Lampreys

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Summary

From the late 1940's to the early 1960's, the harvest from the Great Lakes fishery dropped from 15 million pounds of lake trout in the Upper Great Lakes to approximately 600,000 pounds. This drastic decrease in economic production can be attributed to the explosion in population of the invasive, parasitic sea lampreys. The Great Lakes Fishery Commission has implemented control programs with the use of lampricides, specifically TFM and Bayluscide, given that the removal of lampreys from the ecosystem is valued at an annual value of 7 billion USD. Lampreys have also been of interest to the scientific community for the substantial variation in sex ratio across their different environments and they have been found to exhibit male-dominant populations in environments with high food availability.

We were tasked with analyzing the interactions between sex ratios and resource availability pertaining to sea lamprey populations. We thus chose to model the population of lampreys as well as the sex ratios with respect to local conditions and the presence of lampricides. We began with an age-state model which analyzed existing data to establish parameters of survival rates and birth rate by age class, which were then applied to a transition matrix. We thus established a population model by sex and environment type which yielded the result of greater female proportion in lentic areas and greater male population in the river areas. Our second model pertained to the variation in sex ratio based on the quantity of lampricides present in the environment. We constructed this model using linear regression, which found a positive correlation between the application of Bayluscide and the proportion of males in the population.

Our first model displayed the overall population decline of the lampreys in both lentic and river ecosystems, as shown by the population-time graph as well as the long-term stability of the transition matrices. Its strengths include accurately modeling the variability of lamprey populations as well as the close relationship between the populations of each sex. Weaknesses include the relatively small data set that we extracted survival rates from, the altered reproduction rate due to lack of data on older lamprey generations, and not directly taking into account external factors such as lampricide concentrations, nutrient and oxygen availability, and food sources/predation.

Our second model showed an overall ineffectiveness of TFM as a lampricide to reduce male ratio in river ecosystems but a strong positive correlation between Bayluscide and the lentic male ratio, signifying an effectiveness of Bayluscide to decrease male ratio in populations. The decrease in lentic populations cannot be fully attributed to Bayluscide, however, since this pesticide is highly toxic to many organisms including mollusks; it was likely that the decrease in Bayluscide-treated lamprey populations simply had a negative effect on the ecosystem as a whole, decreasing the lamprey population indirectly through lack of available resources. The strengths of the model include its clear distinction between two different kinds of lampricides, its success in identifying a high correlation between Bayluscine and the male ratio in lentic environments, and its graphical specificity that highlights the uniqueness of the area. Weaknesses include possibility of oversimplification, limited environmental factors combined and inability to conclude causation.

In terms of practical applications of our model, the declining population can assist scientists and governmental agencies to better alter their lamprey regulation policies by indicating the effects of specific lampricides on sea lamprey populations. For example, they might choose to use Bayluscide to decrease the lamprey population effectively through lowering female ratio, while still keeping in mind that it has negative effects on the entire ecosystem. Additionally, scientists can see how different ecosystems affect the lamprey's larval growth stage and change their methods of regulation following this. The model can also be used as data to help form the necessary figures on fish stocking, as well as to model other species populations that depend on lampreys directly, such as predatory birds, turtles, and other fish.

Contents

1 Introduction

Lampreys are carnivorous jawless fish that are native to various regions of the world, particularly in the Atlantic Ocean. Sea lampreys are of distinct interest to the scientific community for their impact on environments they are invasive to. We will focus on sea lampreys, specifically those in the Great Lakes of North America. Sea lampreys are parasitic in that they attach themselves to their prey to leech blood and other fluids from their host. In their native environments, lampreys do not kill their host because of coevolution between the species. However, in the Great Lakes, these coevolutionary links do not exist, so sea lampreys kill their prey and thus occupy a predator class. Each individual lamprey is capable of killing up to 40 pounds of fish over their 12-18 month feeding period [3].

Lampreys were introduced to the Great Lakes through the construction of the Welland Canal in 1833 [4]. However, the sea lamprey population exploded in the late 1940s. They exhibited a sizable impact on the Great Lakes fishery in which the harvest dropped from 15 million pounds of lake trout in the upper Great Lakes to approximately 300,000 pounds by the early 1960s [3]. Lampreys are a threat to this environment because of their high reproductive potential, lack of natural predators, and the ideal environment in the lake waters. The Great Lakes Fishery Commission estimates that removing harmful sea lamprey populations and reimplementating a healthy, native ecosystem in the region has an estimated annual value of 7 billion USD due to the effects on the fishing industry. They responded by implementing control programs that exploit lamprey's vulnerability by targeting larval sea lampreys in tributaries. These control programs rely on lampricides to dampen lamprey population growth [3].

The lamprey life cycle begins with a prolonged larval stage in which they burrow into stream beds and feed on detritus and algae. They then develop into parasitic juveniles, migrate out to the lake where they feed on lake trout and other fishes for a year. Afterwards, they become sexually mature, go back to the rivers to respawn, and die. The mysterious aspect of lamprey development has historically been the process of sex differentiation. For the first 2-3 years of a sea lamprey's life, the single gonad remains undifferentiated. A recognizable ovary is then apparent after this point, while the gonad of future males remains undifferentiated until a recognizable testis develops at 5-7 years of age at metamorphosis [7]. The sex ratios of sea lampreys are highly variable and the exact environmental and genetic factors that control these ratios have long been of interest to the scientific community. However, within the past few decades, research has revealed that sex determination is directly influenced by the larval growth rate of lampreys. In turn, the larval growth rate of lampreys is dependent on food availability in the environment. Environments with greater food availability result in faster larval growth rates and thus male-dominant populations. The converse is also true where environments with lesser food availability result in slower larval growth rates and thus female-dominant populations [3].

Problem Restatement

In this analysis, we were requested to construct a model to examine the interactions between sex ratios and resource availability pertaining to sea lamprey populations. In particular, we were instructed to examine the impact of the larger ecological system and the resulting stability of the ecosystem. Additionally, we were requested to model the advantages and disadvantages to the population of lampreys. Our interpretation thus led us to investigate the interactions of lamprey sex differentiation and lamprey population with respect to local conditions.

Definitions

Lampricide Chemical designed to target larval lampreys in river ecosystems. A pesticide specifically aimed at selectively killing larval lampreys without harming other fish or the ecosystem [8].
Bayluscide (2', 5-dichloro-4'-nitrosalicylanilide) Lampricide that is less expensive and less widely used than TFM. Granular form is typically used on slow-moving or stationary water where TFM cannot be used [8].
TFM (3-trifluoromethyl-4'-nitrophenol) Most widely used lampricide. Applied in liquid form to select tributaries to disrupt larval metabolism. TFM does not bioaccumulate and does not affect most other organisms [8].
Lentic Environment Non-flowing, still bodies of water. In particular in our case, this refers to ponds or connected backwaters of rivers [16].
River Environment Running water habitats. Tributaries refer to a smaller river that flows into a larger river and are thus classified under "River Environment" [16].
Sex Determination The establishment of the sex of an organism [9].
Sex Differentiation The progressive acquisition of male or female characteristics in the genital tract and external genitalia [10].
Sex Ratio The ratio between the number of males and the number of females in a population, expressed as the number of males per 100 females [1].

Relevant Variables:
1. Age-State Model for Sex Differentiation. The relevant variables of this model include the sex ratio, survival rates by sex, and age class.
2. Lampricide-Sex Ratio Linear Regression Model. The relevant variables of this model include the total lampricide, the sex ratio, and the environment type.

Assumptions

Throughout our modeling analysis, we will proceed based on the following assumptions:

1. Age-State Model for Sex Differentiation

i. The first five years are representative of sex differentiation in the lamprey population. Though lampreys live approximately 12 years, we modeled only the first five years instead of all age classes. Sex differentiation occurs only in these years so these classes are those that are relevant to this model.

ii. The data set is indicative of the lamprey population in the Great Lakes, though the numbers are small [1].

iii. The birth rates of when and how much reproduction occurs is assumed in absence of statistics. The parameters are reasonable, so the model's results may be interpreted within reason.

iv. The model of small size is indicative of the greater population. The parameters we have worked with allow us to generalize to some degree due to solid research practices.

2. Lampricide Model

i. The lampricide TFM is only applied in tributaries. It is common practice to apply TFm to river environments.

ii. The lampricide Bayluscide is only applied in the lentic environment. It is common practice to apply Bayluscide in still-water where TFM cannot be used.

Modeling Approach

1. Age-State Model for Sex Differentiation

We used a state model to examine sex differentiation broken down by year. The classes include years 0, 1, 2, 3, 4, and 5. We began by finding a count of each species (Lentic or River) and sex (Male or Female) for each of the five age classes. These numbers were thus used for examining the sex ratio, rather than having specific value in terms of population size. Therefore we were able to find the change in sex ratio between each class, for each environment. This then yielded the survival rates from year to year. Finally, we applied these parameters that we calculated to a state model using a transition matrix. We were therefore able to model the populations of lampreys in the long term because of our choice of a state model. Additionally, the use of classes allows us to analyze the sex ratio by year over the span of time in which lampreys differentiate into each sex.

2. Lampricide-Sex Ratio Linear Regression Model

We created a model to determine the relationship between the use of lampricide and the impact on the percentage of males in the lamprey population. We calculated the sex ratios using information provided from our previous model. Additionally, we calculated parameters of lampricide usage across both lakes. We then plotted total lampricide usage against the sex ratio. We also separated this plot into two separate plots for the lentic and river environments. We thus performed linear regression on these three plots to model the strength of the relationship between lampricide usage and sex ratio. Linear regression as our choice in model is useful in quantifying the interaction between these two variables. Additionally, this model is useful because the variables we are comparing may relay insight into the impact of the environmental conditions on sex differentiation.

2 Model

Model Description

Model One: Age State Model for Sex Differentiation

The first model that we chose to find was based on an age-class model. The dataset [1] contained data from two types of lampreys (river and lentic), their sex, and what year of life they were in, (0-5). To begin to find survival rates for these age classes, we first found a count of each species and sex for each age class. (Figure 1)

	female	male
(0, 'Lentic')	2	2
(0, 'River')	2	9
(1, 'Lentic')	4	3
(1, 'River')	19	44
(2, 'Lentic')	9	56
(2, 'River')	33	68
(3, 'Lentic')	9	51
(3, 'River')	14	15
(4, 'Lentic')	10	17
(4, 'River')	2	2
(5, 'Lentic')	2	6

Figure 1: Counts of Each Species for Age Class

As these population numbers were small, we assumed that the distribution of population would be more indicative of survival rates than the actual numbers. These numbers were artificially created by the group that produced this dataset, and as such are not as large or numerically accurate to use as a progression from age class to age class. As such, we found the proportion of each sex to the age class total population. (Figures 2 and 3)

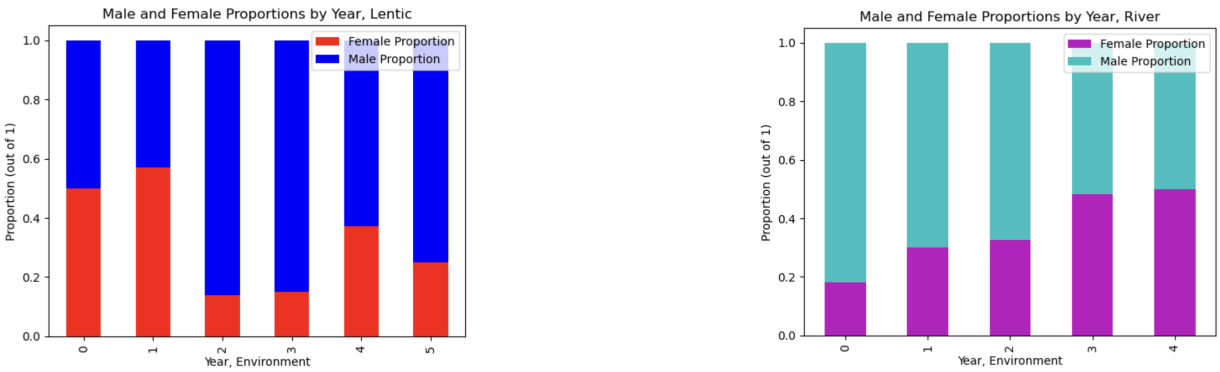
Year	Type	Proportion
0	Lentic	0.5
0	River	0.8182
1	Lentic	0.4286
1	River	0.6984
2	Lentic	0.8615
2	River	0.6733
3	Lentic	0.85
3	River	0.5172
4	Lentic	0.6296
4	River	0.5
5	Lentic	0.75

(a) Male Proportion

Year	Type	Proportion
0	Lentic	0.5
0	River	0.1818
1	Lentic	0.5714
1	River	0.3016
2	Lentic	0.1385
2	River	0.3267
3	Lentic	0.15
3	River	0.4828
4	Lentic	0.3704
4	River	0.5
5	Lentic	0.25

(b) Female Proportion

Figure 2: Proportions for Male and Female Succession by Year



(a) Lentic Proportions, Male vs. Female

(b) River Proportions, Male vs. Female

Figure 3: Proportion Visualization, by Species

Using this information, we found the change in proportion from class to class, differentiated by lentic or river type, to come up with survival rates from year to year. This is of course based on the assumption that these rates will be indicitive of a larger population, and that proportions are an accurate measure of the rate of survival from year to year.

Year	Female Change	Male Change
0-1	0.142858	-0.142858
1-2	-0.757692	1.01026
2-3	0.0833297	-0.0133923
3-4	1.46913	-0.259259
4-5	-0.324999	0.191176

(a) Lentic Survival Rates

Year	Female Change	Male Change
0-1	0.65873	-0.146384
1-2	0.0833789	-0.0360045
2-3	0.477534	-0.231745
3-4	0.0357135	-0.0333326

(b) River Survival Rates

Figure 4: Proportion Numbers, by Species

These numbers only model the first few years of a lamprey's life, which is when sex differentiation is important. Thus, these years are the years we choose to model. But, in order to make this model run we need birth rates for the first age class. These numbers, we will model off of the normal birth rate of lampreys. (female) Lampreys reproduce only once in their lives, with this reproduction yielding around 10,000 viable eggs. They reproduce typically from 4-8 years old [2].

As mentioned before, since the lampreys only reproduce from the ages of 4-8, and the only available data that we have on survival rates is from 4-5, we treated the final class' reproduction rate as the reproduction rate of the entire 4-8 age group. This reproduction rate followed a random variable that produced a birth rate of 50 offspring per lamprey in the 4-5 class 25% of the time. However, since this would not be a completely representative model, since it would produce approximately 25% of the actual number of births per year, this rate was changed to 200 offspring per year times a random sample of size 1 from a Bernoulli(0.25) distribution.

We structured a model around these facts, creating 2 stochastic models of lamprey populations in the lentic and river environments. The models contained 5 classes, 0-1, 1-2, 2-3, 3-4, and 4-5, which was based on the available data with respect to the survival rates. These simulations were run for lentic and river populations twice: once for a duration of 10 years and another for a duration of 50 years. The results of the simulations were graphed. The general form of the population model is as follows:

$$\text{For male: } \begin{cases} m_0(n) = \frac{1}{2}b \\ m_1(n) = (1 - 0.142858)m_0(n) \\ m_2(n) = (1 + 1.01026)m_1(n) \\ m_3(n) = (1 - 0.0133923)m_2(n) \\ m_4(n) = (1 - 0.259259)m_3(n) \\ m_5(n) = (1 + 0.191176)m_4(n) \end{cases} \quad \text{For female: } \begin{cases} f_0(n) = \frac{1}{2}b \\ f_1(n) = (1 + 0.142858)f_0(n) \\ f_2(n) = (1 - 0.757692)f_1(n) \\ f_3(n) = (1 + 0.833297)f_2(n) \\ f_4(n) = (1 + 1.46913)f_3(n) \\ f_5(n) = (1 - 0.324999)f_4(n) \end{cases}$$

$m_i(n)$ is the male growth model, $f_i(n)$ is the female growth model, and the birth rate b is based on lamprey birthrates of (on average, 10,000 babies per female, once in their life from ages 4-8). We modeled this with 200 births per age group (4-5).

Model 2: A Lampricide Model

We chose to secondarily create a model based on the change in sex ratio of lampreys due to lampricide in the Great Lakes. Since the lampreys in our study is an invasive species in the Great Lakes, there are no major predators for them. As we mainly study the larvae lampreys, the most important factor impacting them is the use of lampricide. Thus, as the lampreys that we study are in rivers and lentic areas from Lake Michigan and Huron, we focus on lampricide uses in those two lakes. In our first general model, we recorded the changes in total lampricide uses in Lake Michigan and Huron from 2007 to 2012 in a line graph [11]. The second graphs (figure 6) show the usage of the same lampricides in rivers used in the data for Model 1 [13]. These correlations will become clear later.

Assumptions: 1. All the bayluscide are used in lentic areas (since TFM cannot be used in lentic areas) 2. All the TFM are used in stream areas.

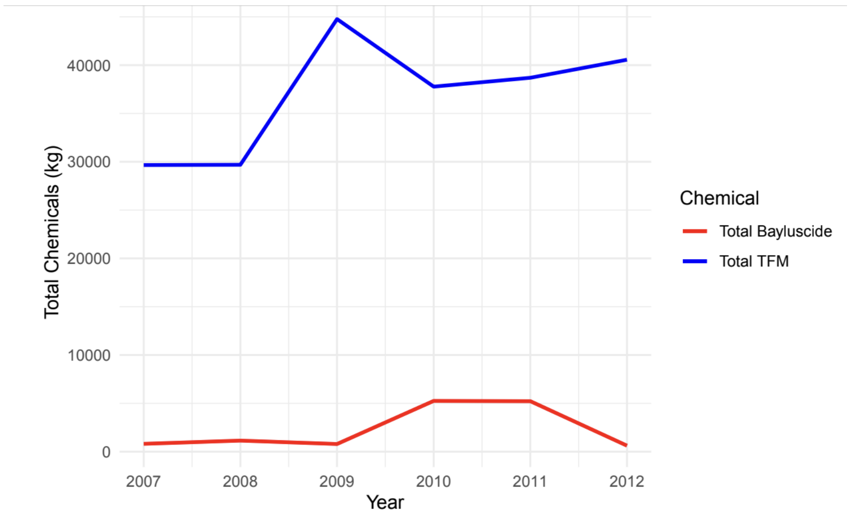
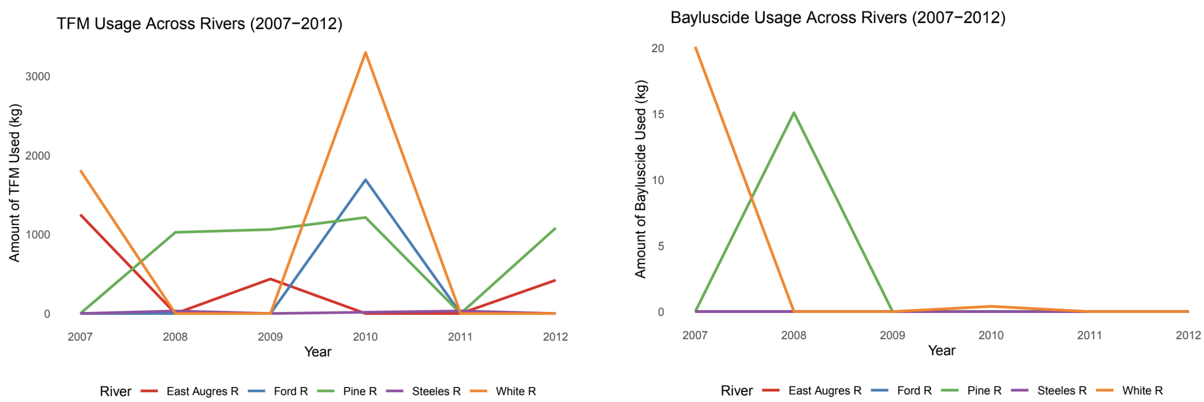


Figure 5: Total TFM and Bayluscide Used in Lake Michigan and Lake Huron (2007-2012)



(a) TFM Usage

(b) River Survival Rates

Figure 6: Lampricide Usage in Rivers in Sex Differentiation Model

We then compare the data with our sex ratio graph (Figure 3 above) and correlate the total uses of two different kinds of lampricide with our separate sex ratio graphs in river areas and lentic areas.

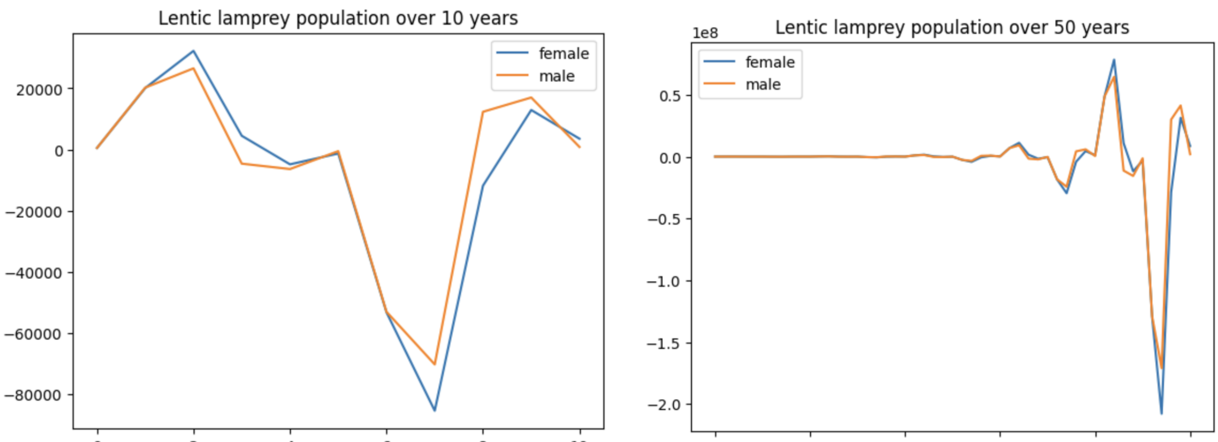
In creating the model shown in the following model application, supplemental data from [12], [13] [14], (All Johnson et. al.) was used, in conjunction with earlier proportions found.

Model Application

Model 1:

Using modeling software, we iterated the sex ratio model found above for 10 and 50 years in both lentic and river environments. We found that our model more accurately predicted the lamprey population the first few years, before becoming more unpredictable.

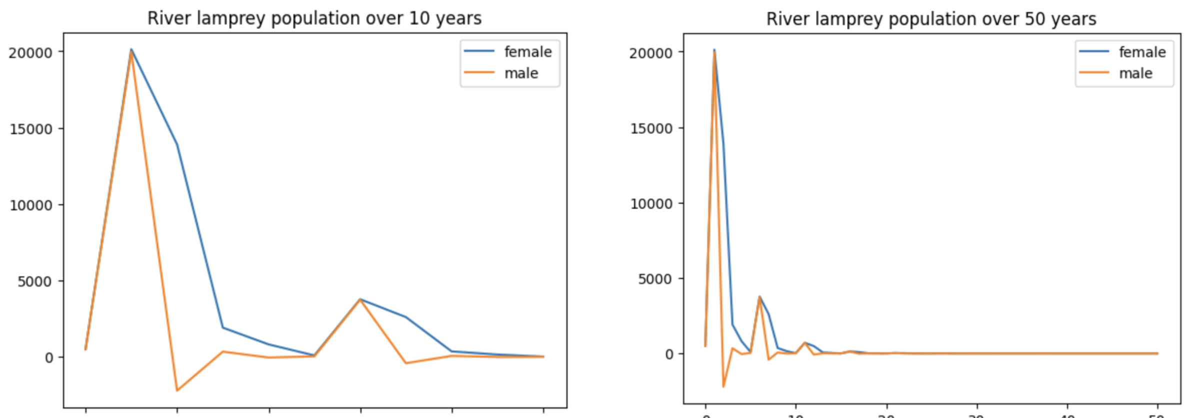
Lentic:



(a) Lentic over 10 Years

(b) Lentic over 50 Years

River:



(a) River over 10 Years

(b) River over 50 Years

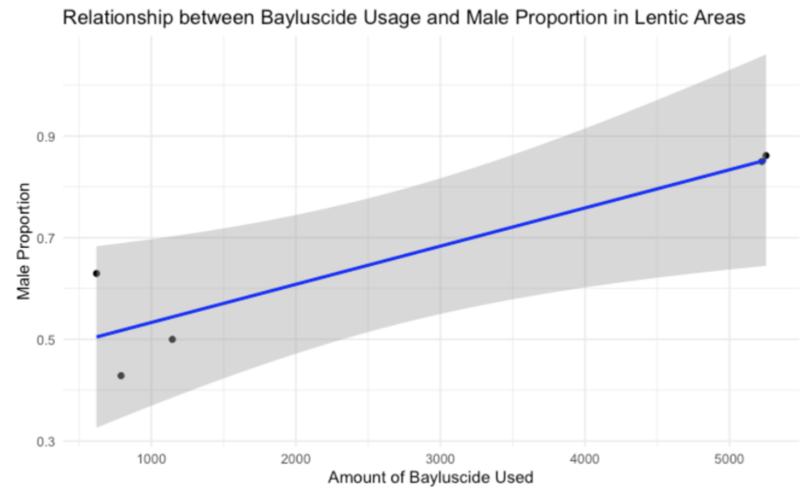
These figures show a close relationship between the sexes, but definitely a few key differences in these relationships between lentic and river areas.

In the lentic population, there is a closer relationship between the two sexes. Female, however, appears to ultimately have the upper hand in terms of proportions, which does not seem to fit our projected idea of sex differentiation, but food is likely more available in this area.

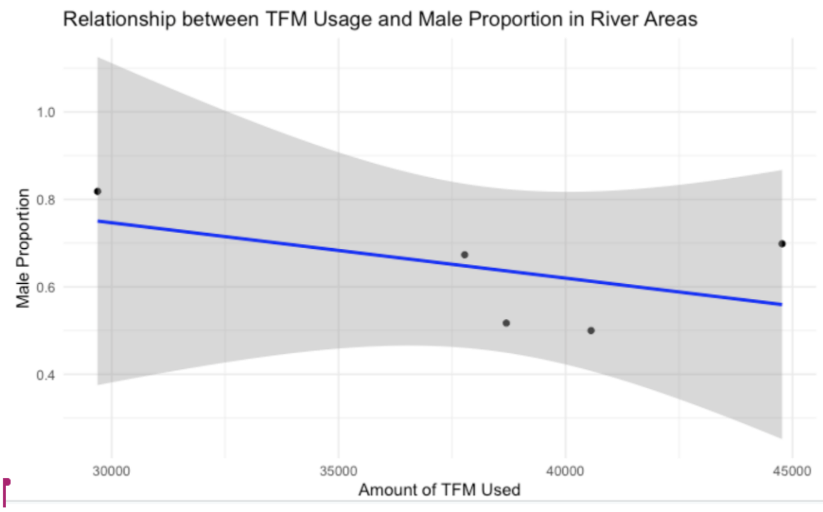
The river model has a higher male population, almost overall, and does not have the dip below zero like the lentic population does. We can see the stability more of the river population, and the typical growth we might expect of a male dominated sex differentiation. Still, the numbers of the population drop rather quickly, and stay around zero.

Model 2:

These models both show correlations between the different lampricides and the proportion of male lampreys. Correlation coefficients were calculated for each relationship.



(a) Bayluscide Correlation, Correlation = 0.9148



(b) TFM Correlation, Correlation = -0.5233

Figure 7: Male Proportion Relationship for the Specific Lampricides

It shows a positive relationship with correlation = 0.9148 between bayluscide and male proportion in lentic areas, suggesting that the male proportion increases as the amount of bayluscide increases.

Analyzing the relationship between TFM and male proportion in river areas did not receive an as clear result. It shows a more moderate negative relationship with correlation = -0.5240. It may be possible that the river environment has stronger liquidity than lentic environment, such that the sex ratios are not as significantly affected by TFM uses.

Thus, we modeled again the response to TFM, based on Figure 6, seen below. This was in order to reduce the influence of confounding variables. We collected TFM data specifically used in the 5 tributaries that we studied to conduct linear regression again. It is shown that there exists a moderate positive relationship with a moderate correlation coefficient = 0.3643.

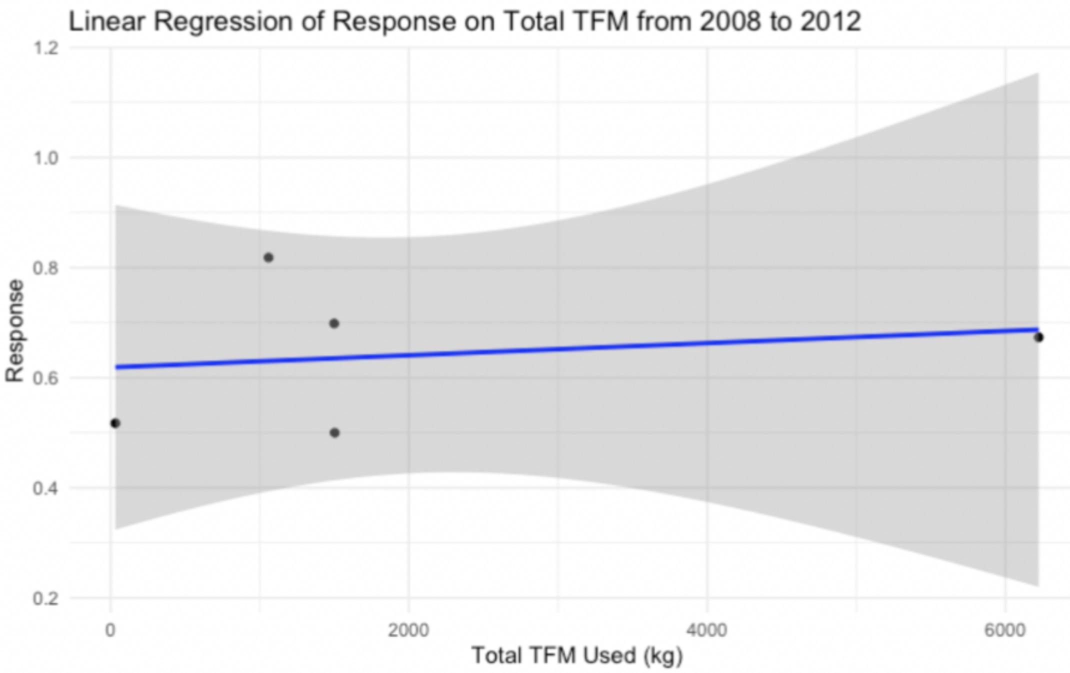


Figure 8: TFM From 2008-2012

Both of these models correspond to a prediction model by the government which detailed their efforts at lampricide use. The variance seen in our prediction model is seen in this model as well, and the population tending towards zero can be explained by environmental factors like lampricide (figure 9) [15].

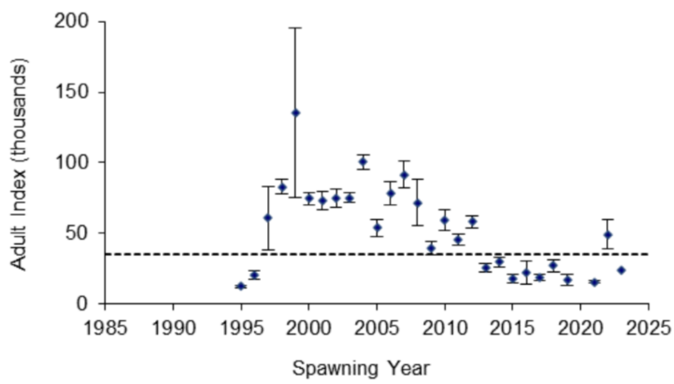


Figure 9: Government Prediction Model

Model Analysis

Model 1: We did some model analysis of long-term stability on the transition matrices for each sex and location of the lampreys. The corresponding dominant eigenvalues were:

Female lentic: 0.9754273, with eigenvector: $< -0.9830, -0.1439, 0.1118, 0.0095, 0.01439, -0.00479 >$

Male lentic: 0.4479838, with eigenvector: $< 0.8551, 0.2045, -0.2306, 0.0000, 0.00299, -0.00191 >$

Female river: 1.1337729, with eigenvector: $< -0.8639, -0.5019, -0.0369, -0.0155, -0.004897608 >$

Male river: 0.3820780, with eigenvector: $< 0.933, -0.3574, 0.0336, -0.0204, 0.00178 >$

Thus, each of these populations is declining, as evidenced by the graphs and by the long-term stability of the model. The factors that may affect this are their food availability, lampricides (discussed more below), and that the model was inaccurate, and based on small data sets.

This model is weak in a few ways: it is based off of the assumptions stated above, the small data set, and a changed birth rate to keep the model smaller. If given budget, this model could be improved through further knowledge of actual lampreys alive in the areas we modeled. Furthermore, the model doesn't take into account the later lampricide discussion, or other environmental factors, as we assumed that since they were predators, there were no important competing factors for this model. Furthermore, the model could be improved by the addition of the other age classes until death, which was not added as there was no data to support these claims of survival rates. Also, the model dips below 0, which is not possible for a population, and thus invalidates some of the findings.

Yet, there are some strengths to the model, including the modeling of the variability of lamprey population. Several other studies have found similar results, seeing lamprey population fluctuate over time, and tend towards zero. Furthermore, the model captures the close relationship of the sex differentiation over time. While the numbers are likely more varying, the two categories do mirror each other throughout time.

When testing the model for validity, we could perform more statistical tests to determine the correlation with actual lamprey succession data. Furthermore, finding a way to prevent the population from hitting zero, or finding out when that is would be a large improvement to the model. Another way to vastly improve the model would be to include more data from lamprey births and deaths, and model more populations to determine differences in sex ratio. We would have preferred to use data from all of the rivers and tributaries separately, in order to really determine the differences between location and sex differentiation.

Model 2: There are several strengths to the lampricide model. There was a focus on the lampricide types. By distinguishing between the effects and difference of TFM and Bayluscide, the lampricide model offers targeted insights into how different lampricides influence the lamprey's sex ratio differently. Secondly, The strong positive correlation (0.9148) between Bayluscide usage and male proportion of lamprey in lentic areas suggests a significant biological or environmental interaction that could be further explored for ecological management and control strategies. Finally, the geographical specificity. Concentrating on Lake Michigan and Huron allows for a more controlled analysis of environmental and ecological variables that may not be as uniform in other areas.

Some weaknesses of the model include: the assumption of lampricide application areas. The assumption that TFM is only used in rivers and Bayluscide in lentic areas might oversimplify the application practices and environmental dynamics, possibly overlooking several river areas where their uses overlap. Nevertheless, the overlap situation is rare and usage of bayluscide is often minimal in those cases. Secondly, the causal relationships are unclear. While correlations provide useful initial insights, they do not establish causality. Factors other than lampricide application might influence the observed changes in sex ratios.

3 Conclusion

Throughout our study, we found many correlations between lampreys environment and the way that they both survived, and thus were able to sex differentiate. That is what led us to creating two models, that coexist and interact to predict some of the variation in lamprey behavior.

The stacked bar charts representing sex ratios in lentic and river lampreys from Model 1 demonstrates this difference between the two environments as was stated by Johnson et al. [1]. Since sea lampreys in a river environment have shown significantly more rapid larval growth, these types of populations are likely to overcome more drastic changes in ecosystem, such as nutrient and oxygen levels, temperature, lampricide concentration, and available food sources. Being as such, the river graphic displays a general uptrend in the female population in relation to the male population, which signifies a higher level of overall growth as a population. On average over the 5 recorded years, the proportion of female river lampreys is increasing at a rate of 7.955% per year. On the other hand, sea lampreys inhabiting lentic ecosystems have a slower larval growth rate of average, making the population less apt to respond quickly to changes in environment. Following this, the lentic lamprey sex ratio bar chart demonstrated more erratic behavior, including both increases and decreases in the female proportion with no general trend when graphed against year. In fact, the proportion of female lentic lampreys was actually decreasing by 5.0% over the 6 recorded years. Thus, we can come to the conclusion that at higher temperatures, higher nutrient levels, and higher levels of dissolved oxygen in the water is generally beneficial to the female lamprey population, and subsequently is more beneficial to the lamprey population as a whole.

Previous studies showed that larvae sea lampreys in lentic environments grew two to four times slower than larvae from the stream environments. (Johnson et al. 2014 and Johnson et al. 2016) [12], [14]. Lentic areas are susceptible to temperature due to small bodies of water, low nutrient levels and low dissolved oxygen. Therefore, the average temperature around the year is lower. The lower temperature and nutrient levels together lead to a delayed growing process for larval lampreys.

While the correlation between the amount of TFM and male proportion of lamprey in river areas is relatively moderate, the amount of bayluscide is shown to have a strong positive correlation with the proportion of male lampreys in lentic areas. It can be explained in a way that when lampricides are used, the growing rate of lamprey is negatively impacted.

The correlation between the amount of bayluscide used in a given lentic ecosystem and the corresponding male lamprey proportion is both positive and strong since the coefficient was calculated to be 0.9148. This data suggests that there exists a correlation between bayluscide concentration and the larval growth rate of lentic sea lampreys since the larval stage is when sex differentiation occurs. According to our model, by introducing this effective lampricide into lentic ecosystems, governing bodies will be able to increase the male sex ratio of the larval lampreys, which then in turn would cause the entire lamprey population to decrease. Here, an important application of our modeling system can come into play since marine biologists and those who are interested in decreasing the invasive species' prosperity can use this data to see which lampricides are more effective than others. Here, we noted a strength of our model based on the fact that we deliberately isolated the two lampricides. If this was not done, the model likely would have shown a general decrease in lamprey population after using both TFM and bayluscide, but we would not have been able to pinpoint which pesticide was more significant in affecting sex ratio.

It is studied that Bayluscide is much less selective and more toxic than TFM (Dawson, 2003, Wilkie et al., 2019) [17]. Bayluscide was originally used as a molluscicide to eliminate snails, therefore mollusks are extremely sensitive to Bayluscide. Since Bayluscide eliminates the mollusk population in lentic areas, the population of fish that prey on mollusks will therefore be negatively influenced, causing the whole ecosystem to be even less productive.

Producing eggs is nutritionally consuming for female lampreys. Compared to males, female lampreys need more nutrition to develop their reproductive system. Therefore, it is not surprising that lampreys in lentic areas tend to have a larger proportion of males when compared to those in river areas. Previous research suggests that the unique sex-determination system of lampreys may be influenced by factors such as larval density or nutrient availability. Larval lampreys tend to grow larger in nutrient-rich environments, where producing energy-intensive eggs is more feasible. Consequently, in such environments, there is a tendency toward a higher proportion of females [12].

Application of the Model

As mentioned before, it is important to track the population and sex ratios of lampreys because they are a highly invasive species that has detrimental effects on both the native ecosystem of the Great Lakes region as well as lasting economic ramifications on the fishing industry. Because of this, our model can be useful to government agencies like the Great Lakes Fishery Commission, who can use these figures to modify their lamprey regulation systems. For example, in our model, TFM was proven to have a generally negligible effect on the sex ratios of fish, while it does affect the general population. On the other hand, bayluscide, which is a generally less ubiquitous choice in the lampricide industry, was proven to increase the male ratio of lentic lampreys, therefore decreasing the long-term longevity of the lamprey population. Therefore, based on this model, it would behoove the Commission to ramp up the usage of bayluscide in their regulation systems.

This model could also be useful in providing data and trends to any government agencies that are centered around the management of certain large fish species in the region, either for the preservation of the ecosystem or for fishing and game purposes. Michigan's Department of Natural Resources is an organization that is involved with fish stocking, the practice by which fish are raised to partial maturity in captivity and then released into the wild to join local populations. Using our model, which predicts a decrease in lamprey population after utilizing lampricides in a regulation framework, the Department of Natural Resources would be able to gain a better understanding of the lamprey population in order to scale down how many fish they are introducing into the wild. If there were to eventually be a drastic decrease in the lamprey population, but the Department was continuing to stock the large fish populations at a constant rate, this larger proportion of large fish inhabiting the region might have a large impact on other species such as insects, birds, algae, turtles, and plants.

Finally, this model can be applied as supplementary data for the purposes of modeling other species in the area. As was mentioned before, numerous species that inhabit the Great Lakes area are in some way or another reliant on the lamprey population to live, whether it be through predation, decomposition, or symbiosis. If the population of one of these species needs to be modeled in the future, this model contains vital data to understand the role of sea lampreys in the larger scope of the ecosystem.

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5 Code Chunks

Listing 1: Finding proportions and Survival Rates

```
count_lentic = pd.DataFrame({'Years': [0, 1, 2, 3, 4, 5], 'Female':
[2, 4, 9, 9, 10, 2], 'Male': [2, 3, 56, 51, 17, 6],
'Total': [4, 7, 65, 60, 27, 8]})
female_prop_lent = count_lentic['Female'] / count_lentic['Total']
male_prop_lent = count_lentic['Male'] / count_lentic['Total']

count_river = pd.DataFrame({'Years': [0, 1, 2, 3, 4], 'Female':
[2, 19, 33, 14, 2], 'Male': [9, 44, 68, 15, 2],
'Total': [11, 63, 101, 29, 4]})
female_prop_river = count_river['Female'] / count_river['Total']
male_prop_river = count_river['Male'] / count_river['Total']

female_prop_year = count_by_sex['female'] / total_count_byyear
male_prop_year = count_by_sex['male'] / total_count_byyear

lentic_change = pd.DataFrame({'Year': ['0-1', '1-2', '2-3', '3-4', '4-5'],
                              'Female Change': [(0.571429 - 0.500000)
                              / 0.5, (0.138462 - 0.571429)/0.571429,
                              (0.150000 - 0.138462)/0.138462, (0.370370
                              - 0.150000)/0.15, (0.250000 - 0.370370)
                              /0.370370],
                              'Male Change': [(0.428571 - 0.500000)/0.5,
                              (0.861538 - 0.428571)/0.428571, (0.850000 -
                              0.861538)/0.861538, (0.629630 - 0.850000)/
                              0.85, (0.750000 - 0.629630)/0.629630]})
river_change = pd.DataFrame({'Year': ['0-1', '1-2', '2-3', '3-4'],
                              'Female Change': [(0.301587 - 0.181818) /
                              0.181818, (0.326733 - 0.301587)/0.301587,
                              (0.482759 - 0.326733)/0.326733, (0.500000
                              - 0.482759)/0.482759],
                              'Male Change': [(0.698413 - 0.818182)/
                              0.818182, (0.673267 - 0.698413)/0.698413,
```

```
                    (0.517241 - 0.673267)/0.673267, (0.500000
                    - 0.517241)/0.517241]})
```

Listing 2: Second Model: Correlation Coefficients and Data Wrangling

```r
years <- c(2007, 2008, 2009, 2010, 2011, 2012)
lake_michigan_tfm <- c(11359.2, 14722.5, 31913.7, 13346.4, 17504, 22531.3)
lake_michigan_bayluscide <- c(110.1, 219.4, 291.9, 92.1, 135.7, 224.3)
lake_huron_tfm <- c(18301.7, 14966.9, 12856.5, 24431, 21190.5, 18030.3)
lake_huron_bayluscide <- c(698.5, 925.9, 498.3, 5160.8, 5088.4, 395.9)
# Calculate total TFM and Bayluscide across both lakes
total_tfm <- lake_michigan_tfm + lake_huron_tfm
total_bayluscide <- lake_michigan_bayluscide + lake_huron_bayluscide
# Combine into a data frame
data <- data.frame(years, total_tfm, total_bayluscide)

years <- c(2007, 2008, 2009, 2010, 2011, 2012)
percent_males <- c(53, 57, 54, 58, 60, 60)
total_chemicals <- total_tfm + total_bayluscide

correlation <- cor(data$total_chemicals, data$percent_males)

river_data <- data.frame(
year = c(0, 1, 2, 3, 4), # Assuming year or index for matching
male_prop = c(0.8181818, 0.6984127, 0.6732673, 0.5172414, 0.5000000),
TFM = c(29660.9, 29689.4, 44770.2, 37777.4, 38694.5)
)
# Correlation Analysis
correlation <- cor(river_data$male_prop, river_data$TFM, method = "pearson")

lentic_data <- data.frame(
year = c(0, 1, 2, 3, 4),
male_prop = c(0.5000000, 0.4285714, 0.8615385, 0.8500000, 0.6296296),
Bayluscide = c(808.6, 1145.3, 790.2, 5252.9, 5224.1)
)
correlation <- cor(lentic_data$male_prop, lentic_data$Bayluscide, method =
"pearson")
```

Listing 3: Applying model one

```
def population(x, survival_tuple):
    s12, s23, s34, s45 = survival_tuple
    T = pd.DataFrame(np.array([[0, 0, 0, 0, 200],
                               [s12, 0, 0, 0, 0],
                               [0, s23, 0, 0, 0],
                               [0, 0, s34, 0, 0],
                               [0, 0, 0, s45, 0]]))
    return T.dot(x)

# FEMALES
sf = (0.142858, -0.757692, 0.0833297, 1.46913)
depf = [[100, 100, 100, 100, 100]]
for x in range(0, 10):
    depf.append(population(depf[x], sf))
sumsf = []
for row in depf:
    sumsf.append(sum(row))
plt.plot(range(0, 11), sumsf)

# MALES
sm = (-0.142858, 1.01026, -0.0133926, -0.259259)
depm = [[100, 100, 100, 100, 100]]
for x in range(0, 10):
    mixed = depm[x]
    mixed[4] = depf[x][4]
    depm.append(population(depm[x], sm))
sumsm = []
for row in depm:
    sumsm.append(sum(row))
plt.plot(range(0, 11), sumsm)
plt.title("Lentic lamprey population over 10 years")
plt.legend(['female', 'male'])

# FEMALES
sf = (0.65873, 0.0833789, 0.477534, 0.0357135)
```

```
depf = [[100, 100, 100, 100, 100]]
for x in range(0, 10):
    depf.append(population(depf[x], sf))
sumsf = []
for row in depf:
    sumsf.append(sum(row))
plt.plot(range(0, 11), sumsf)

# MALES
sm = (-0.146384, -0.0360045, -0.231745, -0.0333326)
depm = [[100, 100, 100, 100, 100]]
for x in range(0, 10):
    mixed = depm[x]
    mixed[4] = depf[x][4]
    depm.append(population(depm[x], sm))
sumsm = []
for row in depm:
    sumsm.append(sum(row))
plt.plot(range(0, 11), sumsm)
plt.title("River lamprey population over 10 years")
plt.legend(['female', 'male'])
```

Emma Morrison: Found proportions and created survival rates for model one from the data, formatted the final paper in Overleaf and compiled all pieces of work, created some of presentation, did transition matrix analysis on model one, wrote part of the conclusion

____ X

Yinqi Yao: Did line graph of total lampricide uses from the data, conducted linear regression on model 2 to analyze the correlation between lampricide and sex ratio, helped modify the population prediction model, wrote part of the conclusion

Yinqi Yao

____ X

Audrey Garcia: Wrote introductory section including background, problem restatement, definitions, assumptions, and description of modeling approach. Wrote summary sheet.

____ X

Zane Ching: Completed the second part of Model 1 using python, created the conclusion slides, assisted with conclusion writing in the write-up. Assisted in writing the summary sheet (model analysis and applications).

Zane Ching

____ X