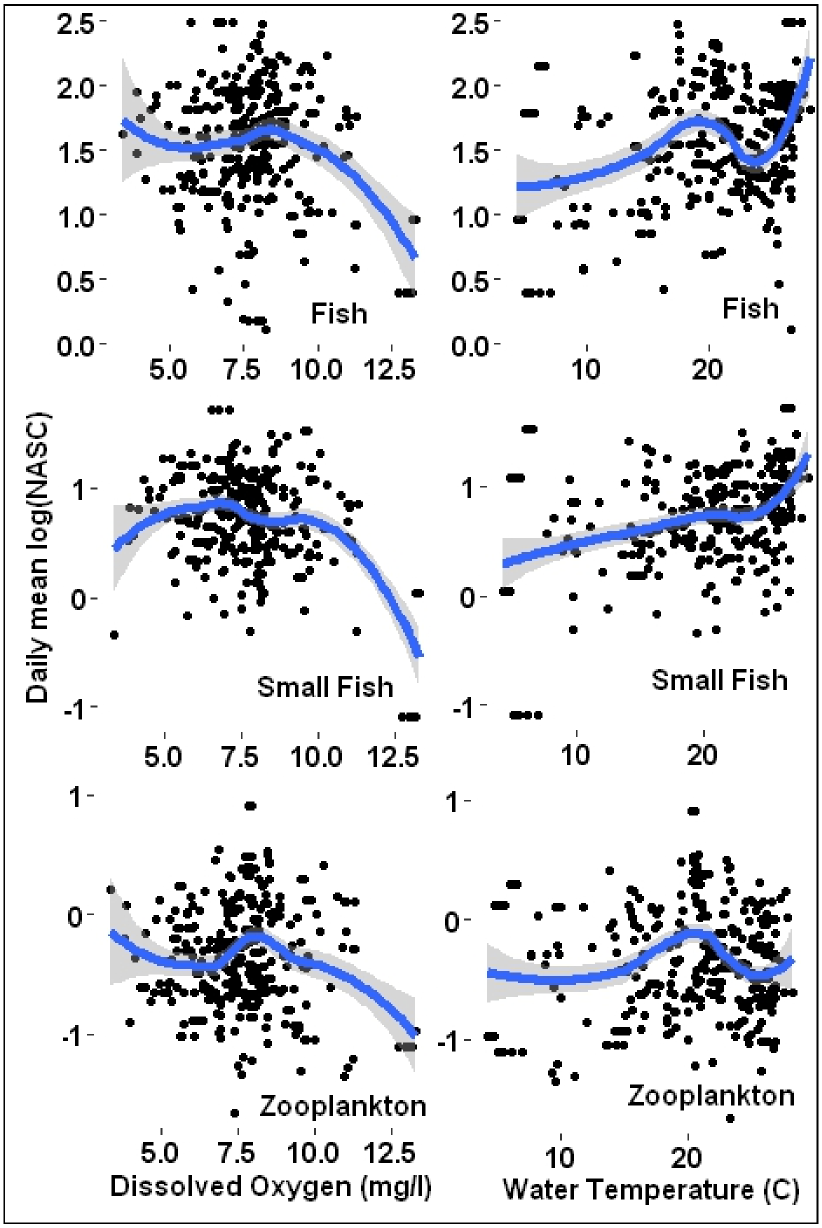


Figure 29. Fish, Small Fish and Zooplankton abundance (as measured by daily mean backscatter) in the Hudson River Estuary from 2013-2015 were highest when dissolved oxygen levels were between 7-8 (mg/l), however they were present at a wide range of dissolved oxygen concentrations reflecting a biological community present in extremes. Zooplankton have the greatest backscatter values between 19-23 degrees C, small fish backscattering increases with increasing water temperature, and fish backscatter increase with increasing temperature except between 25 – 27 degree C when backscatter decreases. Blue lines are the (locally weighted loess model fits to water temperature and dissolved oxygen with backscatter, and the gray shaded areas are the standard error.

During times of high freshwater discharge, fish, small fish, and zooplankton distribution changed in the HRE between latitudes 40.6 and 42.15 ºN, where acoustic coverage during high and low discharge periods were both well represented in the data. There were 72 days of acoustic data collected during high discharge periods and 126 days of acoustic data collected during low discharge periods for this region.Fish backscatter was the greatest at latitude 41.5 ºN during high and low freshwater discharge periods, which corresponds to Newburgh Bay and the Beacon trawl location (rkm 98). However, scattering from fish declined in all other areas of the HRE, especially north of Beacon, during high discharge periods. Zooplankton scattering was the highest at latitudes 41.3 and 40.65 ºN during periods of low discharge, which correspond to World's End (rkm 78) and the mouth of the estuary in NYC. Small fish scattering was relatively even throughout all latitudes during low discharge periods and decreased at all latitudes during high freshwater discharge periods, especially north of 41.5 ºN.

During periods of high freshwater discharge, zooplankton scattering decreased in all areas of the HRE, except at 41.3 ºN and there remained a peak in scattering at the World's End area. This suggests that fish were impacted by freshwater discharge into the HRE, especially upriver, but there were certain locations where they are able to maintain their regional placement or are advected into those areas. Zooplankton were more impacted by high discharge rates throughout the entire estuary, especially upriver but also experienced some trapping in the midriver reaches (Figure 30). NASC-weighted distributions for each group were calculated and showed a decrease in the mean value for all three groups during periods of high discharge when compared to period of low discharge (Table 11).

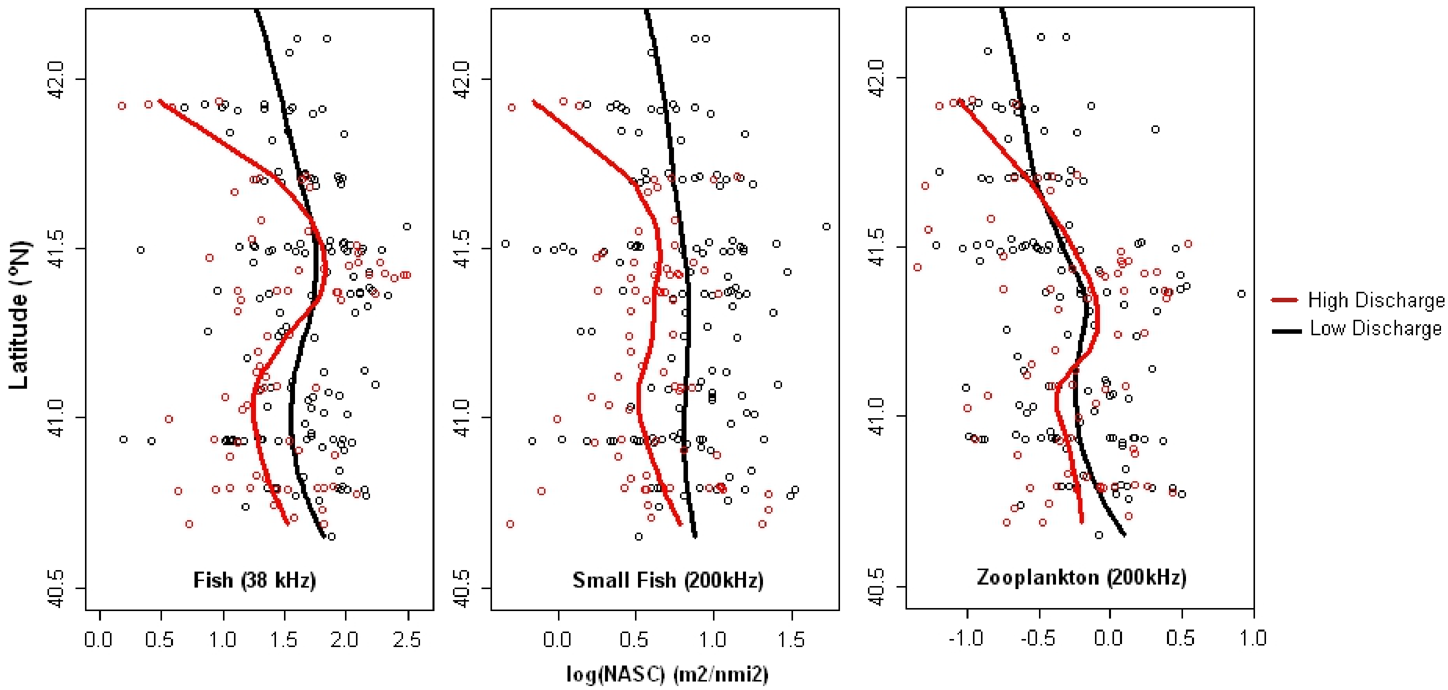


Figure 30. There are distinct patterns in latitudinal distribution of backscatter from fish, small fish, and zooplankton, respectively, during periods of low (black) and high (red) freshwater discharge in the Hudson River Estuary between 40.6 ºN and 42.3 ºN. Plot shows fish and zooplankton backscatter decreases at all latitudes except 41.5 ºN during high discharge and small fish backscatter decreases at all latitudes. Lines are a locally weighted polynomial regression (LOESS) curve fit to backscatter at each latitude.

Table 11. Mean weighted latitudes were lower during high discharge periods compared to low discharge periods on the HRE between 40.6 ºN and 42.3 ºN for all three groups (fish, small fish, and zooplankton). There were 72 days of acoustic scattering data collected during high discharge periods and 126 days during low discharge periods.

Discharge rates (m^3/s)	NASC- weighted Latitude (ºN)		
	Fish	Small Fish	Zooplankton
Low (<315.4)	41.39	41.36	41.26
High (>315.4)	41.21	41.06	41.18

Discussion:

Distribution patterns between taxonomic groups - Zooplankton were not spatially correlated with either fish or small fish on either large temporal or spatial scales (i.e., entire estuary over the entire study period). This could be due to predation pressure by fish and small fish limiting zooplankton density, or may suggest that fish and small fish are not spatially correlated with zooplankton due to a mismatch in their habitat preferences and optimal environmental conditions. However, when considered on smaller scales of space and time (i.e., within a single day), zooplankton were more spatially correlated with fish and small fish. This suggests that the scale at which predator-prey interactions between the spatial correlations for fish and zooplankton on the HRE must be carefully considered. On smaller scales, the abundances of zooplankton and fish were more related than when analyzed over multiple years and hundreds of kilometers. The trophic link between juvenile or adult fish feeding on zooplankton has been well established in the HRE in other studies conducted at smaller spatial and temporal scales (Pace and Lonsdale, 2006; Grabe, 1996; Tipton, 2003).

There have not been many studies on the HRE documenting the spatial or temporal correlations between trophic groups which highlight the important relationships between predator and prey (Strayer *et al.*, 2004). In this study, backscatter from fish and small fish were spatially correlated with each other at large scales (i.e., the entire estuary over the three year study period). At the small scale (of a single day) fish and small fish spatial correlations with each other were much weaker. It is possible that larger fish and small fish are spatially correlated due to preferred habitat or environmental conditions rather than due to predation.

Seasonal and regional distribution patterns - Duncan and Kubecka (1996) found that the variability in backscatter from fish in the Thames River was due to patchiness in their geographic distribution. In this study, the large variability in measured backscatter was a function of the patchiness of the distribution in fish and zooplankton on the HRE. There were a number of time periods (generally lasting several days) when mean backscatter increased and variability in backscatter decreased in all three groups, which could be related to fish densities increasing estuary-wide due to spring spawning and migration events.

Seasonal variations in fish populations frequently show patterns of spring increases followed by much smaller fall increases in both numerical abundance and biomass due to reproduction and growth (Hagan and Able, 2003; Curti 2005; Peterson 1996; Kraus and Secor 2004). In this study, spring and fall peaks in abundance for fish were measured. In addition to seasonal peaks in fish abundance, there was also a pattern of increasing backscatter from fish and small fish throughout 2014, which could be growth in the average size of fish or an increase in the abundance of fish from April to October.

Spring and fall blooms in zooplankton have been observed in many temperate regions of the world (Andersen *et al.* 2001, Bautista and Harris 1990, Conover and Mayzaud 1984), including the Hudson River (Pace *et al.* 1992, Lonsdale *et al.* 1996, Pace and Lonsdale 2006). This study measured a large spring bloom and smaller fall bloom in zooplankton abundance. The lower August and September backscatter from zooplankton, compared to the preceding and following months, may be a result of predation pressure, decrease in prey availability, or possibly reaching a temperature tolerance threshold which could cause zooplankton to die in the summer months.

Regional patterns in backscatter show that the Albany and New York City regions had greater abundance of fish and small fish. This could be due to overlapping habitats between marine and estuarine fish in the NYC Region, migratory and spawning behavior in the Albany region (as was suggested in the seasonal patterns), or possibly a response to changing conditions after the zebra mussel invasion. Pelagic fish abundance in the freshwater reaches of the HRE decreased with declines in zooplankton immediately after the introduction of the zebra mussel (Strayer *et al.,* 2006), however the findings of this study may indicate preliminary signs of a recovery in the past three years as the invasive bi-valve impact on zooplankton has decreased. High scattering from fish and small fish increased in the NYC region throughout the year, this could be due to fish echo strength increasing with growth of fish, or could be due to an increase in abundance of fish throughout the year to that region.

Seasonal patterns between the regions for fish and small fish could be due to spring spawning and migration to the upriver regions (Poughkeepsie and Albany) of the HRE. Zooplankton scattering generally increased as proximity to the Atlantic Ocean decreased, except for a spring, and smaller fall, peak in abundance in the Poughkeepsie region that may be the typical a spring and fall zooplankton blooms in this area. The similar regional distribution patterns exhibited by fish and small fish could be evidence of similar habitat preferences between these size groups, or could be evidence of large fish preying upon small fish. The very different regional distribution pattern exhibited by zooplankton could be evidence of fish and small fish predation pressure limiting zooplankton abundance, or could be a result of the taxonomic groups exhibiting different habitat preferences, or this could possibly be an example of too large a spatial scale to observe predator-prey patterns (Smith, 1978).

Biological distribution and environmental conditions - Zooplankton populations have been shown to be regulated by advective transport with abundance decreasing in the HRE during periods of higher freshwater discharge into the system (Pace *et al.* 1992). Backscattering from zooplankton decreased during higher discharge periods in all parts of the estuary in this study except near World's End (rkm

78), where scattering increased. This is possibly related to World's End being the deepest and narrowest part of the HRE with the strongest tidal currents which may produce backscatter from turbulence in the water column (Warren *et al*., 2003) or from the currents concentrating organisms. Zooplankton abundance decreased differentially along the rest of the latitudinal gradient of the estuary, with the largest decreases in the freshwater reaches of the upper estuary (rkm 128-240) and near the mouth of the estuary (rkm 0). Zooplankton may become concentrated in one part of the estuary when freshwater discharge rates are high.

The center of fish populations often move down river during years of higher average freshwater discharge into the HRE (Strayer *et al.* 2014). Decreases in weighted latitudes for all three groups (fish, small fish, and zooplankton) during high freshwater flow periods indicate a down-river shift in scattering for all three groups. Fish abundance shifted latitudinally in this study on a smaller time-scale and with a more complex pattern as well. Fish scattering decreased in the upriver freshwater (rkm 128-240) and the downriver reaches of the HRE (<rkm 90) during periods of high flow, however, it remained relatively the same in Newburgh Bay (rkm 98). Small fish backscatter decreased at all latitudes during periods of high freshwater discharge, especially in upriver areas (rkm 128-240) and Haverstraw Bay (rkm 40). Juvenile fish may be impacted most heavily by increases in discharge on a latitudinal scale, by being flushed out of the estuary, and thus may be the most vulnerable group to changes in flow rates.

Fish, small fish, and zooplankton backscatter were collected concurrently (on the same temporal and spatial scales) in this study, however, it has been shown that the scale at which each group are analyzed may influence abundance and distribution patterns (Levin, 1992). Rose and Loggett (1990) found that at smaller (< 3 km) spatial scales predator and prey were not spatially correlated in the Atlantic Ocean, however at larger (> 4 km) scales they were correlated with each other. The differences in spatial correlations were attributed to different drivers impacting fish distribution at larger (environmental conditions) or smaller scales (avoidance behavior). In the HRE, environmental conditions, such as water temperature and salinity, may impact the distribution and patchiness of fish or zooplankton on a 100-1000 m scale (Duncan and Kubecka, 1996), where as the spatial correlations between predator-prey may impact the distribution of fish and zooplankton on a 0.1 – 10 m scale (Tipton, 2003).

Local environmental variables at the time of sampling have been shown to be less important than preceding temperature and flow conditions to the population dynamics of fish in estuaries (Wingate and Secor, 2008). One of the hypotheses we tested, was that biological distribution and abundance patterns would be positively correlated with salinity, however, we found no clear patterns in fish, small fish, or zooplankton distribution associated with particular salinity ranges. Fish and zooplankton distributions were also not associated with river depths, however, some of the regional differences in backscatter may be river bathymetry varying in these regions. Scattering from fish and small fish increased with temperature, however, this may be a secondary effect of fish backscatter increasing throughout the year. Fish scattering was the highest in well-oxygenated (7-8 mg/l) waters, however, there were high levels of backscatter measured at the low (3 mg/l) dissolved oxygen levels suggesting fish in the HRE can tolerate a wide range of oxic conditions.

Local environmental conditions (such as dissolved oxygen, water temperature, salinity, and turbidity) and time of day did not have measurable relationships with the distribution of fish and zooplankton in the HRE. Geographic region, season, and fresh water discharge did influence the distribution and abundance of acoustic backscatter from fish and zooplankton on the HRE. Another hypothesis tested was that fish and zooplankton distribution and abundance were impacted by freshwater discharge differently. The decrease in weighted latitudes based upon scattering during high discharge periods compared to low discharge periods, suggests that all three groups shifted downriver during increases in freshwater flow to the HRE, Fish, small fish, and zooplankton backscatter decreased during high freshwater discharge periods in latitudinal patterns different from each other as well. Small fish backscatter decreased at all latitudes along the river, whereas fish and zooplankton decreased the most in the upriver regions of the HRE as well as near the mouth of the estuary, but not at certain mid-estuary regions. This could be the result of fish and zooplankton maintaining their positions intentionally or being trapped in certain areas.

The abundance and distribution of fish in the Hudson River have been studied with great interest as environmental conditions increasingly vary due to climate variability, anthropogenic river uses, and newly introduced species to the system (Howarth *et al.,* 1996; Pace *et al.,* 1992; Pace and Lonsdale, 2006; and Limburg *et al.,* 2006, Strayer *et al.* 2004). The use of new technologies, such as fisheries acoustics to this complex system has provided some important insights into animal abundance and distribution already, but the applications of acoustics to study fish and zooplankton have been extremely limited in either (or both) their spatial or temporal coverage (Zahn, 1993; Hartman and Nagy, 2006; Tipton, 2003; Able *et al.* 2013; and Grotheus and Able, 2010). This data set is the most extensive acoustic survey (both temporally and spatially) on the Hudson River Estuary to date.

This study is a valuable example of how ships of opportunity can be used for biological acoustic surveys while providing extremely high temporal and spatial resolution data over large geographic areas and time periods. Examining patterns in fish and zooplankton abundance and distribution in very complex systems, such as estuaries, is benefited by the use of long term data series covering wide geographic ranges. As the impacts of climate variability and anthropogenic habitat alterations perpetually alter these biologically important regions, studies that can take advantage of increased sampling capabilities will become increasingly valuable to the scientific and regulatory communities.

Fish, crab, and zooplankton distribution and abundance are variable both spatially and temporally on fine (meters, and days to weeks) and coarse (100s of meters, and months to years) scales. Examining trends in biological distribution and abundance patterns are best done on a regional scale, rather than considering the entire HRE system as a whole because underlying regional trends become masked by system-wide patterns. Local climate conditions, such as freshwater discharge rates and winter NAO index, impact biological abundance patterns in certain regions of the HRE.

Bibliography

Able, K. W., Grothues, T. M., and Kemp, I. M. (2013). Fine-scale distribution of pelagic fishes relative to a large urban pier. Marine Ecology Progress Series, 476, 185-198.

Able, K. W., Grothues, T. M., Rackovan, J. L., and Buderman, F. E. (2014). Application of Mobile Dual-frequency Identification Sonar (DIDSON) to Fish in Estuarine Habitats. Northeastern Naturalist, 21(2), 192-209.

Abood, K. A., Apicella, G. A., and Wells, A. W. (1992). General evaluation of Hudson River freshwater flow trends. Estuarine research in the 1980s. State University of New York Press, Albany, 3-28.

Andersen, V., Gubanova, A., Nival, P., and Ruellet, T. (2001). Zooplankton community during the transition from spring bloom to oligotrophy in the open NW Mediterranean and effects of wind events. 2. Vertical distributions and migrations. Journal of Plankton Research, 23(3), 243-261.

ASA. Analysis and Communication Inc. (2010). Year Class Report for Hudson River Monitoring Program. Prepared for and jointly funded by Central Hudson Gas and Electric Corporation. Consolidated Edison Company of New York, Inc. 2003.

Ashizawa, Donna, and Jonathan J. Cole. (1994). Long-term temperature trends of the Hudson River: a study of the historical data. Estuaries 17.1, 166-171.

Bain, M. B. (2011). Target fish communities for restoration of waterways supporting society and nature. Journal of Applied Ichthyology, 27(s3), 86-93.

Basu, B.K. and Pick, F.R. (1996). Factors regulating phytoplankton and zooplankton biomass in temperate rivers. Limnol. Oceanogr. 41(6): 1572-1577

Bautista, B., and Harris, R. P. (1992). Copepod gut contents, ingestion rates and grazing impact on phytoplankton in relation to size structure of zooplankton and phytoplankton during a spring bloom. Marine Ecology Progress Series, 82(1), 41-50.

Beamish, F. W. H. (1966). Vertical migration by demersal fish in the Northwest Atlantic. Journal of the Fisheries Board of Canada, 23(1), 109-139.

Bezerra-Neto, J. F., Brighenti, L. S.,and Pinto-Coelho, R. M. (2013). Implementation of hydroacoustic for a rapid assessment of fish spatial distribution at a Brazilian Lake-Lagoa Santa, MG. Acta Limnologica Brasiliensia, 25(1), 91-98.

Bradbury, James A., S. Lawrence Dingman, and Barry D. Keim.(2002) New England Drought and Relations with Large Scale Atmospheric Circulation Patterns. Journal of the American Water Resource Association: 38(5)1287-1299.

Brierley, A. S., Ward, P., Watkins, J. L., and Goss, C. (1998). Acoustic discrimination of Southern Ocean zooplankton. Deep Sea Research Part II: Topical Studies in Oceanography, 45(7), 1155-1173.

Brown, C. L., Doroshov, S. I., Nunez, J. M., Hadley, C., Vaneenennaam, J., Nishioka, R. S., & Bern, H. A. (1988). Maternal triiodothyronine injections cause increases in swimbladder inflation and survival rates in larval striped bass, Morone saxatilis. Journal of Experimental Zoology, 248(2), 168-176.

Carruthers, T. R., Ahrens, R. N., McAllister, M. K., & Walters, C. J. (2011). Integrating imputation and standardization of catch rate data in the calculation of relative abundance indices. Fisheries Research, 109(1), 157-167.

Churchill, E. P. (1919). Life History of the Blue Crab. Bulletin of the Bureau of Fisheries. 36(870), 95-122.

Cole, JJ, Solomon, CT. (2012). Terrestrial support of zebra mussels and the Hudson River food web: A multi-isotope Bayesian analysis. Limnol. Oceanogr., 57(6) 1802-1815

Conover, R. J., and Mayzaud, P. (1984). Utilization of phytoplankton by zooplankton during the spring bloom in a Nova Scotia inlet. Canadian Journal of Fisheries and Aquatic Sciences, 41(2), 232-244.

Curti, K. L. (2005). Patterns in the Distribution, Diet and Trophic Demand of the Hogchoker, Trinectes Maculatus, in the Chesapeake Bay, USA (Master's thesis).Retrieved from http://drum.lib.umd.edu/bitstream/handle/1903/2572/umi-umd-2459.pdf.

Daniels, R, Limburg, K.E, Schmidt, R.E., Strayer, D.L., Chambers, R.C. (2005). Changes in Fish Assemblages in the Tidal Hudson River, New York. American Fisheries Society Symposium 45,471-503

D'Elia, M., Warren, J. D., Rodriguez-Pinto, I., Sutton, T. T., Cook, A., and Boswell, K. M. (2016). Diel variation in the vertical distribution of deep-water scattering layers in the Gulf of Mexico. Deep Sea Research Part I: Oceanographic Research Papers.115, 91-102.

de Vries, M.P., and Weiss, L.A., (2001). Salt-Front Movement in the Hudson River Estuary, New York--Simulations by One-Dimensional Flow and Solute-Transport Models. U.S. Geological Survey Water-Resources Investigations Report 99-4024, 69.

Dew, C. B., and Hecht, J. H. (1994). Hatching, estuarine transport, and distribution of larval and early juvenile Atlantic tomcod, Microgadus tomcod, in the Hudson River. Estuaries, 17(2), 472-488.

Duncan, A., and Kubecka, J. (1996). Patchiness of longitudinal fish distributions in a river as revealed by a continuous hydroacoustic survey. ICES Journal of Marine Science: Journal du Conseil, 53(2), 161-165.

Echoview Software Pty Ltd. (2015). Echoview software, version 6.1.44. Echoview Software Pty Ltd, Hobart, Australia

Geyer, W. R., and Chant, R. (2006). The physical oceanography processes in the Hudson River estuary (pp. 13-23). Cambridge University Press.

Grabe, S. A. (1996). Feeding chronology and habits of Alosa spp.(Clupeidae) juveniles from the lower Hudson River estuary, New York. Environmental Biology of Fishes, 47(3), 321-326.

Grothues, T. M., and Able, K. W. (2010). Association of Adult Fishes with Piers in the Lower Hudson River: Hydroacoustic Surveys for an Undersampled Resource. Institute of Marine and Coastal Sciences.

Guillard, J. and Vergès, C. (2007). The repeatability of fish biomass and size distribution estimates obtained by hydroacoustic surveys using various sampling strategies and statistical analyses. International Review of Hydrobiology, 92(6), 605-617.

Hagan, S. M., and Able, K. W. (2003). Seasonal changes of the pelagic fish assemblage in a temperate estuary. Estuarine, Coastal and Shelf Science, 56(1), 15-29.

Harrell, F. (2015). Regression modeling strategies: with applications to linear models, logistic and ordinal regression, and survival analysis. Springer.

Hartman, K. J., Nagy, B., Tipton, R. C., and Morrison, S. (2000). Verification of hydroacoustic estimates of fish abundance in Ohio River lock chambers. North American Journal of Fisheries Management, 20(4), 1049-1056.

Hartman, K. J., and Nagy, B. W. (2006). Winter distribution and abundance of Hudson River fishes using hydroacoustics. In American Fisheries Society Symposium (Vol. 51, p. 175). American Fisheries Society.

Howarth, R. W., R. Schneider, and D. Swaney. (1996). Metabolism and organic carbon fluxes in the tidal freshwater Hudson River. Estuaries 19.4: 848-865.

Howarth, R. W., Marino, R., Swaney, D. P., and Boyer, E. W. (2006). 10 Wastewater and Watershed Influences on Primary Productivity and Oxygen Dynamics in the Lower Hudson River Estuary. The Hudson River Estuary, 121.

Hurst, T. P., and Conover, D. O. (2002). Effects of temperature and salinity on survival of young-of-the-year Hudson River striped bass (Morone saxatilis): implications for optimal overwintering habitats. Canadian Journal of Fisheries and Aquatic Sciences, 59(5), 787-795.

Hurst, T. P., McKown, K. A., and Conover, D. O. (2004). Interannual and long-term variation in the nearshore fish community of the mesohaline Hudson River estuary. Estuaries, 27(4), 659-669.

Juanes, F., Marks, R. E., McKown, K. A., & Conover, D. O. (1993). Predation by age-0 bluefish on age-0 anadromous fishes in the Hudson River estuary.Transactions of the American Fisheries Society, 122(3), 348-356.

Kerr, L. A., Secor, D. H., and Piccoli, P. M. (2009). Partial migration of fishes as exemplified by the estuarine-dependent white perch. Fisheries, 34(3), 114-123.

Kraus, R. T., and Secor, D. H. (2004). Dynamics of white perch Morone americana population contingents in the Patuxent River estuary, Maryland, USA. Marine Ecology Progress Series, 279, 247-259.

Kubecka, J., Frouzová, J., Vilcinskas, A., Wolter, C., and Slavík, O. (2000). Longitudinal hydroacoustic survey of fish in the Elbe River, supplemented by direct capture. Management and Ecology of River Fisheries, 14-25.

Lake, Thomas R., and Robert E. Schmidt. (1996). Seasonal presence and movement of fish populations in the tidal reach of Quassaic Creek. Final Reports of the Tibor T. Polgar Fellowship Program: 1-36

Levin, S. A. (1992). The problem of pattern and scale in ecology: the Robert H. MacArthur award lecture. Ecology, 73(6), 1943-1967.

Levinton, JS and Waldman, JR. (2006). The Hudson River Estuary: Executive Summary. Cambridge University Press. NY, NY.

Limburg, K. E., and Waldman, J. R. (2009). Dramatic declines in North Atlantic diadromous fishes. BioScience, 59(11), 955-965.

Llansó, R. J., Scott, L. C., Dauer, D. M., Hyland, J. L., and Russell, D. E. (2002). An estuarine benthic index of biotic integrity for the mid-Atlantic region of the United States. I. Classification of assemblages and habitat definition. Estuaries, 25(6), 1219-1230.

Lonsdale, D.J., Cosper, E.M., and Doall, M. (1996). Effects of zooplankton grazing on phytoplankton size-structure and biomass in the lower Hudson River estuary. Estuaries 19:874-89.

Love, R. H. (1971). Measurements of fish target strength: a review. Fish. Bull, 69(4), 703-715.

Maclennan, D.N., Fernandes, P.G. and Dalen, J., 2002. A consistent approach to definitions and symbols in fisheries acoustics. ICES Journal of Marine Science: Journal du Conseil, 59(2), pp.365-369.

McCairns, R. S., and Fox, M. G. (2004). Habitat and home range fidelity in a trophically dimorphic pumpkinseed sunfish (Lepomis gibbosus) population. Oecologia, 140(2), 271-279.

Moritz, Steffen (2015). imputeTS: Time Series Missing Value Imputation. R package version 0.4. http://CRAN.R-project.org/package=imputeTS

Moritz, S., Sardá, A., Bartz-Beielstein, T., Zaefferer, M., & Stork, J. (2015). Comparison of different Methods for Univariate Time Series Imputation in R. arXiv preprint arXiv:1510.03924.

Niemisto, M. and Warren, J. D. In Review Seasonal and annual patterns in fish and crab abundance, assemblage, and distribution in the Hudson River Estuary from 1999 to 2015. Estuaries and Coasts.

NOAA North Atlantic Oscillation Data: http://www.cpc.ncep.noaa.gov/data/teledoc/nao.shtml

O'Connor, M. P. (2010). Identifying Critical Fish Habitat and Long-term Trends in Fish Abundances in the Hudson River Estuary (Doctoral dissertation). Retrieved from http://scholarworks.umass.edu/cgi/viewcontent.cgi?article=1207&context=open_access_dissertations.

O'Connor, M. P., Juanes, F., McGarigal, K., and Gaurin, S. (2012). Findings on American Shad and striped bass in the Hudson River Estuary: a fish community study of the long-term effects of local hydrology and regional climate change. Marine and Coastal Fisheries, 4(1), 327-336.

O'Connor, M. P., Juanes, F., McGarigal, K., and Caris, J. (2012). Describing juvenile American shad and striped bass habitat use in the Hudson River Estuary using species distribution models. Ecological Engineering, 48, 101-108.

O'Conner, MP. (2012). Findings on American Shad and Striped Bass in the Hudson River Estuary: A Fish community study of the long-term effects of local Hydrology and Regional Climate Change. Marine and Coastal Fisheries 4(1):327-336

O'Conner, M.P. and F. Juanes (2006). Development of an Upper Hudson River Estuary GIS-Based Fish Data Resource. Section IV:28pp. In W.C. Neider and J.R. Waldman, Final Reports of the Tibor T. Polgar Fellowship Program. Hudson River Foundation.

Pace, Michael L., Stuart EG Findlay, and David Lints.(1992). Zooplankton in advective environments: the Hudson River community and a comparative analysis. Canadian Journal of Fisheries and Aquatic Sciences 49.5: 1060-1069.

Pace, Michael L., and Darcy J. Lonsdale. (2006). The Hudson River Estuary: River Zooplankton Community.: 217

Peebles, E. B., Burghart, S. E., and Hollander, D. J. (2007). Causes of interestuarine variability in bay anchovy (Anchoa mitchilli) salinity at capture. Estuaries and coasts, 30(6), 1060-1074.

Peterson, T. L. (1996). Seasonal migration in the southern hogchoker, Trinectes maculatus fasciatus (Achiridae). Gulf Research Reports 9(3): 169-176.

Peterson-Curtis, T. L. (1997). Effects of salinity on survival, growth, metabolism, and behavior in juvenile hogchokers, Trinectes maculatus fasciatus (Achiridae). Environmental Biology of Fishes, 49(3), 323-331.

Ralston, D. K., Geyer, W. R., & Lerczak, J. A. (2008). Subtidal salinity and velocity in the Hudson River estuary: Observations and modeling. Journal of Physical Oceanography, 38(4), 753-770.

Rose, G. A., and Leggett, W. C. (1990). The importance of scale to predator‐ prey spatial correlations: an example of atlantic fishes. Ecology, 71(1), 33-43.

Samedy, V., Josse, E., Guillard, J., Pierre, M., Girardin, M., & Boët, P. (2013). Comparison of vertical mobile hydroacoustic survey strategies for monitoring fish distributions in the Gironde estuary (France). Estuarine, Coastal and Shelf Science, 134, 174-180.

Samedy, V., Wach, M., Lobry, J., Selleslagh, J., Pierre, M., Josse, E., and Boët, P. 2015. Hydroacoustics as a relevant tool to monitor fish dynamics in large estuaries. Fisheries Research, 172, 225-233.

Schwartz, F. J., amd Jachowski, R. (1965). The age, growth, and length-weight relationship of the Patuxent River, Maryland ictalurid white catfish, Ictalurus catus. *Chesapeake Science*, 226-229.

Seaby, R. M., and Henderson, P. A. (2006). Species diversity and richness version 4. Pisces Conservation Ltd., Lymington, England.

Schneider, T. (2001). Analysis of incomplete climate data: Estimation of mean values and covariance matrices and imputation of missing values. Journal of Climate, 14(5), 853-871.

Singkran, N. and Bain, M. (2008). Abundance exchange models of fish assemblages along the Hudson River Estuary Gradient, New York. Water Science and Techonology. 58(11):2133-2142

Simmonds, John, and MacLennan, David N. (2008). Fisheries acoustics: theory and practice. John Wiley & Sons.

Smith, P. E. (1978). Biological effects of ocean variability: time and space scales of biological response. Rapports et Proces Verbaux des Reunions.

Sprent, P., and Dolby, G. R. (1980). Query: the geometric mean functional relationship. Biometrics, 36(3), 547-550.

Stainbrook, Karen M., Karin E. Limburg, Robert A. Daniels, and Robert E. Schmidt. (2006). Long-term changes in ecosystem health of two Hudson Valley watersheds, New York, USA, 1936–2001. Hydrobiologia 571(1): 313-327.

Stanton, Timothy K., Dezhang Chu, and Peter H. Wiebe. (1998). Sound scattering by several zooplankton groups. II. Scattering models. *Journal of the Acoustical Society of America* 103 (1), 236-253.

Stehlik, L. L., Pikanowski, R. A., and McMillan, D. G. (2004). The Hudson-Raritan Estuary as a crossroads for distribution of blue (Callinectes sapidus), lady (Ovalipes ocellatus), and Atlantic rock (Cancer irroratus) crabs. *Fishery Bulletin,* 102(4), 693-710.

Stepien, Jeanne C., Thomas C. Malone, and Mira B. Chervin. (1981). Copepod communities in the estuary and coastal plume of the Hudson River. Estuarine, Coastal and Shelf Science13.2: 185-195

Strayer, D. L., Hattala, K. A., and Kahnle, A. W. (2004). Effects of an invasive bivalve (Dreissena polymorpha) on fish in the Hudson River estuary. Canadian Journal of Fisheries and Aquatic Sciences, 61(6), 924-941.

Strayer, D.L., Cole, J.J., Findlay, S.E., Fischer, D.T., Gephart, J.A., Malcom, H.M., PACE, M.L. Rosi-Marshall, E.J. (2014). Decadal-Scale Change in a Large-River Ecosystem. Journal of BioScience. 64(6):496-510

Strayer, D. L. (2006). 21 Alien Species in the Hudson River. The Hudson River Estuary, 296. Cambridge University Press, New York.

Strayer, D.L., K.Hattala, A. Kahnle (2014). Effects of an invasive bivalve (Dressena polymorpha) on fish in the Hudson River esturay. Canadian Journal of Fisheries and Aquatic Sciences. 61(6):924-941

Stehlik, L. L., Pikanowski, R. A., and McMillan, D. G. (2004). The Hudson-Raritan Estuary as a crossroads for distribution of blue (Callinectes sapidus), lady (Ovalipes ocellatus), and Atlantic rock (Cancer irroratus) crabs. Fishery Bulletin, 102(4), 693-710.

Taylor, Christopher J., and Peter S. Rand. (2003). Spatial overlap and distribution of anchovies (Anchoa spp.) and copepods in a shallow stratified estuary. Aquatic Living Resources16.03: 191-196.

Tipton, R. C. 2003. Distributional ecology of bay anchovy Anchoa mitchilliin the Hudson River Estuary, New York. West Virginia University, Morgantown

US Army Corp of Engineers. (2015). Fact Sheet: http://www.nan.usace.army.mil/Media/FactSheets/FactSheetArticleView/tabid/11241/Article/487535/fact-sheet-hudson-river-channel-ny-40-ft.aspx

USGS Green Island Discharge data: http://waterdata.usgs.gov

Urmy, Samuel S. SDWBA.jl: A Julia package for modeling acoustic backscatter from zooplankton, v0.1. URL: https://github.com/ElOceanografo/SDWBA.jl. DOI:10.5281/zenodo.56814.

Waldman, John R. (2006). The Diadromous Fish Fauna of the Hudson River: Life Histories, Conservation Concerns, and Research Avenues. The Hudson River Estuary: 171

Warren, J.D. Stanton, T. K. Wiebe, P. H. and Seim, H. E. (2003). Inference of biological and physical parameters in an internal wave using multiple-frequency, acoustic-scattering data. ICES Journal of Marine Science. 60(5): 1033-1046

Wingate, R. L., & Secor, D. H. (2008). Effects of winter temperature and flow on a summer-fall nursery fish assemblage in the Chesapeake Bay, Maryland. Transactions of the American Fisheries Society, 137(4), 1147-1156.

Zahn, Stephen Michael.(1993) A hydroacoustic examination of the distribution and swimming behavior of fish in the lower Hudson River Estuary (Doctoral dissertation). State University of New York at Stony Brook.