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Migrational Changes of Diadromous Fish in the San Francisco Bay Due to Anthropogenic Climate Change: A Correlational Research Study

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Abstract

Recently, there has been consistent research within the field of environmental science focused on anthropogenic, or human-caused, climate change and understanding its trends and causes. Similarly, much of this research has been focused on its effects and understanding what can be done to mitigate those effects. Rising oceans, melting glaciers, and changes in weather patterns are some of the overarching impacts within the focus of this field. However, a similar, understudied effect is how climate change affects the migration of species, specifically, the migration of diadromous fish species. Diadromous refers to marine species that migrate between freshwater and saltwater within their lifetime in order to feed or spawn. Within this study, the research focuses specifically on the San Francisco Bay in California, United States, with the bay being not only defined as the saltwater that makes it up, but also the various rivers and estuaries that surround it, to which diadromous fish migrate to or from. In the San Francisco Bay, this study focuses on three diadromous species: the coho salmon, Chinook salmon, and steelhead trout. In order to understand these three species' changes in migratory patterns, a correlational design using quantitative data was performed by running T-tests on each of the species. The T-tests compared the temperature of the bay from 2014 to 2024 to the optimal temperatures for migration of each of the species' populations. The results gave insight into the potential for species' migration to be altered depending on the amount of time they were outside of their optimal range.

Keywords

Anthropogenic, Diadromous, San Francisco Bay, Migratory Patterns, Optimal Temperature, Climate Change

1. Introduction

Anthropogenic climate change and its impacts on the modern world have been consistently at the forefront of many aspects of society in today's time, notably in the scientific community [1]. As explained by Finn *et al.* [1] in their study on climate change in the Pacific Ocean, anthropogenic climate change is defined as any long-term change in climate or weather due to human activity. Finn *et al.* [1] continue down the path of climate, noting the varying impacts of climate change, which include, but are not limited to, effects on the global economy, rising sea levels, human population distribution, as well as its most significant impact on wildlife. One of these impacts on wildlife is explained by Crozier *et al.* [2] on species vulnerability to climate change, in which they find 47% of the 976 species they studied faced extinction due to anthropogenic climate change and the subsequent changes to their environment. This finding is similar to that of Worthington *et al.* [3], a study aimed at protecting swimways of migratory fish, in which it is found that of the 665 fish studied, 109 were deemed as threatened due to loss of their migratory habitat caused by climate change. A subclassification of these migratory species is called diadromous fish [3]. This is defined by Reist *et al.* [4] in their study of Arctic diadromous fish as species of fish that migrate between freshwater and saltwater to reproduce or feed. For example, Ueda *et al.* [5] studied marine migration in the northwest of the Pacific Ocean, which included coho salmon in their study, a diadromous species that migrates inland once in their lifespan in order to spawn. Overall, anthropogenic climate change and its effects on wildlife are overlooked, as explained by the University of Glasgow [6], by drawing trends from Scotland, showing that wildlife's struggles with climate change are often glossed over as humans tend to prioritize their safety over that of wildlife, making it even more necessary for a focus to be placed on wildlife.

In order to understand the impact of anthropogenic climate change on the migration of the three diadromous species of fish, this study focuses on the San Francisco Bay (SFB), Chinook salmon, coho salmon, and steelhead trout. The literature review will aim at uncovering examples from outside the SFB in non-marine and marine species, as well as specifically diadromous species. The literature review pulls examples from previous studies from across the globe in order to understand how anthropogenic climate change impacts similar circumstances within the SFB itself.

As described by Seebacher [7], in their study on causes of migrational change, one of the most significant impacts on wildlife can be observed in migration and species distribution, with many species unknowingly altering their habits, patterns, and evolved behaviors to accommodate environmental fluctuations as a result of climate change. This example, because of its pervasiveness, can be narrowed into specific species as described by the National Oceanic and Atmospheric Administration (NOAA) [8], finding that certain species of sharks, specifically the scalloped hammerhead and lemon shark, require very shallow water to survive relative to similar species. They find that their habitat shrinks increasingly every year because the more shallow the water, the quicker it warms, pushing the scalloped hammerhead into deeper water, which they are unfamiliar with [8]. This finding is not only specific to marine environments, however, as exemplified by Dingle, whose study focuses on insect migrational changes. Dingle [9] finds that *Callosobruchus maculatus,* commonly known as the pea weevil, has produced a 65% migrant morph. This migrant morph shows that within the population studied in Nigeria, 65% have been recorded to have shown differences in their migration due to anthropogenic climate change [9]. These examples can be further narrowed down to the realm of marine environments, in which there are continued exemplifications of climate change's causation of migrational changes.

Larger-scale marine examples of climate change impacting migration are seen in a report from Acadia National Park in Maine, which encompasses a portion of the coastal region on the Gulf of Maine [10]. The park reports that its marine species are consistently moving farther north, following cooler water, as the ocean temperature in the Gulf of Maine has risen by 3 degrees Fahrenheit since 2004 [10]. The park also notes the specific species, reporting changes in the green crab, black sea bass, and longfin squid [10]. Similar findings are presented by van Weelden *et al.* [11], who specifically studied the impacts of climate change on cetaceans, a family of animals that includes dolphins, whales, and porpoises. Their research concludes that cetaceans in northern latitudes, primarily those closer to the North Pole, have been forced to alter their migration patterns as a result of changes in ice floe positioning because of rising temperatures [11]. Comparable changes are also exemplified in a study done by Langan *et al.* [12], who studied migrational species and climate change in Narragansett Bay, Rhode Island, by analyzing quantitative data from the University of Rhode Island School of Oceanography collected since 1959. This takeaway from Langan *et al.* shows that, of the 12 species that had data collected consistently between 1959 and 2016, migrational habits became increasingly unpredictable as the data approached the present, because the impacts of anthropogenic climate change have increased over time [12]. More specifically, Langan *et al.* note particular species in the bay where this occurs, such as the Atlantic herring, a winter-migratory fish, which stayed in their previous location in the bay longer as winter began than they generally do by 16 days [12]. Similar findings have been observed in Scotland in a study conducted by Hasler *et al.* [13] on solutions to migrational changes in salmon. Hasler *et al.* found that particular species of salmon in Scotland respond to changes in the environment by migrating to completely different rivers from their regular habits, exemplified by using their home rivers' scent in a new river, observing that the fish follow the smell rather than the river they know, displaying how easily environmental cues can influence migration [13]. Continued research is drawn from the Mid-Atlantic Regional Ocean Assessment, a compilation of marine data from the United States' Atlantic coast, in which further exemplifications of marine migration changes can be seen through the winter flounder and black sea bass, which have consistently shifted northward, along the Atlantic coast since 1968 [14].

Marine examples can be continually narrowed further to specific types of fish, specifically diadromous fish, which can be defined as fish that migrate between freshwater and saltwater [15]. This Bloom and Lovejoy study aims to understand the evolution of diadromy, describing the three subdivisions of diadromy: anadromy, fish born in freshwater and migrate to saltwater, catadromy, which are species that perform the opposite, and amphidromy, fish that migrate between the two fluidly and for growth purposes rather than reproduction [15]. The significance of diadromy in relation to climate change is explained in a study performed by Crozier and Siegel [16], aimed at understanding how anadromous fish adapt. They explain that diadromous species of fish are more vulnerable to climate change because they are in contact with a greater number of variables that are impacted by climate, as they cover a larger range compared to many species [16]. This finding is aligned with the findings of Reist *et al.* [4], a study of Arctic diadromous species, in which the vulnerabilities of diadromous fish to climate change are described as due to their large range, as well as the high number of environmental cues being changed. Specific examples of these vulnerabilities in diadromous fish can be seen in an attribute evolved in migratory fish species called olfactory imprinting, in which the salmon subconsciously imprint the scent of their home river in their mind, so they can return to it [5]. This process is disrupted by climate change as it alters the potential of hydrogen (pH) levels, which give off different scents, causing the salmon to be unsure of where to migrate [5]. Further examples are seen in Wenger *et al.* [17], an examination of trout and their reactions to climate change in North America, in which Wenger uncovers that trout have extremely restrictive temperature ranges, which, with changes in temperature due to climate, force them to migrate less far upstream each year because water is warmer further upstream. However, climate change does not just alter temperature, as shown in a study performed by Seyedhashemi *et al.* [18] of climate change in various river basins across Europe, who find that climate change caused the currents to change in the Loire River in France, causing migratory diadromous fish populations in the river to decline in subsequent years. Noted in Arevalo *et al.* [19], an analysis on further adaptations of fish to climate change, these changes, such as those with the olfactory imprinting and currents previously mentioned, create maladaptations in diadromous fish, causing changes to their migratory patterns in response to the climate changes experienced.

The San Francisco Bay (SFB) is home to a multitude of diadromous species of fish and is an area of the world where research on climate change and migration has been consistently overlooked. Despite this, it is an extraordinarily susceptible area to climate change and migration as it holds many of the key variables, such as uncommon changing current patterns and uneven salinity levels, that make bodies of water such as this susceptible to such things (18, 20). This is shown by Lin *et al.* [20] in a study of a specific diadromous species of fish, the Australian grayling, in which it was found that their habits are highly impacted because of the varying salinity levels of the waters they inhabit on the coast of southeast Australia. Similar changes and circumstances may be occurring in the SFB and with the diadromous species that reside within it. These species are exemplified by the San Francisco Estuary Partnership [21], a non-profit organization working with cities around the SFB to maintain the estuaries, the bay, and the wildlife within them, with many anadromous and catadromous species inhabiting the bay. They note many different species of diadromous fish within the SFB; however, the three main species and the species focused on within the study are the coho salmon, Chinook salmon, and steelhead trout, as these are the three most important of the diadromous species to the SFB ecosystem [21]. Within the SFB, there has yet to be a comprehensive research study focused on the changes of these diadromous species' migration in relation to anthropogenic climate change. This particular gap leads to the formation of the following research question: *How has anthropogenic climate change impacted the migratory patterns of diadromous fish species in the San Francisco Bay and surrounding freshwater rivers and estuaries from* 2014 *to* 2024?

Based on the review of literature, previous studies suggest that the migration of the diadromous fish species within the SFB this study focuses on, the steelhead trout, coho, and chinook salmon, will be affected by the increases in temperature, affecting the ecosystems and environmental cues in the SFB that these species of diadromous fish require to migrate properly according to their usual patterns [5, 16]. By using a correlational research design, one can compare the changes in temperatures in the SFB to the optimal temperature ranges of the specific populations of species in order to understand how often each population is outside of its optimal range.

2. Methodology

2.1. Research Design

A correlational research method with a quantitative design was used for this research by comparing two databases of information, one of optimal species temperature and the other of climate changes in the bay, hoping to uncover how the changes in climate impact migrational changes of diadromous fish, so they can be better understood and predicted in the future. Two datasets were compared, one from a protective organization specific to migratory fish species in California, CalTrout, which provided the optimal temperature ranges for migration for the specific SFB populations for the three species, and from NOAA, which provided the climate data spanning from 2014 to 2024. An organizational spreadsheet was utilized in order to outline and organize the data gathered from each data set to make it easier to see and draw connections between the two. This was the best method as it is the only one that compares two separate data points to one another in order to interpret and uncover trends and correlations between the two.

In the process of sampling for this study, data were gathered from the two datasets previously mentioned. Both are in the public domain and can be found simply with a Google search on both the websites of CalTrout and NOAA. No further gathering was required because both organizations had the data necessary to conduct the correlational design and be able to connect migrational data to climate within the bay.

2.2. Limitations

Overall, the main limitation within this study was that it relied on datasets and correlational research rather than an experimental research design. It was limited to what could be gleaned from the data provided by NOAA and CalTrout, as well as the connections that could be drawn between them. These two sets may not take into account all variables present in the situation or weigh variables based on importance to migration, and therefore present a limitation. Alternatively, an experimental research design could have been used within the frame of this research. In order to achieve this, one could use spatially explicit adaptive migration models (SAMMs) as used in a study by Howard *et al.* [22], explaining them as a method of predicting future migrational changes in any area required. However, there are multiple drawbacks to this method. Firstly, as a high school student, it is difficult to write the code required to run a SAMM, and it would be a better fit for someone with more time and experience in the topic. Along with this, to run a SAMM properly, one would need far more data than I could acquire; environmental factors as small as annual runoff would be required. This is something I cannot reasonably acquire considering my limited time and experience. Because of this, the study is limited to the two datasets collected.

2.3. Ethical Considerations

Within this research, there are no ethical concerns; the research conducted was non-human and did not involve the usage of potentially sensitive information or data. On top of this, the two datasets from CalTrout and NOAA were both public domain, allowing them to be accessed by anyone, making it so that there are no ethical concerns with the gathering of data either.

Overall, I hold the belief that anthropogenic climate change is a negative entity, having countless negative impacts on many aspects of life on this planet, and that in the current state of this world, it is imperative that a solution to the issue be found. With me holding this position, I recognize that it may happen that, within my research, connections may have been drawn that may not be present or, at most, coincidental, surrounding the impacts of anthropogenic climate change on the migration of diadromous fish.

3. Results

Subsequent to the collection of data through the methods described in the previous section, an inferential statistics analysis was conducted in order to understand the correlation between diadromous fish migration within the SFB and climate change. As defined by Leedy and Ormrod [23], an inferential statistics analysis is an analysis of data that uses inference to apply general findings from a smaller sample to a larger group. The analysis compared the optimal temperature range for migration of each species examined with the changes in temperature over time in their habitat of the SFB in order to understand if a relationship exists and, if so, how closely correlated the two are in order to understand future implications of the potential issue.

3.1. Average Habitat Temperature

The first step within the statistical analysis was to understand the changes in temperature in the SFB within the range of time for my study, 2014 to 2024. In order to understand and interpret information uncovered by the comparative analysis run later, it was first necessary to understand how the temperature of the SFB changed over time. To do this, a simple linear regression model was performed, using the data acquired from NOAA's dataset on the temperature of the bay, providing a trendline for the habitat temperature data as well as its R-squared value and equation. As seen in **Figure 1** below, the equation for the trendline of the data was $y = -0.166x + 396$, along with the r-squared value for the data, which came out to be 0.298.

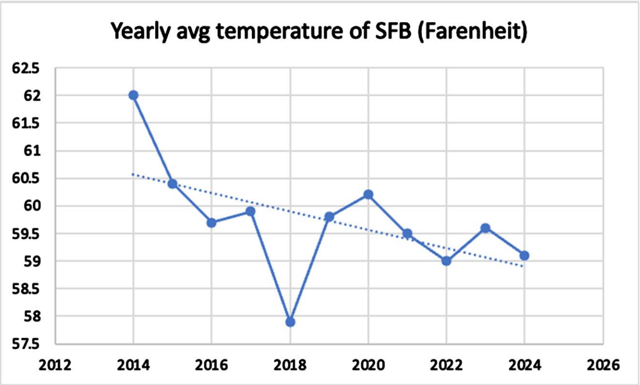

Figure 1. The linear regression model was run for the temperature data collected from the SFB spanning from 2014 to 2024. This model shows the overall trend in yearly average temperature used in the research to compare optimal fish temperature ranges with average temperature.

Also seen in **Figure 1**, the average temperature of the SFB had a slight decline from 2014 to 2024, with the highest end of the range being in 2014, sitting at 62 degrees Fahrenheit as opposed to the lowest in 2018 at 57.9 degrees. The equation of the trendline, as depicted by the dotted line running through the graph, suggests that the average temperature of the SFB declined by approximately 1.66 degrees throughout the ten-year span. The r-squared value of this data, noted earlier as 0.298, suggests that the connection between the years and temperature change is not strong and, at least for the small scale of the ten-year span, relatively random.

This brings up the second piece to the data analysis of this study, three consecutive t-tests ran for each of the three main diadromous species of fish residing in the SFB, and that the study focuses on: coho salmon, chinook salmon, and steelhead trout. *t*-tests are a tool used in inferential statistics that determines if a trend exists between two sets of data and if the trend is coincidental or is a real correlation [23]. *t*-tests were used in order to compare the optimal temperature for their migration, and living to the average habitat temperature from **Figure 1** in order to determine how often the fish is outside of that range.

3.2. Relationship of Average Temperature and Optimal Temperature

The two most important pieces of data from each test run are the *p*-value, two-tailed, and the *t*-value, each giving the most insight into the correlation between average temperature and each fish's optimal temperature. More specifically, the two-tailed p-value is the number provided by the *t*-test that shows if the trend is coincidental or a real trend, and the *t*-value represents the determination of correlation between the means of the data. In the context of this study, if the *t*-value is greater than 2, then there is a high correlation between the means of the data, and if the *p*-value is below 0.05, then the trend is likely not coincidental. These two statistics will be the focus of each of the next three sub-sections.

3.2.1. Coho Salmon

The first *t*-test was run on the coho salmon. The test uncovered a two-tailed *p*-value of 0.01722001 and a *t*-value of 2.80177509. The *t*-value of this test reveals that the correlation is highly significant because it is significantly greater than 2, given the small sample size. However, the more important statistic of the two is the *p*-value of this test, which reveals that the trends present between habitat temperature and optimal range of the coho salmon are likely real trends and not an off-chance occurrence.

3.2.2. Chinook Salmon

The second t-test was run on a similar species to the coho salmon under the same family, the Chinook salmon. The test uncovered a two-tailed *p*-value of 0.000076352 and a *t*-value of 6.10934536. The *t*-value of this test indicated an even stronger correlation than the previous test, as it is much larger than the last and well above the benchmark of 2. The *p*-value also reveals similar results to the previous test, indicating that the Chinook salmon population's trends between optimal temperature and fluctuating water temperatures are also not coincidental, with the *p*-value being far less than the required number of 0.05.

3.2.3. Steelhead Trout

The third and final *t*-test was run on the steelhead trout populations inhabiting the SFB. This *t*-test uncovered a two-tailed *p*-value of 0.0000028259 and a *t*-value of −8.7284712. Because the absolute value of the *t*-value is very large ($|t| = 8.728$) and the *p*-value is far below the conventional significance level of 0.05, the null hypothesis is rejected. The results, therefore, provide strong evidence that there is a statistically significant relationship between the changes in water temperature and the steelhead trout's optimal range, suggesting that there are implications for their migrational habits.

4. Discussion

Overall, the general finding of the study presented above is that the three species of diadromous fish studied, coho salmon, Chinook salmon, and steelhead trout within the SFB, are, on average, outside of the range of their optimal temperatures. This presents multiple issues and future implications for these species when it comes to their migration. Previous findings suggest that being outside the optimal temperature range consistently for a species causes its migration patterns to change. This is exemplified by Wenger *et al.* [17] with their findings suggesting changes in temperature altered the time of year that a population of fish migrated, slowly over time, in the populations of trout focused on in their research. Similarly, changes in temperature outside the range of specific species can impact where a fish population migrates to, as noted by the NPS in Acadia National Park, who find certain species off the coast of Maine are migrating farther north than their usual patterns would predict them to [10]. Other examples of potential changes include in Japan, with Pacific coho salmon changing the rivers they migrate to due to pH level changes caused by anthropogenic climate change, as well as species in European rivers migrating less far upriver [5,18]. Overall, this raises two overarching implications for the species focused on in this study within the SFB, where they migrate to, and the time of year they migrate, because, as shown, it is easily impacted by anthropogenic climate changes in the environment and water of the area.

As shown by previous research and examinations of climate change and migration in diadromous species, it is clear that as the temperature changes, the tendency, as previously described, is for the species to adapt to that temperature change and migrate either at different times or to slightly different places, whether consciously to find better conditions, or unconsciously by just following their natural tendencies. These changes may seem small enough to be insignificant, but they can create issues that could end up harming the species more. For example, Howard *et al.* [22] explain how the records and accounts of species migration and population will become inaccurate as the fish migration changes. This is important as it will impact protective organizations and governments' abilities to protect species that need conservation from things such as overfishing and habitat loss [22]. This finding is similar to that of the San Francisco Estuary Partnership, who note this specific implication within the SFB itself, as their records and ability to protect species by working with cities and local governments in the SFB would be hurt significantly by changes to their migratory patterns [21].

The findings described above, within the analysis section, however, do not outline specifically how the species studied changed from the time period studied, only how often they were outside their optimal temperatures, as represented by the p-values and t-values of each of the species of fish. With this, it is hard to perfectly examine the changes that happened spanning the ten-year range of the study; it can only be inferred that these changes occurred due to the amount of time fish were outside their optimal temperature range, high correlation between the two means, and trends recognized in previous literature. This differs from other studies conducted around the world on diadromous fish that examined a certain species of diadromous fish more closely, so that it could be understood exactly how their habits changed. For example, Lin *et al.* [20] followed specifically the Australian grayling in order to understand the exact specific changes in their movements using tracking technology. A study such as this would have yielded more specific results than those gleaned from this study.

5. Conclusions & Future Directions

The study aimed to understand the correlation between anthropogenic climate change and the migratory patterns of the three main diadromous species within the SFB: coho salmon, Chinook salmon, and steelhead trout. Overall, the results indicate that from the years 2014 to 2024, the populations of the three species studied were consistently outside their optimal range of temperature, suggesting that their migration patterns were impacted by the changes in temperature. The findings of this study may be a step in the direction of understanding the implications of climate change on fish populations, specifically within the SFB, as issues such as this have already been consistently studied outside of the SFB.

Future research may be applied and built on this study, aimed at more closely studying each specific species of fish in order to understand how we can begin to protect them with changes in their migration. Previous studies have used more predictive methods of studying the effects of climate change on fish, such as SAMMs [22]. Applying these different methods to the same populations and species of fish studied within the SFB could potentially uncover more closely how they could be protected. By working with protective organizations and non-profits such as CalTout and the San Francisco Estuary Project, future research, using these predictive methods, is the key to the future of these species and the protection of their migratory habitats and grounds within the SFB and its surrounding estuaries and rivers. The more general approach of this study provides a foundation for future research in that its findings present the issue in a light not seen previously, so that hopefully it can be seen by more researchers to be acted upon in the future.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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