CHANGING FISH ASSEMBLAGES IN A MID-ATLANTIC ESTUARY: SENSITIVITY ANALYSIS OF A LONG-TERM TIME SERIES TO CLIMATE CHANGE AND GUILD CONSTRUCTION

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ABSTRACT OF THE THESIS

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At the beginning of the 21st century, climate change is among the foremost of ecological concerns in both marine and terrestrial habitats. Generally, mobile species, such as fishes, have shifted their ranges poleward in response to changing climatic conditions in the Northern Hemisphere. On a local scale, however, different fish species have displayed differing shifts in latitude and habitat. It is therefore important to study the change in assemblage shifts on a local scale. I examined the change in fish assemblages, environmental conditions, and the relationship between them, over time in the Mullica River-Great Bay estuary, located in southern New Jersey. I used a long-term time series collected by the Rutgers University Marine Field Station and the Jacques Cousteau National Estuarine Research Reserve's System Wide Monitoring Protocol. I also organized fish species into guilds based on reproductive or origin characteristics, and into abundant and rare species assemblages as a proxy for species, and examined the change in these guilds over time as compared to the full assemblage. Water temperatures in the system rose on average, with Average Summer Temperatures explaining the most variance in the change of fish assemblages. Both the full assemblage and guild analyses also indicated that freshwater-favoring and spawning species increased in importance, while juveniles of estuarine spawners decreased overall. Marine spawners and species did not change significantly, suggesting that change in species local to the system has had a greater effect on the assemblage than change in recruits from the marine environment.

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CHAPTER 1

GENERAL INTRODUCTION

In both marine and terrestrial habitats, climate change is among the foremost of ecological concerns of the century. The U.S. Environmental Protection Agency defines climate change as "any significant change in the measures of climate lasting for an extended period of time" ("Climate Change: Basic Information" 2016). This would include factors such as temperature, precipitation, storm intensity, wind patterns, and atmospheric composition, among other variables (Lynch et al. 2015). Changing temperatures will vary across different latitudes and habitats, with a projected rise of up to 7 °C globally by 2100 (Sheridan and Bickford 2011). Melting sea ice is projected to raise air temperatures in high-latitude areas, with ocean temperature responding in a similar fashion over time (Rijinsdorp et al. 2009). Deep areas will change more slowly than shallow systems, due to the climate-moderating effects of water's high heat capacity, and the time required for this heat to reach deeper water (Hulme et al. 2002). Precipitation is projected to increase in some areas, while decreasing in others, and the associated change in runoff volume will affect factors such as nutrient load, salinity, and stratification in certain areas near the coast (IPCC 2007). Wind pattern and strength shifts are currently unprojected for most of the regions in question. These variables affect current flow and mixing, altering the strength and pattern of upwelling within the shallower coastal and shelf ecosystems (Rijnsdorp et al. 2009). In general, poleward shifts are projected in a number of different species, with delayed biological and environmental autumn events, especially at mid to high latitudes (Polockzanska et al. 2016).

All of these changes are potentially important for determining fish assemblage composition (Attrill and Power 2002, Lynch et al. 2015). Fish species are of particular interest to climate change because they are ectotherms, their metabolic rates, and therefore their physiological processes, are tied to temperature, so fishes tend to respond to climatic shifts as they happen (Pinsky et al. 2013, Perry et al. 2005). The expected effects of climate change on fishes can be divided into four basic categories; physiological, behavioral, population-level, and ecosystem-wide (Rijnsdorp et al. 2009).

One of the strongest of physiological effects is the response to temperatures. At higher temperatures, metabolic rates increase, and as a result, more energy is required for survival and maintenance of physiological processes (Sheridan and Bickford 2011). If increased caloric intake is not possible, energy may be diverted from other processes, including somatic growth and reproduction (Sheridan and Bickford 2011). Body size tends to decrease at higher environmental temperatures, not just in fishes, but in other animal taxa as well, from insects to mammals (Sheridan and Bickford 2011). Oxygen stress also becomes a factor at higher water temperatures. In fact, it has been hypothesized that the limiting factor for species' response to changing temperature was thermally limited oxygen delivery (Portner and Knust 2007). This is caused by the circulatory system of the animal being unable to meet oxygen demand as a result of altered performance at a temperature for which the system is not adapted, a problem that is exacerbated by reduced oxygen saturation in warmer waters. Some temperate species can acclimatize at the cost of other aspects of performance (Portner and Knust, 2007). The effect was pronounced in larger and older individuals of Zoarces viviparous, resulting in a population shift toward smaller individuals, before the overall abundance begins to decline (Portner and Knust 2007). In

general, smaller fish tend to be less fecund, which could have negative effects on overall population size.

In addition to the potential for decreased fecundity due to smaller body size, some species demonstrate ontogenetic effects, with climate affecting development at the egg and larval stages. Fish have complex life histories and growth strategies, generally increasing their body size by a factor of roughly 10⁵ and requiring multiple habitats at different life stages in order to grow to full maturity (Rothschild 1986). Access to these habitats at critical times in development is crucial to the survival of larval and juvenile fish. For instance, many larval fish spend development time in the estuarine habitat, given its ample sources of food and hiding places (Baker and Sheaves 2006, 2007). In addition, major currents play a role in transporting larval fish to suitable habitats, such as the Gulf Stream, which connects the Mid-Atlantic and South-Atlantic Bights (Rowe and Epifaino 1994, Grothues and Cowen 1999). Changes in the speed and location of these major currents due to climate change could also affect the distribution of larval fishes, and their ability to reach these suitable habitats. Climate change may also cause bottlenecks in the life histories of fishes requiring certain spawning habitats, such as diadramous or anadramous fishes (Lynch et al. 2015). These fishes depend on cues from both the freshwater and marine habitats to spawn, and changes to the timing of temperature changes in both habitats may be detrimental to the success of species moving between them (Lynch et al. 2015).

It has also been generally noted, however, that larval growth and metabolism increased at higher temperatures, and that tropical fish larvae had increased swimming ability as temperatures increased (Pimentel et al. 2014). When reared in the laboratory, for instance, winter flounder (*Pseudopleuronectes americanus*,) grew faster and survived longer at higher temperatures, as compared to those reared at lower and intermediate temperatures (Chambers et al. 2001). This pattern may be beneficial to the larvae themselves, as less time is spent in the vulnerable juvenile stages where early mortality is high. Additionally, Hiddink and Hofstede (2008) noted that the North Sea experienced an increase in species richness as bottom temperatures in the environment warmed over time. This could be caused by southern species shifting northward as temperatures in an area become better suited to their preferences and ideal habitat conditions (Dulvy et al. 2008).

Fish behavior is also likely to change as environmental conditions shift. Behavioral responses are comprised of migration, movement, reproduction, and foraging. Larval fish in temperate areas have a particularly hard time moving away from unfavorable environmental conditions, while tropical fish larvae are better swimmers (Franks 2001, Leis 2006). Adults and juveniles are able to seek out more optimal conditions (Kraus et al. 2015). The conditions which fish seek out as "optimal" are not easily predicted in terms of trade-offs due to the complexity of their environment, but are likely to be affected by increasing temperature. Additionally, other behavioral changes, such as swimming speed, reaction to fishing gear and predators, and annual migrations, are also affected by increased temperature, though the last is poorly understood (Rijnsdorp et al. 2009).

Individual fishes' response to changing climate can add up to a change at the population level. Population dynamics generally regard the overall production of a fish population, measured in net biomass gain (Rijnsdorp et al. 2009). This is measured by taking the total production of a population over a time period, made up of egg production, growth, and recruitment, and subtracting mortality and loss through emigration. Mortality tends to be high in the early stages, especially when spawning or egg-production habitats is sub-ideal, and recruitment of larvae depends on both optimal growth temperatures and food availability. Both of these will be affected by climate change, although it is not known whether there is a general trend, or, like ontogenetic temperature responses, the effects will differ from species to species (van der Veer et al. 2000, Wilderbuer et al. 2002, Sims et al. 2004). In general, fish also tend to be somewhat plastic in their size and age of sexual maturity (Rijnsdorp et al. 2009). When combined with Portner and Knust's (2007) finding that smaller fish are less sensitive to temperature effects, one might project that, as temperatures rise and thermal stresses grow, fish are more likely to put more effort into reproduction at earlier age and smaller size, rather than growth. An argument for earlier mortality follows along simpler lines; at larger temperature extremes, mortality is more likely to increase, whether these temperatures take the form of lethal lows or highs. A decline in winter kill may also occur in certain species as temperatures warm. Atlantic croaker (*Micropogonias undulatus*,) for instance, recruit more strongly at the northern margin of their range when winter temperatures are warm, as juveniles are provided a refuge from otherwise fatal winter temperatures (Hare and Able 2007).

The ecosystem-wide effects of climate change are among the hardest to predict, as they include multiple trophic levels and abiotic factors. As fish are consumers, and are often among the higher trophic levels of the marine food chain, they are dependent on the lower trophic levels for food, so climate change's effects on primary, and often secondary productivity, all have an effect on fish assemblages as well (Cushing 1990). Primary production in events such as phytoplankton blooms, which provide a source of food to which many species time their spawning, could be enhanced by increased upwelling, increased riverine output, or differing species comprising blooms and inhabiting areas due to the changes in available nutrients (Rijnsdorp et al. 2009). The consequences are still unclear.

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It has also been suggested that shallow-water species will be more heavily affected than deep-water fishes, and experience greater range shifts as a result. Species that are primarily pelagic, (living in the water column), will react differently than species living close to the bottom, in a demersal habitat, as bottom temperatures can differ from temperatures in the water column (Rijnsdorp et al. 2009, Dulvy et al. 2008). Shallow and deep water species will also react differently, for similar reasons. Overall, it has been hypothesized that populations at the limits of their latitudinal ranges will exhibit stronger responses than populations at the center of their latitudinal distribution. In the northern hemisphere, northerly species at the southern limits of their distributions have also been hypothesized to decrease, while southerly species at the northern end of their distributions will increase. Northerly species will also retreat to deeper, cooler waters in response to increasing surface temperatures, under these hypotheses (Rijnsdorp et al. 2009).

Life history characteristics may also play a role in determining how species will respond to changing climate, with fishes with longer life cycles or more specialized diets adapting more slowly to the change than those with short generation times or varied food sources (Rijnsdorp et al. 2009). Generalist species are more flexible than specialists, and can move to a different prey item if their staple declines in abundance due to climate effects, while specialists do not have this option. Species with r-selection strategies and K-selection strategies tend to differ in effects based on the longevity of the species that utilize each strategy. Those with r-selection strategies tend to be shorter-lived, reproducing quickly, producing abundant offspring and providing little parental care (Southwood et al. 1974). Because the generation times of most r-strategists are so short, they are thought to be better able to adapt to changing conditions, with offspring passing on favorable genes relatively quickly (Perry et al. 2005). K-strategists, on the other hand, produce fewer offspring that are more suited to compete in the current environment, and often mature more slowly (Rijnsdorp et al. 2009).

The changes in the physiology, behavior, and population dynamics of each species of fish in an area result in changes in survival and reproduction of each species. These changes ultimately cause a shift in the number and types of fish species found within a specific locale. This collection of species is known as a fish assemblage. Fish assemblages in the North Sea have become a well-known case study of assemblage-wide shifts as a result of changing climate. The movements of six different species were observed, in association with warming temperatures, including some species heavily exploited by fishing pressure (Perry et al. 2005). In each group, the species assemblage shifted toward colder water, both latitudinally and depth-wise, in response to a rise in water temperatures in the North Sea by roughly 1.05 °C over the period 1977 - 2001. Fishing effort was factored into the dataset, and was found to have remained steady over the course of the study, suggesting that increased fishing pressure was not driving the shifts in species range observed. Most species shifted north as well, with the exception of two; Trisopterus esmarkii shifting southward due to cooler water temperatures at a lower latitude, and Solea solea suspected shift south because of a restoration in important nursery habitat in the Thames estuary. Dulyy et al. (2008) further expanded on these results by examining both the latitudinal shift and the deepening and shallowing, or movement into deeper or shallower water, with regard to climate records over a 25 year period. By examining groundfish trawl survey data, the authors were able to support the assertion of Perry et al. (2005) that the species assemblages in the North Sea had deepened coherently, by a total of 3-6 m over the course of a decade. This response in occupied depth, although unclear regarding ecological implications, was more coherent than the latitudinal range shifts. As a result, it was proposed as a useful indicator for

change on moderate-term climate scales and for semi-enclosed basins, such as the Mediterranean. Moreover, the authors note that not all species shift along the same timescales, resulting in the potential creation of interactions that did not exist before, as species' ranges begin to overlap one another. Musumeci et al. (2013) also note this trend in their study on *Anguilla rostrata* and *Conger oceanicus* in southern New Jersey. Data collected over a 21 year period suggests that there has been a change in timing of each species' ingress into the estuary, and that the two overlap more, which may result in increased competition for habitat space resources. Additionally, *C. oceanicus* attacked and consumed *A. rostrata* in a laboratory setting, suggesting that there may be predator-prey interactions in the field that were not previously as prevalent, given their limited historical overlap.

Marine taxa track local climate velocities, shifting in latitude as temperatures change (Pinsky et al. 2013). These shifts were not universally northward in direction; however, with individual species shifting in different directions, and overall local assemblages shifting both longitudinally, and zonally. As this is typically the case, the study of assemblages on a local scale is also important, as the composition of a local assemblage can change in a different ways than the broad, global pattern, and climate velocities may vary from region to region (Pinsky et al. 2013). This tendency of assemblages to shift with changing climate presents another problem, however, as fishes are highly migratory, and larvae are often transported far from their spawning site by currents, resulting in populations recruiting outside of their ideal or native range (McBride and Able 1998, Grothues et al. 2002, Pinsky et al. 2013). The effects of transport and migration can be difficult to tease out from those of climate, though the two are probably integrated.

In this study I used a time series of primarily young-of-the-year fish data, along with climatic data, to examine the relationship between climate change and fish assemblage composition in a Mid-Atlantic estuary, using both a full species composition and a guild approach. An attempt was made to determine whether fish assemblages in the study system showed an inter-annual change in composition consistent with changing climatic variables, such as water temperature and weather patterns. Finally, I assessed the use of guilds based on reproductive characteristics and origin relative to the system to explain the change in fish assemblages in the study system, as compared to a full-assemblage analysis. By establishing broad patterns of change within the estuary in an exploratory study, I hope to pave the way for further, more targeted and hypothesis-driven studies of the system and the fishes inhabiting it.

CHAPTER 2

Long-Term Change in Fish Assemblages in a Mid-Atlantic Estuary: Analysis of a Decades-Long Time Series

ABSTRACT

Changing climate causes fish species to shift their ranges. While there is a general northward trend to the shift in the northern hemisphere, local assemblages can shift in a different direction based on changes in climatic conditions specific to the area in which they reside. I examined the change in climate in a mid-Atlantic estuary, and the effects that this change had on the fish assemblage within the system during summer and fall months over a 16 year time series. Using environmental data collected by the Jacques Cousteau National Estuarine Research Reserve's System-Wide Monitoring Program, and fish abundance data from the Rutgers Marine Field Station's long-term otter trawl program, I performed principal components analysis to determine whether the fish assemblages within the Mullica River-Great Bay estuary were changing over the years, followed by canonical correspondence analysis in order to determine if some routinely measured environmental factors could account for the largest explained variance on these changing assemblages. The composition of fish assemblages in the area has changed, shifting especially towards increased relative importance of White Perch (Morone americana), White Catfish (Ameiurus catus,) and Alewife (Alosa pseudoharrengus) overall, and away from Atlantic Silverside (Menidia menidia) and Northern Pipefish (Syngnathus fuscus). Changes in average summer temperatures explained the greatest variation of changing fish assemblages, with standard deviation of summer temperatures also statistically important. This indicates that summer temperatures, which are increasing in the system, have a strong role in changing the

assemblage composition over time. Overall, this study is exploratory in nature, and lays the groundwork for future mechanistic examination of species in the system.

INTRODUCTION

In both marine and terrestrial habitats, climate change is one of the foremost of ecological concerns. Changing temperatures will vary across regions, with a projected rise of up to 7 °C globally by 2100 (Sheridan and Bickford 2011). Precipitation is projected to increase in some areas, while decreasing in others, and the associated change in runoff volume will affect factors such as nutrient load, salinity, and stratification in coastal areas, all of which are potentially important influences on fish assemblage composition (IPCC 2007, Najjar et al. 2000, Attrill and Power 2002, Lynch et al. 2015).

Fish species are of particular interest with respect to climate change because fishes are ectotherms. Their metabolic rates, and therefore their physiological processes, are tied to temperature. Because of this, fishes tend to respond to climatic shifts as they happen (Pinsky et al. 2013, Perry et al. 2005). At higher temperatures, metabolic rates increase, and more energy is required for survival and maintenance of physiological processes (Sheridan and Bickford 2011). In order to meet metabolic needs, energy may be diverted from other processes, including somatic growth and reproduction, if increased caloric intake is not possible (Sheridan and Bickford 2011). In addition to the potential for decreased fecundity due to smaller sizes on average, some species demonstrate ontogenetic effects, with climate affecting development at the egg and larval stages (Rijnsdorp et al. 2009). Increased metabolism leads to faster larval growth. When reared in the laboratory, for instance, winter flounder (*Pseudopleuronectes americanus*,) a cold-water affiliated species, grew faster and survived better at higher temperatures, as compared to those reared at lower and intermediate temperatures (Chambers et al. 2001). This pattern may

be beneficial to the larvae themselves, as with increased growth due to temperature, less time is spent in the vulnerable juvenile stages where early mortality is high. Additionally, some tropical fish larvae increased swimming ability as temperatures increased, resulting in higher mobility (Pimentel et al. 2014). Fish have complex life histories and growth strategies, generally increasing their body size by a factor of roughly 10⁵ over their lifetime, and requiring multiple habitats at different life stages in order to grow to full maturity (Rothschild, 1986). Access to these habitats at critical times in development is crucial to the success of surviving larval and juvenile fish. For instance, many larval fish spend development time in estuarine habitat, given its ample sources of food and refuge (Baker and Sheaves 2006, 2007). If access to these crucial habitats changes as a result of changing climate, fish growth and survival could be affected.

In addition to changes in physiology, change is also likely in fish behavior as environmental conditions shift. Behavioral responses include migration, movement, reproduction, and foraging. Larval fish in temperate areas have a particularly hard time moving away from unfavorable environmental conditions (Leis 2006, Franks 2001). Adults and juveniles are able to seek out more optimal conditions because of their increased swimming ability (Kraus et al. 2015). The conditions which fish seek out as "optimal" are not easily predicted in terms of trade-offs, but are likely to be affected by increasing temperature. Additionally, other behavioral changes, such as swimming speed, reaction to fishing gear and predators, and annual migrations, are also affected by increased temperature, though the last is poorly understood (Rijnsdorp et al. 2009).

Individual fishes' response to changing climate can add up to a change at the population level. This is measured by taking the total production of a population over a time period, made up of egg production, growth, and recruitment, and subtracting mortality and loss through emigration. Mortality tends to be high in the early stages, especially when spawning or eggproduction habitat is sub-optimal, and recruitment of larvae depends on both optimal growth temperatures and food availability. Both of these will be affected by climate change, although it is not known whether there is a general trend, or the effects will differ from species to species (van der Veer et al. 2000, Wilderbuer et al. 2002, Sims et al. 2004). The changes in the physiology, behavior, and population dynamics of each species of fish in an area result in changes in survival, reproduction, and movement (adult migration and range) as well as their response to competitors and predators that are themselves responding to climate. These changes ultimately cause a shift in the number and types of fish species found within a specific locale.

The general trend of marine fish species shifting their ranges toward higher latitudes with changing climate has been widely noted (Perry et al. 2005, Pinsky et al. 2013.) On a local scale, however, the shifting of individual species' ranges, and even of assemblage's ranges, is not as uniform. Fish assemblages in a local area do not necessarily follow the trend of a higher-latitude or northward shift. In fact, several temperate assemblages and species were shown to shift southward, to the east or west, or not at all (Pinsky et al. 2013). Fish population centers track shifts in local climate as they occur, matching the local "climate velocity." This presents a case for studying both changes in climate over time within a specific locale, and local fish assemblage composition, as the two are linked, and could run counter to global trends (Pinsky et al. 2013). An awareness of climate change on a local scale, and how it is affecting the local fish fauna, is important to managing commercially and recreationally important species, and in making local conservation decisions.

In this study, I examined fish assemblages in the Mullica River-Great Bay ecosystem using long-term datasets collected by the Rutgers Marine Field Station and Jacques Cousteau National Estuarine Research Reserve. The objectives for the study were 1) to determine whether climate in the system has been changing and how, 2) to determine whether fish assemblage composition within the study system has been changing, and 3) to determine if and how these are related.

MATERIALS AND METHODS

Study system

The Mullica River-Great Bay estuary, in southern New Jersey (Figure 2.1), is a shallow drowned river valley with an average depth of about 2 m and a surface area of 41.6 km² (Kennish et al. 2004). The freshwater-saltwater interface is located near Lower Bank in the Mullica River, which is roughly 34 km upstream from Little Egg Inlet. Great Bay is polyhaline, with semidiurnal tidal input from Little Egg Inlet. Tidal velocities can reach an excess of 2 m/s. Salt marshes surround most of the study system's shoreline.

The study system has many factors in common with other Mid-Atlantic Bight estuaries, such as a broad seasonal temperature range between -2 to 28 °C and a tidal range of roughly 1.1 m near the mouth of the bay declining to 0.9 m at the freshwater-saltwater interface upriver (Martino and Able 2003). Physiochemical parameters are notably well-defined in the system, with salinities ranging between 0.1 to 35 during periods of high freshwater flow, and from 10 to 35 during summer drought periods. Of particular note is the strong pH gradient of about 3 units along the salinity gradient. This results from naturally acidic conditions in the surrounding New Jersey Pinelands ecosystem. Most of the Mullica River's watershed is sparsely developed and populated, a fact attributable partially to historical precedent, and to the area's inclusion in the Pinelands National Reserve. The Mullica River-Great Bay system is encompassed by the Jacques Cousteau National Estuarine Research Reserve (JCNERR), partially by virtue of this

relatively unaltered state (Kennish et al. 2004). Together, these systems comprise one of the least altered estuaries along the east coast of the U.S.

Environmental monitoring

Environmental water quality data were collected through the JCNERR System Wide Monitoring Protocol (SWMP). The protocol was established in 1996 to track physical and ecological processes in the Mullica River-Great Bay system using a set of standardized water quality monitoring procedures and quality assurance protocols (Mills et al. 2008). Salinity, temperature, pH, dissolved oxygen and depth measurements have been recorded in 15-30 minute intervals from four water quality data loggers (Yellow Springs Instrument Company Model 6600 UPG) installed along the salinity gradient from the inlet to the freshwater-saltwater interface at Lower Bank (Kennish and O'Donnell 2002, Figure 2.1). Meteorological monitoring of Wind Speed and Wind Direction, has been performed every 5 s since 2002, with a local mean compiled every 15 minutes. The single meteorological recorder is located at Stockton University's Nacote Creek Marine Field Station. The meteorological station logger was installed according to the National Weather Service guidelines (Mills et al. 2008). Data are compiled, quality checked, and served through the Central Data Management Office (CDMO) at Baruch Labs, NC (Kennish and O'Donnell 2002, http://www.nerrsdata.org). Thus, the two monitoring programs have a similar timeframe (Mills et al. 2008).

Biological sampling

Fish samples were collected via the Rutgers University Marine Field Station's Long-Term Otter Trawl Survey (Able and Fahay 2010). This survey was performed bi-annually, during the day in July and September, at sites throughout the estuary, Mullica River, and offshore area near Little Egg Inlet (Figure 2.1). The survey used a semi-balloon otter trawl with width of 4.9 m, a wing mesh of 19 mm, and a cod end of 6 mm bar mesh. Three two-minute tows were performed per site. For each species captured, the lengths of the first twenty individuals were recorded for each tow, using total length or fork length depending on the structure of the caudal fin.

Trawling sites were classified into three broad area categories or halozones; Riverine, Estuarine, and Marine (Figure 2.1). Halozone divisions were delineated based on physiochemical and geographic parameters throughout the estuary following Martino and Able (2003). This division both simplifies the dataset, which contains a large number of individual stations, and makes the spatial scale of the analysis relevant to climatic drivers of conditions among halozones but not patches within a halozone. The sampling protocol is consistent since 1997 across all three halozones, but data was first collected in 1988, and did not include the Riverine or Marine sites at the time (Martino and Able 2003, Able and Fahay 2010, Figure 2.1).

Catch data from three trawls at each site were combined into one sample of site, year, and month and then combined as the sum of stations within a halozone as a measure of catch per unit effort. The abundance of fishes over the period of the dataset was examined, and species with only a single occurrence in the dataset were dropped. Species appearing only once in the dataset, species displaying highly periodic abundance in low numbers over the study period, and individuals unable to be identified at the species level were also removed from the assemblage analysis due to a lack of confidence in their true distribution. The remaining sixty species were analyzed.

DATA ANALYSIS

Environmental analysis

I initially performed trends analyses of the environmental data collected by SWMP independent of the fish data because it has a much higher temporal resolution than the trawl survey, and could thus be influenced by event-scale perturbations. Water temperature, wind speed and direction, and salinity levels were examined as they are projected to be the most strongly affected by climate change. Precipitation was not included due to a lack of confidence in the accuracy of precipitation data from the JCNERR logger. The effect of pH is treated by spatial separation of fish collections as detailed below. Dissolved oxygen measurements were not included because dissolved oxygen rarely falls to stress levels in this system and because it is highly patchy within a halozone, allowing fish to move locally in response (Sackett et al. 2008) without affecting amalgamated catch.

Trends analysis was performed in MATLAB using native functions (e.g. regress.m, regstats.m. xcorr.m, nanmean.m). Variables were averaged by season, with all measurements collected in December, January and February making up the "winter" season, March, April and May defined as "spring," June, July, and August defined as "summer," and September, October, and November making up the "fall" season. This seasonal binning reduced the data to variables scaling to the months-long periods of larval duration, settlement and juvenile growth, including an accounting for the lag between spawning and capture. Factors such as survival in previous seasons affect the species found within the assemblage in a subsequent season, and environmental conditions from seasons previous to fish sampling were therefore included.

Temperature has a high annual amplitude (~30 °C in the daily mean) in this system, meaning that missing data can greatly bias calculated seasonal means. Temperature was expressed as the anomaly of each date's mean measure from its grand day-of the-year mean, smoothed by LOESS following Cleveland et al. (1990). Missing temperature data were replaced by their day-of-year mean from all of the years for which temperatures were available on that day-of-year. Thus, only actual measured values could cause deviations from the annual seasonal means used in correlations against fish abundance. Wind events were classified on the Beaufort Scale, and the number of events within each category was summed for each year of the study period. A cross-correlation analysis of summer and winter temperatures in all three halozones examined the relationship between summer and winter temperature highs and lows.

Assemblage analysis

Analytical structure of the datasets reflected the constraints of the different periods and spatial extents over which environmental data and parts of or all of the fish data were collected. I examined latent trends in fish assemblage of just the estuarine component from 1988 until 2013, using the full span of data available across the time series and then again for all stations from 1997 to 2013, the period during which protocol was consistent across all three halozones of the system (Figure 2.2). Next, I correlated environmental and fish abundance trends for all three halozones across the system, but only for 2003 to 2013, the last year for which SWMP data was available at the time of the project. Assemblage analyses consisted of three ordinations appropriate to different scales. One principal components analysis (PCA) maximized available time series data, but was spatially constrained to the Estuarine halozone. A second PCA, calculated across the entire spatial area of the study, was constrained by time, using the first year in which sampling occurred in all three halozones as a starting point. Finally, a canonical

correspondence analysis (CCA) related environmental and abundance data. Abundance data for each analysis were standardized to catch-per-unit-effort (CPUE) and log_{10} (y+1) -transformed before analysis. Samples were centered by species and standardized.

Testing of the PCA first axis scores for each of the three halozones (Estuarine, Marine, and Riverine) and month (July and September) was separately performed in Microsoft Excel. I tested the null hypothesis that there has been no change in the fish assemblage of each area, during each of the two months of the study, as well as in the entire study system overall. A linear regression with ANOVA (regressing first PCA axis sample scores on year) was performed for each halozone and each month to test this hypothesis.

Additionally, a canonical correspondence analysis (CCA) directly correlated trends between the fish assemblage and environmental data. Data used in the CCA were constrained to those matching SWMP (from 2003 to 2013 as detailed above). Environmental data submitted to CCA included Average Temperature in Fall, Average Temperature in Winter, Average Temperature in Spring and Average Temperature in Summer, Average Salinity in Fall, Average Salinity in Winter, Average Salinity in Spring and Average Salinity in Summer, Standard Deviation (SD) of Temperature in Spring, SD of Temperature in Fall, SD of Temperature in Summer, SD of Salinity in Spring, SD of Salinity in Summer, SD of Salinity in Fall, SD of Salinity in Winter, and percentage of total wind events comprising Light Winds, Moderate Winds, and Strong Winds, breakdowns of Beaufort Scale categorizations, separately. A partial Monte Carlo permutation test identified and ranked individually significantly (alpha = 0.05, Smilauer and Leps 2014) contributing variables in a forward selection algorithm. An unrestricted Monte Carlo Permutation Test followed the final iteration as a guard against interpretation of random pattern. As before, abundance data were log₁₀ (CPUE+1) -transformed before analysis. Samples were centered by species, with biplot scaling. Both the PCAs and the CCA applied Canoco software (v 4.5, ter Braak and Smilauer 2012).

RESULTS

Environmental change

Average yearly water temperatures during the truncated 2003 to 2013 study period rose by 2.9 °C in the Estuarine zone, and by 2.0 °C in the Riverine zone. This upward trend in temperature was significant and stronger in the Estuarine zone (Logger B126, m = 0.1595, $r^2 =$ 0.3259, p = 0.0123, Logger B139, m =0.1843, $r^2 = 0.2093$, p = 0.0427), than in the Riverine zone (Logger Chestnut Neck m = 0.1031, $r^2 = 0.1145$, p = 0.1085, Logger Lower Bank m = 0.1320, r^2 = 0.1071, p = 0.1165), where it was not significant (Figure 2.3). Water salinity values generally remained level over the course of the study period, displaying no significant annual or seasonal change (Estuarine m = 0.1547, $r^2 = 0.3717$, p = 0.065, Marine m = 0.0533, $r^2 = 0.0493$, p = 0.627, Riverine m = 0.0873, $r^2 = 0.0771$, p = 0.431, Figure 2.4). While average salinities in the system have risen by roughly 1.2 ppt on average, they are much lesser in magnitude than the average tidal salinity change of 6 ppt. Wind speeds did not change significantly over the period of the study. The most common wind speed in the area, making up 60% of measured wind events, fell under the Gentle Breeze category, between 3.4 and 5.5 m/s (Figure 2.5).

Fish assemblage change across halozones

In total, the 1997-2013 dataset contained 248,813 fish (Table 2.1). The majority of fishes captured were < 100 mm in length, and predominantly young of year (YoY) (July Mean = 91.61, July Mode = 55, July Range = 5-770, September Mean = 106.26, September Mode = 65, September Range = 5-825, Figure 2.6). Of the total species captured within the time period, 27

were eliminated for being highly sporadic, and 60 were retained for further analysis (Table 2.1, Appendices Ch. 2). The fish assemblage measured across all halozones (first eigenvalue = 0.191, Table 2.2), changed significantly over the 16 year study period (Figure 2.7). The temporal trend in assemblage was leveraged by *Morone americana*, first axis amplitude = 0.8988, *Ameiurus catus*, (first axis amplitude = 0.8179), *Trinectes maculatus*, (first axis amplitude = 0.7542), and Alosa pseudoharrengeus (first axis amplitude = 0.6987) on one assemblage endpoint, and by Syngnathus fuscus (first axis amplitude = -0.7606), Menidia menidia (first axis amplitude = -(0.7119), and Spheroides maculatus (first axis amplitude = -0.588) on the other (Figure 2.7). An overall shift occurred toward higher relative abundance of freshwater-favoring species, while moving away from estuarine/marine species, including economically and ecologically important fish such as *Pseudopleuronectes americanus* (first axis amplitude = -0.444), and *Paralichthys dentatus* (first axis amplitude = -0.2678). Inspection of change over time in the Estuarine and Riverine halozones did not show an increase in the number of freshwater-favoring species captured in the Estuarine halozone, but a decrease in capture of *M. menidia* and *S. fuscus* was apparent over the analysis for all halozones (Figure 2.12).

Trends analyses of first axis scores over the study period showed differing levels of significance throughout the system and in different months (Figure 2.8). The July assemblage from the Estuarine halozone changed significantly (m = 0.042, $R^2 = 0.4961$, F = 14.77, SS = 1.45, df = 16, p = 0.00152) over time, while the September assemblage did not (m = 0.0243, $R^2 = 0.1547$, F = 2.74, SS = 1.56, df = 16, p = 0.115261). The July Marine assemblage (m = 0.0627, $R^2 = 0.5126$, F = 15.78, SS = 3.13, df = 16, p = 0.001161) and the September Marine assemblage (m = 0.0745, $R^2 = 0.4507$, F = 12.31, SS = 5.02, d = 16, p = 0.003062) also changed significantly. The July Riverine assemblage did not change significantly (m = 0.0346, $R^2 =$

0.2042, F = 3.85, SS = 2.39, df = 16, p = 0.073493) nor did the September Riverine assemblage (m = 0.0185, R² = 0.0348, F = 0.541, SS = 4.00, df = 16, p = 0.487896).

Estuarine fish assemblage change

The 26 year Estuarine halozone assemblage change reflected that of the full halozone analysis (first eigenvalue = 0.154, Table 2.3, Figure 2.9). Trends in the assemblage of this halozone were leveraged by a relative increase in (first axis amplitude = 0.588), with *Trinectes maculatus* (first axis amplitude = 0.3405), and *Gobiosoma bosc* (first axis amplitude = 0.3095) also playing a large role. The assemblage shifted away from relative abundance of *P. dentatus* (first axis amplitude = -0.3014), *P. americanus* (first axis amplitude = -0.3779), *Brevoortia tyrannus* (first axis amplitude = -0.2404), *Anchoa mitchilli* (first axis amplitude = -0.3163) and *Bairdiella chrysoura* (first axis amplitude = -0.3005, Figure 8). The July assemblage of the Estuarine halozone changed significantly (m = -0.113, F = 21.5187, SS = 24.69607, d = 20, p = 0.000177) as did the September assemblage (m = -0.0638, F = 7.319137, SS = 15.88201, d = 20, p = 0.014145, Figure 2.10).

Assemblage and environment correlations

Of the environmental values submitted for forward selection in CCA, Average Summer Temperature (F = 3.18, p = 0.002), Standard Deviation of Summer Temperature (F = 2.44, p = 0.028), Average Summer Salinity (F = 14.50, p = 0.002), Average Fall Temperature (F = 1.80, p = 0.02), Percentage of Light Winds (F = 1.97, p = 0.002), and Standard Deviation of Summer Salinity (F = 1.87, p = 0.0240) had a significant effect on the ordering of species and were retained for the final iteration (Table 2.4, Figure 2.11).

Cross-correlations of summer temperatures to other seasonal temperatures were all best at lag = 0, and were strong for the Estuarine halozone (winter coefficient = 0.9678, fall coefficient = 0.9990, spring coefficient = 0.9914), Marine halozone (winter coefficient = 0.9742, fall coefficient = 0.9978, spring coefficient = 0.9859), and Riverine halozone (winter coefficient = 0.9598, fall coefficient = 0.9991, spring coefficient = 0.9485), suggesting that there is an estuary-wide relationship between the magnitude of temperatures in the summer and preceding or following seasons. The same is true for average salinity, with lag = 0 producing the best results, and strong correlations in the Estuarine (fall coefficient = 0.9983, spring coefficient = 0.9983), Marine (fall coefficient = 0.9983, spring coefficient = 0.9991) and Riverine halozones (fall coefficient = 0.9731, spring coefficient = 0.9414). While moderate winds and light winds were highly correlated, with lag = 0 and a coefficient of 0.9671, strong winds and light winds were not as strongly correlated, with the best results at lag = 1 and a coefficient of 0.7562.

Standard deviations of temperatures were highly correlated for the most part, with lag = 0 for all but the Marine Summer and Winter values (lag = -1) and strong correlations in the Estuarine (winter coefficient = 0.9389, spring coefficient = 1.00, fall coefficient = 0.9653), Marine (winter coefficient = 0.8100, spring coefficient = 0.7156, fall coefficient = 0.8221), and Riverine halozones (winter coefficient = 0.9726, spring coefficient = 0.8669, fall coefficient = 0.9712). Standard deviations of salinities were not as well-correlated, with most combinations best at lag = 0, but the two exceptions of Marine Summer and Spring (lag = -1) and Summer and Fall Marine variables (lag = -2). Correlations were fairly strong across the Estuarine (spring coefficient = 0.8386, fall coefficient = 0.8920), Marine (spring coefficient = 0.8551, fall coefficient = 0.7899) and Riverine halozones (spring coefficient = 0.9528, fall coefficient = 0.9663), though not as highly correlated as other examined variables.

Of the species captured, *Astroscopus guttatus*, *Chaetodon ocellatus*, *Aluterus schoepfii*, *Chasmodes bosquianus*, *Gobionellus boleosoma*, and *Lucania parva* (RMS Tolerances < 0.1457), were most highly associated with warmer winter temperatures, and with more variable summers. *Ameiurus catus*, *Esox niger*, *Ameiurus nebulosus*, *M. americana*, *Ictalurus punctatus*, and *Lepomis gibbosus* (RMS Tolerances < 0.8104), were most highly associated with higher summer temperatures. *Mustelis canis*, *Rhinoptera bonasus*, *Spheroides maculatus*, *Syngnathus fuscus*, and *Menidia menidia* were most associated with high summer salinities (RMS Tolerances < 0.3935). *Pomatomus saltatrix*, *A. mitchilli*, *B. tyrannus*, *Anguilla rostrata*, and *Caranx hippos* (RMS Tolerances < 0.7524), were associated with average conditions within the estuary, displaying a high degree of tolerance.

DISCUSSION

Over the long-term period of the study, a change in the fish assemblages of the Mullica River-Great Bay estuary has occurred at two different time scales during the study period; from 1997 to 2013, and from 1988 to 2013. This change can be linked to changes in environmental conditions. Annual average summer water temperatures explained the greatest amount of variation within the assemblage. Summer temperatures were highly cross-correlated with winter temperatures, suggesting that warmer winters predicate warmer summers, and that temperature is an important factor in determining the composition of the juvenile assemblage captured in the summer and fall. It is likely that resident and overwintering transient individuals that survive milder winter water temperatures are more likely to be subsequently collected during summer months. This was definitively shown to be the case for *Micropogonias undulatus* during an earlier time period (Hare and Able 2007). Inversely, species adapted to cold conditions, possibly as a predator refuge, such as *P. americanus*, would experience higher predation by *Crangon* *septemspinosa*, a common component of the fauna, during early vulnerable stages and thus appear less frequently in summer samples (Manderson et al.1998, Witting et al. 1999). While salinities did not change significantly over time, they did show significance in CCA analysis, indicating that water salinity is an important factor in driving the abundance of different species in the various parts of the system. Because the average value is not changing over time, however, this variable is not likely to be a strong driver of change in the system's fish assemblage composition.

The analysis of the entire study system across all three halozones (1997-2013) generally shifted towards a greater relative abundance of YoY of freshwater-favoring species, such as A. *catus* and *M. americana*. However, these species are not increasing in abundance at Estuarine stations; the leveraging of those stations is an artifact of the consequent reordering of all stations along the trend in PCA. This, and similar trends such as a decline in commonly found estuarine/marine species (*M. menidia*, *S. fuscus*) across the Estuarine halozone was apparent. This result also increases the relative weight of freshwater-favoring species within the system. In general, the summer assemblages showed a stronger trend than fall assemblages, though all but one assemblage trends are significant. This could indicate that summer conditions are changing more rapidly than fall conditions, an assertion that is supported by the strong significance of Average Summer Temperatures when compared to that of Average Fall Temperatures, or that summer is when heat stress thresholds are reached, and change starts to occur throughout the system as fishes change location in order to contend with heat stress. Whether the temperature itself has an effect on the species found in the system, or whether it is a correlate with or driver of other factors affecting assemblage change, or some combination thereof, is not clear.

Extending the analysis over a 26 year period, constrained to the Estuarine halozone, revealed a relative increase in the populations of transients that are southern summer residents, such as *B. chrysoura*, and of commonly found species, such as *A. mitchilli* and *B. tyrannus*. The pattern of decreased importance of *M. menidia* and *S. fuscus* evident in analysis of the full study system was not observed as strongly in this analysis, suggesting that a decline in the abundance of these species has been more prominent in recent years. The shift toward the increase in abundance of larvae and juveniles of southern species, and declining abundance of northern species in the system has been noted for rarer components of the larval fauna (Able and Fahay 2010), given an understanding of overwinter mortality relative to feeding ability in a moribund state (Sogard 1997, Hale and Able 2010, Able and Fahay 2010). The larvae and juveniles of warm-water southern species, such as *S. maculatus*, are seen more frequently in estuaries across the Mid-Atlantic, suggesting that this pattern holds true in the region (Collie et al. 2008, Wood et al. 2009).

When environmental variables and fish assemblages were analyzed together, many freshwater-favoring species were associated with higher summer temperatures. Species associated with lower summer temperatures tended to be primarily marine. These results are supported by the increase in the number of freshwater YoY captured, and by the environmental analysis, which shows temperatures rising more rapidly in the Estuarine halozone than in the Riverine halozone. When temperatures at capture for the most highly weighted freshwater species were compared to annual averages for each year, these species tended to be captured in waters of roughly average, or warmer than average, temperature. This suggests that freshwater fishes are not moving laterally in response to rising temperatures, in an attempt to utilize deeper, cooler water. Both *M. menidia* and *S. fuscus*, the species with the lowest first axis amplitudes in
PCA, were associated with lower summer temperatures, but displayed high tolerance scores, suggesting that their noted decline may not be primarily due to direct changes in temperature. *Sphyraena borealis, Leucoraja erinacea, Notemigonus crysoleucas*, and *A. catus*, all displayed high abundances and lower tolerances, suggesting that these species are good indicators of change within the system. Because their statistical tolerances of environmental conditions are relatively narrow, they are expected be among the first species to respond to shifts in climate as they occur. Analyzing trends in the abundance and location of these species, in conjunction with environmental monitoring could help to track the changes in local climate, as outlined in Pinsky et al. (2013).

The importance of spring precipitation to fish life cycles has been noted in many previous studies (Peer and Miller 2014). Many fishes use the change in water chemistry due to an influx of freshwater as a cue to spawn, to find ideal habitats to settle in, or to begin a migration (Sullivan et al. 2006, Peer and Miller 2014). A change in the amount and timing of spring precipitation could, therefore, change the timing of life history patterns of certain species. An increase in freshwater inflow into the system in spring could increase the number of recruits from the oceanic sources, while a decrease could result in lower recruitment. Additionally, the timing of these recruits' arrival could change, if precipitation patterns in the spring change. Warmer winters with less snow and more rain, and with snowmelt occurring earlier in the year, would change the timing of freshwater cues driving ingress into the system, resulting in earlier or later arrival of oceanic recruits, and changes in the timing of their capture in the trawl survey. This might be tracked using salinity patterns in the estuary on an individual species basis. It is also important to note that, although salinity may not be changing significantly in a linear pattern, a different model might show significant change over time.

In general, fishes residing in temperate estuaries experience a high degree of temperature variation throughout the year, and must therefore be hardy to temperature changes, sometimes experiencing more change (> $6 \, {}^{\circ}$ C) in a single tidal cycle than tropical or sub-temperate species experience across an entire year (Ng et al. 2007, Sackett et al. 2008). As many of the species, toward which the overall assemblage is shifting are residents within the system, the importance of local conditions in determining assemblage change relative to changes occurring in the marine environment follows evidence from the literature about the greater importance of local climate and environmental conditions to species within a system, when compared to large-scale patterns (Pinsky et al. 2013, Genner et al. 2004). Additionally, rare nonresident species contribute to this change in the assemblage, displaying higher first axis amplitudes than more common species and the residents toward which the assemblage is shifting. This illustrates the importance of stragglers and pioneers to assemblage composition (Murray et al. 1999). For example, Moonfish Selene setapinnis and Lookdown Selene vomer, both of which were rare and therefore excluded from this analysis, have been captured with increasing frequency over the more recent years of the time series. These species are not resident within the system, primarily residing in southern waters, yet their increasing abundance may have an effect on the overall structure of the assemblage over time, as has been suggested (Able and Fahay 2010). This pattern is reflected by the more abundant but similarly southern-affiliated B. chrysoura. Merluccius bilinearis, on the other hand, a species associated with cold conditions (but also excluded from PCA analysis), has not been captured in trawl surveys since 2006.

While a suggestion of the reasons for assemblage change can be gleaned from the PCA and CCA results, the factors affecting the abundance of individual species within the system are not clear. To capture the mechanisms of change associated with climate, more detailed autecological studies will be needed. Such detailed analyses could have applications for commercially and recreationally important species, with management plans being tailored for each individual species in order to address concerns regarding the effects of changing climate on populations. It is also important to note that other biological factors may have a more significant impact on the abundance of a species within the system than climatic conditions, but those factors might be themselves subtly tied to climate. While assessing the entirety of the assemblage does give a complete picture of the system and how it is changing, a full fish assemblage can contain tens to hundreds of species, and answering specific questions about the factors causing changes in fish populations can be difficult at this broad-scale level. The use of tools to parse the assemblage into coarser units than the species level, such as guilds, can help to simplify this problem by highlighting commonalities. It should also be noted that this study only takes into account the effects of climate on fish species and their presence or absence within the system. Other factors, such as fisheries catch, may play a larger role in determining whether fishes increase or decrease in abundance in the estuary. **Table 2.1** Abundance (248,813 fish overall) of species collected in the Mullica River-Great Bay trawl survey, and their distribution among halozones, as applied to PCA from the 1997-2013 data set. Species were summed over the course of the study period for each halozone (Marine, Estuarine, Riverine), combining months and years. Species used in the PCA based on their abundance over the years of the study are indicated.

Scientific Name	Common Name	PCA Total		Estuarine	Marine	Riverine
				Total	Total	Total
Alosa aestivalis	Blueback herring	No	61	5	0	56
Alosa mediocris	Hickory shad	No	11	4	0	7
Alosa	Alewife	Yes	1410	25	0	1385
pseudoharengus						
Ameiurus catus	White catfish	Yes	897	0	0	897
Ameiurus nebulosus	Brown bullhead	No	281	0	0	281
Ammodytes	American sand	Yes	4	0	4	0
americanus	lance					
Anchoa hepsetus	Broad-striped Yes 44 anchovy		443	119	314	10
Anchoa mitchilli	Bay anchovy	No	108436	69945	31823	6668
Anguilla rostrata	American eel	Yes	132	53	8	71
Apeltes quadracus	Fourspine Stickleback	Yes	2935	81	2602	252
Astroscopus guttatus	Northern stargazer	Yes	10	10	0	0
Bairdiella	Silver perch	Yes	1510	1083	375	52
chrysoura						
Brevoortia tyrannus	Atlantic menhaden	Yes	2292	1880	4	408
Caranx crysos	Blue runner	Yes	5	0	5	0
Caranx hippos	Crevalle jack	Yes	29	18	1	10
Catostomus	White sucker	Yes	25	0	0	25
commersoni						
Centropristis	Black sea bass	Yes	247	207	32	8
striata						
Chaetodon	Spotfin	Yes	5	5	0	0
ocellatus	butterflyfish				0	
Chasmodes	Striped blenny	No	2	2	0	0
<i>Bosquianus</i> Chilomystomys	Stringd hyperfigh	Vac	71	4.4	26	1
schoenfi	Surped burnish	res	/1	44	20	1
Conger oceanicus	Conger eel	No	6	1	5	0
Cynoscion regalis	Weakfish	Yes	3078	1522	1463	93
Enoraulis ourostale	Silver anchovy	No	19	2	17	0
Esor niger	Chain nickaral	Vec	13	0	0	13
Loon niger	Chain pickerei		15	U	0	1.5

Etheostoma	Tessellated darter	Yes	128	0	0	128
olmstedi						
Etropus	Smallmouth	Yes	443	80	362	1
microstomus	flounder					
Eucinostomus	Spotfin mojarra	No	3	3	0	0
argenteus						
Fundulus	Banded killifish	Yes	109	0	0	109
diaphanus			1.0.0			
Fundulus	Mummichog	Yes	182	57	45	80
heteroclitus			10	0	0	
Gasterosteus	Threespine	Yes	10	0	8	2
aculeatus	stickleback	NT	2	2	0	
Gobionellus	Darter goby	NO	3	3	0	0
boleosoma Cabiarama hara	Nalzad ashri	Vac	196	161	17	0
Gobiosoma bosc	Naked goby	res	180	101	1/	8
Gobiosoma	Seaboard goby	No	11	8	3	0
ginsburgi	.		1.5	22	10	
Hippocampus	Lined seahorse	Yes	45	32	13	0
erectus	Channel astfish	NT-	152	0	0	152
Ictaturus punctatus	Channel catfish	INO	153	0	0	153
Lagodon	Pinfish	Yes	40	22	17	1
rhomboides			1.401	1100	206	156
Leiostomus	Spot	Yes	1491	1129	206	156
xanthurus	Denvellingen	V	20	0	0	20
Lepomis gibbosus	Pumpkinseed	res	38	0	0	38
Leucoraja erinacea	Little skate	Yes	53	0	53	0
Menidia beryllina	Inland silverside	Yes	12	4	7	1
Menidia menidia	Atlantic silverside	Yes	25696	14600	10965	131
Menticirrhus	Northern kingfish	Yes	79	36	38	5
saxatilis	catilis					
Merluccius	Silver hake	No	4	0	4	0
bilinearis						
Microgobius	Green goby	No	5	4	0	1
thalassinus						
Micropogonias	Atlantic croaker	Yes	791	87	662	42
undulatus						
Morone americana	White perch	Yes	8756	6	0	8750
Morone saxatilis	Striped bass	Yes	36	1	0	35
Mugil curema	White mullet	No	2	1	0	1
Mullus auratus	Red goatfish	No	2	0	2	0
Mustelus canis	Smooth dogfish	Yes	50	28	22	0
Mystaroparag	Gag grouper	No	3	0	3	0
microlepis					5	

Myoxocephalus	Grubby	No	4	3	1	0
aenaeus						
Notemigonus	Golden shiner	Yes	165	0	0	165
crysoleucas						
Ophidion	Striped cusk-eel	Yes	42	3	39	0
marginatum						
Opsanus tau	Oyster toadfish	Yes	352	232	118	2
Paralichthys	Summer flounder	Yes	249	188	35	26
dentatus						
Paralichthys	Fourspot flounder	No	4	0	4	0
oblongus						
Peprilus	Butterfish	Yes	2631	30	2600	1
triacanthus						
Pogonias cromis	Black drum	Yes	16	13	0	3
Pomatomus	Bluefish	Yes	164	85	40	39
saltatrix						
Prionotus carolinus	Northern searobin	Yes	654	34	620	0
Prionotus evolans	Striped searobin	Yes	151	56	93	2
Pseudopleuronectes	Winter flounder	Yes	516	392	110	14
americanus						
Raja eglanteria	Clearnose skate	Yes	88	10	78	0
Rhinoptera bonasus	Cownose ray	No	4	3	1	0
Scophthalmus	Windowpane	Yes	234	35	199	0
aquosus	flounder					
Selene setapinnis	Atlantic moonfish	No	18	1	17	0
Selene vomer	Lookdown	No	15	7	6	2
Sphoeroides	Northern puffer	Yes	7	4	3	0
maculatus						
Sphyraena borealis	Northern sennet	Yes	544	238	302	4
Stenotomus	Scup	Yes	388	257	131	0
chrysops						
Strongylura marina	Atlantic	No	4	0	4	0
	needlefish					
Syngnathus fuscus	Northern pipefish	Yes	4334	1917	2292	125
Tautoga onitis	Tautog	Yes	286	152	132	2
Tautogolabrus	Cunner	Yes	42	37	3	2
adspersus						
Trinectes maculatus	Hogchoker	Yes	1253	67	2	1184
Urophycis chuss	Red hake	Yes	9	0	9	0
Urophycis regia	Spotted hake	Yes	486	0	486	0

Table 2.2 PCA results for the full system fish assemblage of the Mullica River-Great Bay studysystem from 1997 to 2013.

	Eigenvalues	Cumulative Percentage Species Variance
First Axis Full PCA	0.191	19.1
Second Axis Full PCA	0.096	28.7
Third Axis Full PCA	0.053	33.9
Fourth Axis Full PCA	0.048	38.7

	Eigenvalues	Cumulative Percentage Species Variance
First Axis Estuarine PCA	0.154	15.4
Second Axis Estuarine PCA	0.101	25.5
Third Axis Estuarine PCA	0.070	32.5
Fourth Axis Estuarine PCA	0.066	39.2

Table 2.3 PCA results for the Estuarine fish assemblage of the Mullica River-Great Bay study system from 1997 to 2013.

Table 2.4 Results of CCA of fish and select environmental factors in the Mullica River-GreatBay estuary.

	Eigenvalue	Species- Environment Correlation	Cumulative Percentage Variance Species	Cumulative Percentage Variance Species- Environment
First Axis	0.602	0.976	18.8	61.0
Second Axis	0.181	0.788	24.5	79.3
Third Axis	0.083	0.736	27.0	87.7
Fourth Axis	0.058	0.816	28.9	93.6

Figure 2.1 A map of the Mullica River-Great Bay estuary in southern New Jersey. Trawl sites are marked by black dots. The stars indicate the location of the System Wide Monitoring Program (SWMP) loggers, the four-pointed star represents the location of the meteorological monitoring station, and the diamond indicates the location of the Rutgers University Marine Field Station. Each grouping of stations is enclosed in an ellipse, and labeled according to its halozone classification. Loggers are located at Logger B126, Logger B139, Logger Chestnut Neck, Logger Lower Bank.

Figure 2.2 A diagram illustrating the breakdown of the Long-Term Otter Trawl and System Wide Monitoring Protocol datasets. Years used for each dataset are listed at the bottom of each of the boxes, and halozones used are listed inside of each box.

Figure 2.3 Average annual temperatures for each data logger within the system from 2002 to the current year for each of the four SWMP loggers along with lines of best fit. See Figure 2.1 for location of data loggers.

Figure 2.4 Average annual salinities from 2003 to the current year for each of the three halozones along with lines of best fit. See Figure 2.1 for location of data loggers.

Figure 2.5 Percentage of wind events during each year of the study according to the Beaufort Scale. The years 2002 and 2013 had incomplete data due to changes in protocol and weather events. Using percentages helps to standardize these values to the rest of the dataset.

Figure 2.6 Length-frequency distribution of fish species captured in the trawl surveys in both July (Figure 2.2(a)) and September (Figure 2.2(b)). This distribution is taken across the entire assemblage for both months of the survey, during the ten-year period encapsulated by the CCA. The majority of fishes captured are < 100mm in length, and are predominantly YoY.

Figure 2.7 A PCA biplot of species vs. samples across the entire study system between 1997 and 2013. Vectors point in the direction of increasing abundance relative to other species and stations. Longer vectors show stronger trends. The influence of White Perch (Morame), Atlantic Silverside (Menmen), Northern Pipefish (Synfus) and White Catfish (Amecat) is indicated by the length of the vectors representing them.

Figure 2.8 First-axis PCA scores for the three halozones outlined in Figure 2.1; Estuarine, Marine, and Riverine. The right axis displays a selection of the loadings and names of species affecting the sample scores. This analysis included the all halozones in the dataset, ranging from 1997-2013. July and September remain differentiated in order to both account for the difference

between fall and summer assemblages within the system, and to capture the inertia of summer recruits, which enter the system in July and are potentially captured again in September.

Figure 2.9 A PCA biplot of species vs. samples across the Estuarine halozone, between 1988 and 2013. Vectors point in the direction of increasing abundance relative to other species and stations. Longer vectors show stronger trends. The influence of Silver Perch (Baichr) is indicated by the length of the vectors representing it.

Figure 2.10 First-axis PCA scores for the Estuarine halozone. The right axis displays a selection of the loadings and names of species affecting the sample scores. This analysis included the entire timespan of the fish assemblage dataset, ranging from 1988-2013. July and September remain differentiated in order to both account for the difference between fall and summer assemblages within the system, and to capture the inertia of summer recruits, which enter the system in July and are potentially captured again in September.

Figure 2.11 A CCA biplot of species vs. environmental variables across the entire study system from 2003-2013. Vectors point in the direction of increasing abundance relative to other species and stations. Longer vectors show stronger trends. The influence of Average Summer Temperatures is indicated by the length of the vector representing it.

Figure 2.12 Abundance of the three highest amplitude species in the assemblage (*Morone americana, Ameiurus catus, Trinectes maculatus*,) and the three lowest amplitude species (*Menidia menidia, Syngnathus fuscus, Spheroides maculatus*), graphed over both the Estuarine and Riverine habitats. Freshwater-favoring species such as *Ameiurus catus*, did not increase in abundance in the Estuarine zone, changing in abundance in the Riverine zone instead. Species commonly found in the Estuarine zone, such as *Menidia menidia* and *Syngnathus fuscus*, decreased over the period of the study.







Figure 2.2



- Temperature 15 14.5

13.5

12.5

Year



Figure 2.3

18 |

Temperature °C

11 L 0

20 I



Figure 2.4





Figure 2.5



Figure 2.6(a)







Figure 2.7







Figure 2.9



Figure 2.10



Figure 2.11









Spheroides maculatus





Trinectes maculatus











Figure 2.12

CHAPTER 3

Sensitivity of a Fish Time-Series Analysis to Guild Construction: A Case Study of the Mullica River-Great Bay Ecosystem

ABSTRACT

Guilds are defined as polyphyletic species groups delineated by specific attributes selected by the organizer. Functional guilds combine species on the basis of niches and ecological roles and structural guilds combine based on the use of a particular resource. Guilds can be substituted for individual species in an analysis, allowing for insight based on ecological questions smoothed of variance from taxonomic differences. In this case study, I examined guilds based on reproductive characteristics, and on estuarine use. These guilds were used across stations and halozones in lieu of species in a principal components analysis of fish recruitment to an estuary. In both cases, use of the guilds resulted in more explained variation than did use of a full assemblage. Eight-class and twelve-class reproductive guild clusters both explained more than 50% of the total variance on the first two eigenaxes while displaying similar trends across time in comparison with the full assemblage. Use of an abundant species assemblage (excluding infrequently caught species from the assessment) explained slightly more variance than use of the full species assemblage. Guilds based on species origin showed no significant trends over time. Overall, reproductive guilds most accurately reflect assemblage changes within the Mullica-Great Bay ecosystem, while habitat origin guilds do not. Rare species also do not seem to drive change in this particular system. Given the strong similarities between the results of the full assemblage analysis and the reproductive guilds, it can be concluded that reproductive characteristics explain the change in fish assemblages over time with the greatest accuracy.

Further studies should focus on reproductive characteristics, and the ways in which change in the system is affecting them.

INTRODUCTION

Fish assemblages in temperate marine systems are typically made up of tens to hundreds of species responding to many different factors. Changes within the system may affect different species by acting on life history characteristics, reproductive characters, predation and consumption, and habitat preference, among others (Elliot et al. 2007). Monitoring a single species and extrapolating to the rest of the assemblage therefore poses problems. Because individual species change abundance and location at different rates and in different directions, selecting a single species does not translate accurately to an entire assemblage; where the target species may be thriving, other species may be in decline, resulting in a biased view of change in the system (Austen et al. 1994). Likewise, the full species assemblage is difficult to examine for specific characteristics, and the ways in which change affects them. In order to address questions regarding specific mechanisms, a more concise unit is desired.

One of the ways in which ecological questions that involve whole communities can be addressed is through the use of guilds in lieu of individual species. A guild can be defined as a grouping of species present within an ecosystem into classes that denote certain attributes (Elliott et al. 2007). These attributes include life history, habitat use, reproductive strategy, trophic structure, and others relating to a species' ecological function and place within the community structure. Guild classifications are useful as a tool for simplifying the structure of extensive ecosystems (Simberloff and Dayan, 1991) and providing a unit between the species and the ecosystem levels especially in speciose systems (Austen et al. 1994.) In particular, guilds are useful for understanding the functional structure of complex ecosystems, such as estuaries (Franco et al. 2008).

Guilds may function as a "super species" or "surrogate species" of sorts, creating a unit that responds predictably to environmental change, as compared to individual species (Caro and O'Doherty, 1999). As there are notable problems with extrapolating the response of the entire guild based on the monitoring of a single species within the guild, the use of the entirety as a unit may help to streamline large datasets (Garrison and Link 2000, Lobry et al. 2003, Franco et al. 2006). Variance for the entire guild, for instance, would be much lower than attempting to estimate the same values for each individual species within the guild, creating a clearer picture of the system overall, and how fish species respond to environmental change (Austen et al. 1994). Additionally, the use of guilds facilitates the transfer of methodology. By providing a grouping of species based on their niches and life history characteristics, rather than those unique to the study system, the groundwork is laid for the study to be reproduced in different habitat types, at different latitudes, and over different time scales.

Guilds are often designated based on function to test hypotheses relevant to those concepts. One way of doing this is to use species' niches, or "roles" in the community to combine them into groups (Simberloff and Dayan, 1991). Examples of functional traits used to define guilds would include factors such as trophic level, reproductive characteristics (Balon, 1975), and life history strategies (Elliott et al. 2007, Thiel et al. 2003). Potter and Hyndes (1999), for example divided Australian estuarine fishes based on their life histories (marine straggler, marine-estuarine opportunist, estuarine and marine, solely estuarine, semi-anadromous, and catadromous), and assessed each group's contribution to the total number of estuarine fish overall. Thiel et al. (2003) used a similar approach in two European estuaries. Both studies also assessed the total number of individual species' contributions to the assemblage alongside the life cycle guilds. Potter and Hyndes (1999) found that the type of estuary played a role in the species making up the majority of the assemblage; systems perpetually open to marine influence showed many marine stragglers and estuarine opportunists, while estuaries that seasonally closed to marine influence had a majority of primarily estuarine species. Marine estuarine-opportunists dominated the number of individuals captured within the system, further illustrating the importance of marine species to the estuarine assemblage. Thiel et al. (2003) also found that marine species contributed the most to the composition of species in both of their study systems. When the number of individuals captured was taken into account, however, estuarine and anadromous species dominated the catch. While guild selection is variable by nature of what question is addressed, it is important to note that ordination methods, such as cluster analyses, principal components analyses, and correspondence analyses, can be used to standardize the approach (Austen et al. 1994, Franco et al. 2008). This can eliminate some of the subjectivity associated with dividing assemblages into guilds.

The use of guilds does present some challenges. A guild classification intentionally rejects finer-scale community dynamics (Fountain-Jones et al. 2015). Guilds can thereby skew distribution curves, as a single outlier species can statistically weight the data for the entire guild. For instance, if a single species within a guild thrives, while the other members of the guild decline, the outlier may be enough to maintain guild abundance on a statistical level, while in the field, the members of the guild are declining and experiencing negative effects (Caro and O'Doherty 2015). It is important, therefore, to consider both the use of guilds and the species assemblage analysis. The use of guilds can explain certain mechanisms driving change in a system, but only when the full system change also is taken into account.

In the case of this study, a long-term time series is examined for change in assemblage composition over time. The results are made difficult to interpret by the diversity of species within the system, many of which may respond to both internal and external factors. In order to address this complexity, determine which shared characteristics play a role in affecting change in species composition over time, and to explain the variation in long-term time series data, I grouped fish species captured in a long-term otter trawl survey in the Mullica River-Great Bay ecosystem into guilds. I considered guilds based upon habitat use and reproductive characteristics, and assemblages of abundant and rare species. I compared results to those from an analysis using the unclassified species set in order to assess whether the characteristics that the divisions were based upon were sensitive to the same change that the full system assemblage displayed, and how closely they matched this change over time.

MATERIALS AND METHODS

Study System

The Mullica River-Great Bay estuary in southern New Jersey (Figure 3.1), is a shallow drowned river valley estuary, with an average depth of about 2 m, and a surface area of 41.6 km² (Kennish et al. 2004). The freshwater-saltwater interface is located near Lower Bank in the Mullica River, which is roughly 34 km upstream from Little Egg Inlet (Kennish et al. 2004). Great Bay is polyhaline, with semidiurnal tidal input from Little Egg Inlet. Tidal velocities exceed 2 m/s (Kennish et al. 2004). Salt marshes surround most of the study system's shoreline (Kennish et al. 2004).

The estuary has many factors in common with other Mid-Atlantic Bight estuaries, such as a broad seasonal temperature range, between -2 to 28 0 C, and a tidal range of roughly 1.1 m

near the mouth of the bay, declining to 0.9 m at the freshwater-saltwater interface upriver (Martino and Able, 2003). Physiochemical parameters are notably well-defined in the system, with salinities ranging between 0.1 to 35 during periods of high freshwater flow, and from 10 to 35 during summer drought periods (Martino and Able, 2003). Of particular note is the strong pH gradient of about 3 units along the salinity gradient. This strong pH gradient results from acidic conditions in the surrounding New Jersey Pinelands ecosystem (Martino and Able, 2003). Most of the Mullica River's watershed is sparsely developed and populated, a fact attributable partially to historical precedent, and to the area's inclusion in the Pinelands National Reserve (Martino and Able, 2003). This results in the system being relatively undisturbed (Kennish et al. 2004). The Mullica River-Great Bay system is also a part of the Jacques Cousteau National Estuarine Research Reserve (JCNERR), partially by virtue of this relatively unaltered state (Kennish et al. 2004).

Biological Sampling

Fish samples were collected via the Rutgers University Marine Field Station's Long-Term Otter Trawl Survey (Able and Fahay, 2010). This survey is performed bi-annually, during July and September, at a variety of sites throughout the estuary, Mullica River, and offshore area near Little Egg Inlet (Figure 3.1). The survey uses a semi-balloon otter trawl with length of 4.9 m, a wing mesh of 19 mm, and a cod end of 6 mm bar mesh. Three two-minute tows are performed per site. For each species captured, the length of the first twenty individuals was recorded, using total length or fork length depending on the structure of the caudal fin. The remainder of the individuals for each species were counted. The protocol is consistent at all sites since 1997, but data was first collected in 1988, and did not include sites in the riverine section (Martino and Able, 2003, Able and Fahay 2010). For this reason, data used in this study included only those from between 1997 and 2013 (the most recent available when the study began).

Trawl data were organized according to site, with the three trawls at each site combined into one sample of site, year, and month. Species appearing only once in the dataset and individuals unable to be identified at the species level were removed from the assemblage analysis due to a lack of confidence in their true distribution.

Trawling sites were classified into three broad area categories or halozones; Riverine, Estuarine, and Marine (Figure 3.1). This division both simplifies the dataset, which contains a large number of individual stations, and gives a clearer picture of change within the system. Because each station represents a patch within a larger habitat, and because the distribution of fishes is highly patchy on a microhabitat scale not germane to the temporal trend analysis, grouping these small stations into a larger unit increases the overall scale of the study. Halozone divisions were delineated based on physiochemical and geographic parameters throughout the system following Martino and Able (2003).

Guild Classifications

Fish species were assigned to guilds based on reproductive characteristics detailed in Able and Fahay (2010). Characters for consideration included spawning season, place of spawning, and egg type. Species were assigned all characters of a variable that fit with their life history, sometimes with multiple characters assigned to the same category. Species were arranged into a matrix with true-false (1,0 values) conditions for each variable (Table 3.1), and a cluster analysis invoked this matrix. Two different cluster values were established using a dendrogram produced in MATLAB (dendogram.m) with distance calculated as Hamming distance, using complete linkage. The dendrogram was pruned at the eight or twelve cluster level to test sensitivity to guild classification level. Clusters were examined for common reproductive characteristics, and given names based on these characters. For the eight-cluster reproductive guilds, I identified the eight clusters as Unknown Location/Egg Type Spawners, Summer Spawners with Unknown Eggs, Estuarine Live Spawners, Pelagic Summer Spawners, Mid-Atlantic Bight Spawners, Demersal Estuarine Spawners, Freshwater Spawners, and Pelagic Shelf Spawners. The twelve clusters had several identical categories, including Freshwater Spawners, Unknown Spawners, Demersal Estuarine Spawners, Estuarine Live Spawners, and Summer Spawners with Unknown Eggs. The addition of clusters, however, also allowed for the inclusion of Summer Shelf Spawners, Fall Shelf Spawners, Winter Shelf Spawners, and Spring Shelf Spawners. Mid Atlantic Bight Spring Spawners, South Atlantic Bight Pelagic Spawners, and Unknown Pelagic Spawners were also identified.

Another analysis applied guild formation based on characters of origin following Potter et al. (2015) (Table 3.2). Four guilds were defined based on this categorization; Resident Species, Transient Species, Shelf Stray Species, and Southern Stray Species. Information for species classifications were drawn from Able and Fahay (2010).

The three ordinations based on guild were compared with three performed on the specieslevel, one with the full species (here forward "full assemblage analysis") set and another excluding rare species. Species within the tail of an abundance distribution curve are often abundant elsewhere, and can influence the overall shift in an assemblage by virtue of their rarity within the system (Murray et al. 1999). Species represented by less than 20 individuals over the entirety of the dataset were classified as "rare species," and dropped from the assemblage. The remaining species were classified as "abundant species" (here forward "abundant species assemblage") in another analysis (Table 3.3). The excluded "rare" species were also analyzed separately as a group (here forward "rare species assemblage") in order to determine their influence on change in the assemblage. This resulted in a total of 36 trend lines (2 seasonal from each of 3 halozones x 6 classification approaches).

DATA ANALYSIS

A null hypothesis, that the reproductive guilds would not display the steepest slopes and the most significant change, was tested. I hypothesized that the reproductive guilds would display the steepest slopes and the most significant change of the various guild assemblages. As the analysis of change over time in the system previously showed an increase in the importance of freshwater species, and because one of the guilds in the reproductive clusters was defined as "Freshwater Spawners" for both cluster cutoffs, guilds that highlight the importance of these species should show the greatest adherence to change in the system overall.

A principal components analysis (PCA) was performed using Canoco software (v 4.5, ter Braak and Smilauer, 2012), for each set of guilds (eight-cluster reproductive, twelve-cluster reproductive, functional use, abundant, and rare species,) and for the full assemblage. Abundance data were log₁₀ (y+1) -transformed before analysis. Inter-species correlations were not posttransformed. Samples were centered by species, with biplot scaling, and standardized. Permutations were unrestricted (Smilauer and Leps, 2014). This protocol was kept consistent for each individual guild and assemblage analysis in the study.

A linear regression of sample score vs year, for each set of halozone stations for each assemblage/guild characterization, tested for the presence and direction of a linear significant temporal trend. Results were analyzed for significance using linear regression of year vs

abundance with ANOVA in Microsoft Excel's Data Analysis package, with a confidence interval of 95% (p-value = 0.05). PCA scores were regressed against year for all three halozones. Residual plots were examined for each halozone-month combination.

The accumulated variation explained by each guild and assemblage type was calculated across all four available axes of the analysis. Notably, for the origin guild classifications, the use of only four guilds in the analysis would naturally produce an end result of 100% explained variation. This was taken into account when assessing variance explained by each guild and assemblage type.

RESULTS

Halozone Trends Over Time

For the most part, assemblages changed significantly in the Estuarine halozone in the month of July regardless of guild classification or inclusion (Table 3.4). The exception was the origin guilds and rare species assemblage, for which the assemblage did not change significantly in any month or halozone of the study. Similarly, the September Estuarine scores changed significantly in most guild classifications, types over time, again, with the exception of the origin guilds, abundant species assemblage, and rare species assemblage. The July and September Marine scores were also significant for the reproductive guild classifications, but not for the origin guilds, abundant, or rare species assemblages. Finally, the July Riverine scores were significant when guild membership was assigned by reproductive trait or relegated to abundant species. Trends for the September Riverine assemblages did not change significantly over the course of the study for any of the guild treatments (Table 3.4). Trendlines for the eight-cluster and twelve-cluster reproductive guilds, and for the full assemblage and abundant species

assemblage, showed positive slope values over the entire period of the study, as well as a larger slope magnitude than that of the origin guilds and the rare species assemblage (Table 3.4). When proportions of each origin guild were calculated for species in the rare assemblage, the majority were found to be Southern Strays, with Transients making up the second-largest group of rare species (Figure 3.2). This suggests that species considered rare within the system are generally not native to the area. Full assemblage and abundant species assemblage trendlines often overlapped completely, indicating a high degree of similarity between the responses of the assemblage under the two different classifications.

For reproductive guilds, the Freshwater Spawners guild showed an increase in importance in both the eight-cluster and twelve-cluster reproductive guild analyses, while Estuarine Spawners, both Demersal Egg Spawners and Live Birthers, declined in importance. Shelf and Mid/South Atlantic Bight Spawners either showed no change, or declined in importance in both the eight-cluster and twelve-cluster guilds (Figure 3.3, Figure 3.4). Among these, Summer-season spawners appeared to decline more intensely than other seasons. Unknown Spawners increased in importance in both the eight and twelve cluster guilds, though not to the same degree that Freshwater Spawners did.

In the origin guilds, Resident species gained importance within the assemblage, while Transient species declined in importance with the greatest magnitude. Shelf Strays and Southern Strays also displayed a decline in importance, with Shelf Strays declining at a greater amplitude than Southern Strays (Figure 3.5).

Residuals

Residual plots were generally linear in their scatter pattern for the eight-cluster reproductive guild analysis. The September Marine residuals displayed a mild pattern of increase during early and late years of the study, and decrease during middle years. Twelve-cluster reproductive guild residuals showed a similar, largely linear pattern, with the same rise and fall in the September Marine assemblage. Origin guilds showed very scattered residual plots, many of which display visible rises and falls in value over the period of the study. The rare species assemblage displayed mostly linear residual plots, with points clustered tightly around zero, and a few high or low outliers throughout. Most notably, the July Estuarine assemblage residuals spread widely, before dropping back toward zero. The abundant and full assemblages show virtually identical residual plots, most of which were linear. The September Marine assemblages showed high values at the beginning and end of the time series, and a decrease in the middle, much like the reproductive guilds' residual graphs.

Variance

Explained variance accumulated most rapidly in the eight-cluster and twelve-cluster reproductive guilds, leveling off after the first axis (Figure 3.6). The rare species assemblage displayed minimal increase, while the full and abundant species assemblages were separated by roughly 20 percentage points. The origin guilds accumulated at a steadier rate across all four axes, and did not display the same sharp rise in explained variance as the reproductive guilds did. Overall, the eight-cluster reproductive guilds captured the strongest variation with the greatest data reduction, with twelve-cluster reproductive guilds capturing the second-strongest, when the origin guilds are discounted due to the small number of classifications used.

DISCUSSION

The overall fish assemblage in the Mullica-Great Bay system has changed over time, as evidenced by the results of the full assemblage analysis (Nickerson et al. in review). This change is reflected in some of the guilds and specialized assemblages, while others do not show significant change over time. Primarily, the representation of different classes of reproductive guilds and abundant species changed significantly over time, while representatives of the origin guilds and rare species assemblage did not.

The full and abundant species assemblages often overlapped, both displaying similarly positive trends over time, and significance in all three of the same halozones over both months. Residuals were largely linear. Variance accumulated rapidly at the first axis, with subsequent axes explaining less of the variance overall. Freshwater-favoring species *Morone americana, Ameiurus catus, Ameiurus nebulosus*, and *Trinectes maculatus* displayed the highest first axis amplitudes, and estuarine species *Syngnathus fuscus* and *Menidia menidia* displayed the lowest.

When reproductive guilds and their influence on the assemblage were examined, it was found that typically, Freshwater Spawners had a high first axis amplitude, while Estuarine Spawners, both Demersal and Live, had the lowest first axis amplitudes in both the eight and twelve-cluster guilds. Shelf and Bight spawners did not modulate amplitude as the Freshwater and Estuarine spawners over time, highlighting the importance of change in the system, when compared to that of recruits from the oceanic spawning pool. The guilds with the highest and lowest amplitude of change match the change in select species shown by the full assemblage; *M. menidia* is a Demersal Estuarine Spawner, *S. fuscus* is a Live Estuarine Spawner, and *A. catus*, *A. nebulosus*, *T. maculatus* and *M. americana* are Freshwater Spawners. This both indicates the importance of these particular species in driving assemblage change, and illustrates one of the
pitfalls of the use of guilds; these species may swamp the change in others in their guilds, and skew the results of the analysis. Further investigation into other members of the guild and their rates of change would be required to determine whether this is the case.

Both groups also displayed significant change over time in most, if not all, of the halozones in both summer and fall. Finally, the accumulation of variance in the reproductive guilds was strong between the first and second axes, making the results easier to examine overall; because the accumulation of explained variance happens so rapidly, further axes can be left out of the examination of results. The first and second will give sufficient explanations of the variance to predict trajectories. These factors point to the reproductive habits of local species playing an important role in the change in fish assemblages.

The origin guilds do not display the same similarity to the full assemblage analysis as the reproductive guilds do. Their rate of variance accumulation is lower than reproductive guilds, and they do not display a trend of significant change over time. Residuals for these guilds are more scattered than linear, and the overall direction of these lines changes between month and halozone. These factors, when taken together, indicate that one cannot make a strong argument for the origin of a particular species relative to the system as a driving factor in assemblage change. Rare species display a similar lack of significance over time, and also do not display a steady positive or negative trend. Variance does not accumulate strongly at any of the axes, and is not generally high. The two concepts can be linked in the context of climate change; with water temperatures in the system rising, a research focus on the increase of southern-origin species, often considered rare in the assemblage, would be logical, and the rare species assemblage is comprised primarily of transients and southern stray species. The performance of

both origin guilds and rare species, however, suggests that this is not a particularly important factor driving assemblage change in the Mullica River-Great Bay system.

Notably, species with the highest and lowest amplitudes of change belonged to the Transient and Resident guilds in this classification, and Shelf Strays declined in importance at a similar rate to Transient guilds. This supports the results of the reproductive guilds, with species recruiting from an ocean-spawning pool seemingly driving change in the system far less than species spawning within the system. Further breakdown of these guilds based on additional origin characteristics, such as migration, spawning location, and life stage, could help to clarify these trends in the context of change in the system.

In this system, the reproductive guilds appear to reflect change in the assemblage most strongly when compared to the full assemblage. This could indicate that the reproductive habits of species in the system are changing, or that species are spawning elsewhere, and that the change in abundance over time is reflected in the overall assemblage. The conditions favorable to certain species' reproductive habits could also be changing, or the timing of these events. Further research will be required to narrow down which aspects of fishes' reproductive behavior are changing, and why.

It should be noted that the overall selection of guild parameters is subjective; the researcher is responsible for the selection of parameters, which could cause the loss of significant characteristics that would otherwise be reflected. This potential source of bias is difficult to avoid, as the researcher's choice is required to set guild parameters, and though based on data from the literature, the possibility of error cannot be discounted.

In addition, there are many different potential combinations of ecological and life history factors that could be used to set guild parameters, such as predation, larval stage characteristics, and preferred habitat. Though I did not test these factors, they may also play a role in driving change in the assemblage. Similar methods of guild construction and comparison to full assemblage analyses, using other characteristics, may display a significant effect, further explaining change within a system, and the factors contributing to it. Overall, the construction and use of guilds as a method for answering ecological questions about changing fish assemblages in a study system depend on the researcher's unique questions. Which characteristics are examined, and how, depend on the questions asked, and the variables that the study seeks to examine and understand.

Table 3.1 A listing of species in the reproductive guilds. Classifications were made based on the data contained in Able and Fahay (2010) and further literature review, where data was unavailable. The factors taken into consideration in each cluster are listed, with 1 indicating a positive, and 0 indicating a negative. Categories included in the analysis are season of spawning (Sp, Su, F, W) spawning location (FW, SS, Oc, Es, SB, MB), and egg type (Pela, Dem, Bent, Li). Unknown categories were classified as U.

Genspp	Eight	Twelve	IsSp	IsSu	IsF	IsW	InU	IsFW	IsSS	IsOc	IsEst	IsSB	IsMB	IsU	IsPela	IsDem	IsBen	IsLi	IsU
Aloaes	7	12	1	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0
Alomed	7	12	1	0	0	0	0	1	0	0	0	0	0	0	1	1	0	0	0
Alopse	7	12	1	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0
Aluheu	1	7	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	1
Alusch	1	7	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	1
Aluscr	1	7	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	1
Amecat	7	12	0	0	0	0	1	1	0	0	0	0	0	0	0	1	0	0	0
Ameneb	7	12	0	0	0	0	1	1	0	0	0	0	0	0	0	1	0	0	0
Ammame	6	11	0	0	0	1	0	0	0	1	1	0	0	0	0	1	0	0	0
Anchep	4	6	0	1	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0
Ancmit	4	6	0	1	0	0	0	0	0	0	1	0	1	0	1	0	0	0	0
Angros	1	7	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1
Apequa	6	11	1	0	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0
Astgut	4	6	0	1	0	0	0	0	0	0	1	0	1	0	1	0	0	0	0
Baichr	4	5	0	1	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0
Bretyr	8	4	1	0	1	0	0	0	0	0	0	1	1	0	1	0	0	0	0
Carcry	1	7	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	1
Carhip	8	1	0	0	0	0	1	0	0	0	0	1	0	0	1	0	0	0	0
Catcom	1	7	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	1
Censtr	4	6	1	1	1	0	0	0	0	0	0	0	1	0	1	0	0	0	0
Chabos	6	11	1	1	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0
Chaoce	8	1	0	0	0	0	1	0	0	0	0	1	0	0	1	0	0	0	0
Chisch	2	8	1	1	1	0	0	0	0	1	0	0	0	0	0	0	0	0	1

Citarc	1	7	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	1
Cluhar	5	10	1	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0	0
Conoce	2	8	0	1	1	1	0	0	1	0	0	0	0	0	0	0	0	0	1
Cynreg	4	6	1	1	0	0	0	0	0	0	1	0	1	0	1	0	0	0	0
Dacvol	1	7	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	1
Decpun	1	7	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	1
Engeur	8	3	1	1	1	0	0	0	0	0	0	1	0	0	1	0	0	0	0
Eriobl	1	7	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	1
Esonig	1	7	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	1
Etholm	1	7	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	1
Etrmic	4	6	1	1	1	0	0	0	0	0	0	0	1	0	1	0	0	0	0
Eucarg	1	7	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	1
Fistab	1	7	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	1
Fundia	6	11	1	1	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0
Funhet	6	11	1	1	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0
Gasacu	1	7	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	1
Gobbol	1	7	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	1
Gobbos	6	11	1	1	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0
Gobgin	2	8	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1
Hipere	3	9	1	1	0	0	0	0	0	0	1	0	1	0	0	0	0	1	0
Hipobl	1	7	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	1
Ictpun	1	7	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	1
Lagrho	8	2	1	0	1	1	0	0	0	0	0	1	0	0	1	0	0	0	0
Leixan	1	7	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	1
Lepgib	1	7	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	1
Lepmac	1	7	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	1
Lopame	1	7	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	1
Lucpar	6	11	1	1	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0

Lutgri	8	1	0	1	0	0	0	0	0	0	0	1	0	0	1	0	0	0	0
Menber	6	11	1	1	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0
Menmen	6	11	1	1	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0
Mensax	4	6	0	1	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0
Merbil	1	7	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	1
Mictha	2	8	0	1	1	0	0	0	0	0	1	0	0	0	0	0	0	0	1
Micund	4	6	0	1	1	0	0	0	0	0	0	0	1	0	1	0	0	0	0
Morame	7	12	1	0	0	0	0	1	0	0	0	0	0	0	1	1	0	0	0
Morsax	7	12	1	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0
Mugcep	8	2	0	0	0	1	0	0	0	0	0	1	0	0	1	0	0	0	0
Mugcur	8	1	1	0	0	0	0	0	0	0	0	1	0	0	1	0	0	0	0
Mulaur	1	7	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	1
Muscan	5	10	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	0
Mycmic	8	2	1	0	0	1	0	0	0	0	0	1	0	0	1	0	0	0	0
Myoaen	6	11	0	0	0	1	0	0	0	0	1	0	1	0	0	1	0	0	0
Notcry	1	7	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	1
Ophmar	1	7	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	1
Opiogl	8	3	1	1	0	0	0	0	0	0	0	1	1	0	1	0	0	0	0
Opstau	6	11	1	1	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0
Ortchr	1	7	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	1
Parden	8	4	0	0	1	1	0	0	0	0	0	0	1	0	1	0	0	0	0
Parobl	1	7	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	1
Peptri	4	6	1	1	0	0	0	0	0	0	1	0	1	0	1	0	0	0	0
Perfla	1	7	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	1
Pogcro	4	6	0	1	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0
Pomnig	1	7	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	1
Pomsal	8	3	1	1	0	0	0	0	0	0	0	1	1	0	1	0	0	0	0
Pricar	4	6	0	1	1	0	0	0	0	0	0	0	1	0	1	0	0	0	0

Prievo	4	6	0	1	1	0	0	0	0	0	0	0	1	0	1	0	0	0	0
Pseame	6	11	0	0	0	1	0	0	0	0	1	0	1	0	0	1	0	0	0
Psemac	1	7	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	1
Rajegl	1	7	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	1
Rajeri	1	7	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	1
Rhibon	3	9	0	1	0	0	0	0	0	0	1	1	1	0	0	0	0	1	0
Scoaqu	1	7	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	1
Scomac	1	7	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	1
Scosco	1	7	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	1
Selcru	1	7	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	1
Selset	1	7	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	1
Selvom	1	7	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	1
Serzon	1	7	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	1
Sphbor	1	7	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	1
Sphmac	6	11	1	1	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0
Stechr	4	6	1	1	0	0	0	0	0	0	1	0	0	0	1	0	0	0	0
Strmar	6	11	1	0	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0
Synfoe	1	7	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	1
Synfus	3	9	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0	1	0
Tauads	8	4	1	0	1	0	0	0	0	0	0	0	1	0	1	0	0	0	0
Tauoni	4	6	1	1	1	0	0	0	0	0	1	0	1	0	1	0	0	0	0
Tralat	1	7	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	1
Trilep	1	7	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	1
Trimac	4	6	1	1	1	0	0	0	0	0	1	0	0	0	1	0	0	0	0
Urochu	4	6	0	1	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0
Uroreg	4	6	1	1	1	0	0	0	0	0	0	0	1	0	1	0	0	0	0

Table 3.2 A listing of species in the origin guilds. Classifications were made based on the data contained in Able and Fahay (2010) and further literature review.

Species Name	Origin guild
Ameiurus catus	Resident
Ameiurus nebulosus	Resident
Ammodytes americanus	Resident
Apeltes quadracus	Resident
Catastomus commersoni	Resident
Chasmodes bosquianus	Resident
Erimyzon oblongus	Resident
Esox niger	Resident
Etheostoma olmstedi	Resident
Fundulus diaphanus	Resident
Fundulus heteroclitus	Resident
Gobiosoma bosc	Resident
Lepomis macrochirus	Resident
Lepomis gibbosus	Resident
Lucania parva	Resident
Menidia beryllina	Resident
Morone americana	Resident
Myoxocephalus aenaeus	Resident
Notemigonus crysoleucas	Resident
Opsanus tau	Resident
Pseudopleuronectes americanus	Resident
Tautaugolabris adspersus	Resident
Trinectes maculatus	Resident
Astroscopus guttatus	Shelf Stray
Decapterus punctatus	Shelf Stray
Engraulis eurystole	Shelf Stray
Hippoglossina oblonga	Shelf Stray
Leucoraja erinacea	Shelf Stray
Lophius americanus	Shelf Stray
Merluccius bilinearis	Shelf Stray
Paralicthys oblongus	Shelf Stray
Peprilus triacanthus	Shelf Stray
Raja eglantaria	Shelf Stray
Scomber scombrus	Shelf Stray
Seriola zonata	Shelf Stray
Trichiurus lepturus	Shelf Stray
Urophycis chuss	Shelf Stray

Aluterus heudelotii	Southern Stray
Aluterus schopfei	Southern Stray
Aluterus scriptus	Southern Stray
Chaetodon ocellatus	Southern Stray
Citharichthys arctifrons	Southern Stray
Ctenogobia boleosoma	Southern Stray
Dactilopterus volitans	Southern Stray
Fistularia tabacaria	Southern Stray
Lutjanus griseous	Southern Stray
Microgobius thalassinus	Southern Stray
Mullus auratus	Southern Stray
Orthopristis chrysoptera	Southern Stray
Pseudupenus maculatus	Southern Stray
Scomberomorus maculatus	Southern Stray
Selar crumenopthalmus	Southern Stray
Selene setapinnis	Southern Stray
Selene vomer	Southern Stray
Trachurus lathami	Southern Stray
Alosa mediocris	Transient
Alosa pseudoharrengus	Transient
Alosa aestivalis	Transient
Anchoa hepsetus	Transient
Anchoa mitchilli	Transient
Anguilla rostrata	Transient
Bairdiella chrysoura	Transient
Brevoortia tyrannus	Transient
Caranx crysos	Transient
Caranx hippos	Transient
Centropristis striata	Transient
Chilomycterus schoepfi	Transient
Clupea harrenguis	Transient
Conger oceanicus	Transient
Cynoscion regalis	Transient
Etropus microstomus	Transient
Gasterosteus aculeatus	Transient
Hippocampus erectus	Transient
Laaodon rhomboides	Transient
Leistomus xanthurus	Transient
Menidia menidia	Transient
Meticirrhus saxatilus	Transient
Micropogonias undulatus	Transient
Morone saxatilus	Transient

Mugil centralus	Transient
Mugir ceptiulus	
Mugil curema	Transient
Mustelis canis	Transient
Mycteroperca microlepis	Transient
Ophiodon marginatum	Transient
Opisthonema oglinum	Transient
Paralicthys dentatus	Transient
Pogionias cromis	Transient
Pollachius virens	Transient
Pomatomus saltatrix	Transient
Prinonotus evolans	Transient
Prionotus carolina	Transient
Rhinoptera bonasus	Transient
Scopthalamus aquosus	Transient
Spheroides maculatus	Transient
Sphyraena borealis	Transient
Stenetomus chrysops	Transient
Strongularia marina	Transient
Syngnathus fuscus	Transient
Synodes foetens	Transient
Tautauga onitis	Transient
Urophycis regia	Transient

GenSpp	Rarity
Aloaes	Abundant
Alopse	Abundant
Amecat	Abundant
Ameneb	Abundant
Anchep	Abundant
Ancmit	Abundant
Angros	Abundant
Аредиа	Abundant
Baichr	Abundant
Bretyr	Abundant
Carhip	Abundant
Catcom	Abundant
Censtr	Abundant
Chisch	Abundant
Cynreg	Abundant
Engeur	Abundant
Esonig	Abundant
Etholm	Abundant
Etrmic	Abundant
Fundia	Abundant
Funhet	Abundant
Gobbos	Abundant
Hipere	Abundant
Ictpun	Abundant
Lagrho	Abundant
Leixan	Abundant
Lepgib	Abundant
Menber	Abundant
Menmen	Abundant
Mensax	Abundant
Micund	Abundant
Morame	Abundant
Morsax	Abundant
Muscan	Abundant
Notcry	Abundant
Ophmar	Abundant
Opstau	Abundant
Parden	Abundant

Table 3.3 A listing of species in the abundant species and rare species assemblages. Guild classifications were formed based on the number of individuals encountered over the period of the study; those with less than twenty recorded individuals were classified as "rare."

Peptri	Abundant
Perfla	Abundant
Pomsal	Abundant
Pricar	Abundant
Prievo	Abundant
Pseame	Abundant
Rajegl	Abundant
Rajeri	Abundant
Scoaqu	Abundant
Sphmac	Abundant
Stechr	Abundant
Synfus	Abundant
Tauads	Abundant
Tauoni	Abundant
Trimac	Abundant
Uroreg	Abundant
Alomed	Rare
Aluheu	Rare
Alusch	Rare
Ammame	Rare
Astgut	Rare
Carcry	Rare
Chabos	Rare
Chaoce	Rare
Citarc	Rare
Cluhar	Rare
Conoce	Rare
Dacvol	Rare
Decpun	Rare
Eriobl	Rare
Eucarg	Rare
Fistab	Rare
Gasacu	Rare
Gobbol	Rare
Gobgin	Rare
Hipobl	Rare
Lepmac	Rare
Lopame	Rare
Lucpar	Rare
Lutgri	Rare
Merbil	Rare
Mictha	Rare
Mugcep	Rare

Mugcur	Rare
Mulaur	Rare
Mycmic	Rare
Myoaen	Rare
Opiogl	Rare
Ortchr	Rare
Parobl	Rare
Pogcro	Rare
Pomnig	Rare
Psemac	Rare
Rhibon	Rare
Scomac	Rare
Scosco	Rare
Selcru	Rare
Selset	Rare
Selvom	Rare
Serzon	Rare
Sphbor	Rare
Strmar	Rare
Synfoe	Rare
Tralat	Rare
Trilep	Rare

			р	F	df	SS
		Marine	4.25E-6	3.37	16	1.75
		Estuarine	0.00049	19.38	16	3.75
	July	Riverine	8.16E-9	1.54	16	2.75
		Marine	0.021	9.92	16	7.43
		Estuarine	0.031	5.58	16	1.75
Eight-cluster reproductive	September	Riverine	0.86	0.050	15	1.31
		Marine	0.0067	9.83	16	5.00
	July	Estuarine Riverine	0.0028 0.024	12.5 6.44	16 16	4.42 2.83
		Marine	0.019	6.88	16	5.95
Twelve-cluster reproductive	September	Estuarine Riverine	0.037 0.54	12.52 0.35	16 15	0.68 1.39
		Marine	0.12	8.21	16	2.46
		Estuarine	4.78E-37	12.1	16	408
	July	Riverine	0.23	1.63	15	3.07
		Marine	0.23	2.01	16	4.03
		Estuarine	0.15	5.55	16	1.28
Abundant Species	September	Riverine	0.23	1.63	15	3.07
		Marine	0.11	2.79	16	5.56
		Estuarine	0.093	3.18	16	3.57
	July	Riverine	0.85	0.050	16	1.92
		Marine	0.28	1.25	16	9.63
		Estuarine	0.28	1.24	16	5.32
Origin	September	Riverine	0.39	0.72	15	2.03
		Marine	0.58	0.31	16	4.80
		Estuarine	0.12	2.70	16	0.90
	July	Riverine	0.11	2.86	16	0.037
		Marine	0.14	2.42	16	0.008
		Estuarine	0.29	1.20	16	88.2
Rare Species	September	Riverine	0.85	0.038	16	0.017

Table 3.4 Linear regression statistics for halozone and month scores for each guild.Halozone/month score combinations were regressed against year.

	July Estuarine	September Estuarine	July Marine	September Marine	July Riverine	September Riverine
Eight-Cluster Slope	-0.072	-0.0341	-0.0716	-0.0784	-0.475	-0.0034
Eight-Cluster R ²	0.56	0.27	0.40	0.34	0.34	0.003
Twelve-Cluster Slope	-0.0702	-0297	-0.0697	-0.0677	-0.0457	0.0102
Twelve-Cluster R ²	0.45	0.26	0.396	0.31	0.30	0.025
Origin Slope	-0.0391	-0.0315	-0.0462	-0.0426	-0.0039	0.0172
Origin R ²	0.18	0.076	0.16	0.077	0.0033	0.050
Rare Spp Slope	0.0183	0.1266	0.0154	0.0046	0.0038	-0.0003
Rare Spp R ²	0.15	0.074	0.020	0.14	0.16	0.0026
Abundant Spp Slope	0.0364	0.0213	0.0554	0.067	0.039	0.034
Abundant Spp R ²	0.45	0.14	0.51	0.45	0.17	0.13

Table 3.5 Line of best fit slopes and R2 values for each guild or assemblage, across the different month-halozones of the study.

Table 3.6 A representation of the PCA scores for the eight-cluster reproductive guilds. The eight-cluster guilds showed significant change across almost all months and halozones, and explained more of the variation in the assemblage than the twelve-cluster, full assemblage and rarity guilds, though not as much as the origin guilds.

	Eigenvalue	Cumulative Percentage Variance Species
First Axis	0.425	42.5
Second Axis	0.150	57.5
Third Axis	0.124	69.9
Fourth Axis	0.104	80.3

Table 3.7 A representation of the PCA scores for the twelve-cluster reproductive guilds. The twelve-cluster guilds showed significant change across almost all months and halozones. This guild did not explain as much of the variation as the eight-cluster guilds and the origin guilds, but explained more of the variation than the rarity guilds and full assemblage.

	Eigenvalue	Cumulative Percentage Variance Species
First Axis	0.295	29.5
Second Axis	0.142	43.7
Third Axis	0.111	54.8
Fourth Axis	0.097	64.5

Table 3.8 A representation of the PCA scores for the abundant species assemblage. The assemblage showed significant change across most months and halozones. While they explained the least variation of the four guild types, they did explain more variation than the full assemblage.

	Eigenvalue	Cumulative Percentage Variance Species
First Axis	0.225	22.5
Second Axis	0.108	33.3
Third Axis	0.055	38.8
Fourth Axis	0.050	43.7

Table 3.9 PCA scores of fish collections from the Mullica River Great Bay estuary after organization into origin guilds.

	Eigenvalue	Cumulative Percentage Variance Species
First Axis	0.449	44.0
Second Axis	0.208	65.7
Third Axis	0.179	83.7
Fourth Axis	0.163	100.0

Table 3.10 A representation of the PCA scores for the rare species assemblage. The rare species assemblage did not show significant change across any of the halozones and months, with the exception of the July Estuarine stations.

	Eigenvalue	Cumulative Percentage Variance Species
First Axis	0.064	6.4
Second Axis	0.060	12.4
Third Axis	0.057	18.1
Fourth Axis	0.052	23.4

Table 3.11 A comparison of first eigenvalues and total percentage variance of the full assemblage and guild PCA scores.

	Eigenvalues	Total Percentage Variance of Species Data
Origin Guild Scores	0.449	100.0
Abundant Species Scores	0.225	43.7
Eight-Guild Analysis Scores	0.425	80.3
Twelve- Guild Analysis Scores	0.295	64.5
Full Assemblage Scores	0.125	27.3
Rare Species Scores	0.064	23.4

Figure 3.1 A map of the Mullica River-Great Bay estuary in southern New Jersey. Trawl sites are marked by black dots. The stars indicate the location of the System Wide Monitoring Program (SWMP) loggers, the four-pointed star represents the location of the meteorological monitoring station, and the diamond indicates the location of the Rutgers University Marine Field Station. Each grouping of stations is enclosed in an ellipse, and labeled according to their halozone classification.

Figure 3.2 A breakdown of rare species by origin guild. Most of the species classified as "rare" in the system were either transients, which pass through at a predictable interval each year, or southern strays. This suggests that species considered "rare" within the assemblage are typically not native residents of the area.

Figure 3.3 A biplot of the eight-cluster reproductive guild analysis. The first eigenaxis explains over half the variation in the dataset. Both reproductive guilds showed significant change across most of the halozones of the study.

Figure 3.4 A biplot of the twelve-cluster reproductive guilds analysis. Much like the eightcluster reproductive guild analysis, the first eigenaxis explains over half the variation in the dataset. Both reproductive guilds showed significant change across most of the halozones of the study.

Figure 3.5 A biplot of the origin guilds analysis. The change in guilds over time is not significant in any of the halozones of the study

Figure 3.6 Accumulation of variance at each axis for all five guild types and the full assemblage. The eight and twelve cluster reproductive guilds accumulate the fastest at the first axis. The origin guilds accumulate to 100%, but because only four guilds were used in the analysis, this accumulation is inevitable. The number of axes to full accumulation of 100% variance is shown with respect to the number of axes measured for each guild.







Figure 3.2



Figure 3.3



Figure 3.4



Figure 3.5





GENERAL CONCLUSIONS

Climate change, particularly changing water temperatures, has a direct effect on fishes. This is visible in the Mullica-Great Bay fish assemblage as a change in the composition of summer-caught assemblages, particularly in the month of July, and with the observed importance of summer temperatures to the change in fish assemblage. Freshwater species showed the greatest increase in amplitude, while commonly found estuarine species declined in importance. Given that average yearly temperatures are warming in the bay, it is reasonable to propose that fish assemblages will see further change in the future, as the climate continues to warm.

The specific effects of climate on the assemblage, such as the abundance of species of southern or oceanic origin, are not addressed by the broad assemblage analysis. Narrowing the assemblage down by using guild classifications as a "super-species" and using these guilds as a proxy for individual species' responses to climate change, can help to target these effects. Reproductive guild classifications fit the trends observed in the full assemblage most closely, with freshwater spawning species increasing in importance overall, and estuarine spawners declining in importance. Guilds based on species origin did not display the same significant pattern. Additionally, rare species do not seem to drive change in the assemblage. This points to changes in local conditions outweighing changes in recruits from the marine environment in the case of assemblage change in the Mullica River-Great Bay system. In general, these changes can also be traced back to a decline in commonly captured estuarine species. Both abundance trends, and a lack of significant change in salinity across the time-series in all three halozones support this finding.

I have established that fish assemblages are changing in the system, and that reproductive characteristics fit the trends observed in the full assemblage most closely, while rare and southern-originating species play a minor role, if any, in driving this change. Future studies, then, should focus on individual species, or different guild classifications, and their response to changing climate within the system. Commercially and recreationally important species, for instance, could be analyzed for a pattern of change, and this pattern could be applied to management decisions in the future. Additionally, ecologically important or indicator species would be interesting to examine. This would give an assessment of the change in conditions and ecology of the system, and inform future environmental protection and management policies.

Overall, this study is exploratory in nature, and lays the foundation for further research of change within the system, especially if the time-series can be continued. Examining individual species, and the effects of climate on their abundance, health, and size, is a possible next direction in which to continue this research.

Appendix Figure 1 Abundance plots for each individual species within the assemblage. Species were summed by occurrences in each year across all three halozones, and the summations were graphed across the study period. Each plot is labeled with the first three letters of the species' genus and species. See Table 3.1 for full species names.







Etholm

Years

Eucarg

2008

Years

Funhet

Years

Gobbol

Years

2008 2009 2010 2011 2012 2013

2008 2009 2010 2011 2012 2013

Number of Fish

Number of Fish 2000 0

0 2003

0 2003

1

Number of Fish 100 20 0

Number of Fish

Number of Fish

Number of Fish

0 2003

0 2003

0 2003 2004

2005 2006 2007

0 2003 2004 2005 2006 2007

2004 2005 2006 2007

2004 2005 2006 2007

2004



2010

2011 2012 2013

















Years

97

Appendix Figure 2 Residual plots for each months and halozones of the study for the eightcluster reproductive guilds.



Eight-Cluster Reproductive
Appendix Figure 3 Residual plots for each months and halozones of the study for the twelvecluster reproductive guilds.



Twelve-Cluster Reproductive

Appendix Figure 4 Residual plots for each months and halozones of the study for the origin guilds.



Origin Guilds

Appendix Figure 5 Residual plots for each months and halozones of the study for the rare species assemblage



Rare Species Assemblage

Appendix Figure 6 Residual plots for each months and halozones of the study for the abundant species assemblage



Abundant Species Assemblage

Appendix Figure 7 Residual plots for each months and halozones of the study for the full assemblage



Full Assemblage

ACKNOWLEDGEMENT OF PREVIOUS PUBLICATIONS

In Review: Nickerson KJ, Grothues TM, Able KW (2017) Changing Fish Assemblages in a Mid-Atlantic Estuary: Analysis of a Decades-Long Time Series. Target Journal: Estuaries and Coasts

In Review: Nickerson KJ, Grothues TM, Able KW (2017) Sensitivity of a Time-Series Analysis to Guild Construction: A Case Study of the Mullica River-Great Bay Ecosystem. Target Journal: Marine Ecology Progress Series

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