Interspecies Bioaccumulation of Mercury in Ternary Fish-Fish-Algae Bio-system

An experimental approach at modelling toxic accumulation in aquatic species

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Abstract

Bioaccumulation is the process by which a toxin or heavy metal accumulates within a living organism. Biomagnification describes the process whereby toxin moves up the food chain in progressively greater concentration due to ingestion. The bioaccumulation and biomagnification of mercury in aquatic organisms such as fish and shrimp is of concern, since it can lead to adverse effects for humans once consumed. In an attempt to analyse the impact of mercury in a marine population, we propose a model to predict the effects and concentration of mercury in a ternary fish-fish-algae ecosystem. Our results conclude that larger organisms suffer a greater decrease in population due to the bioaccumulation and biomagnification of mercury. In addition, the stable population density that was achieved before introducing mercury was easily destroyed due to mercury. Interestingly, this results in a slight increase in the population of prey species. In order to fully validate our model, we suggest that real-world experiments ought to be conducted which seek to determine mercury levels and biodiversity in aquatic ecosystems.

Introduction

Mercury pollution is one of the biggest environmental concerns since the last decade. This highly toxic element that emits naturally or through human activities can be converted into methylmercury and enters into the ocean. This form of mercury can be taken up by plankton, sediments or algae. Fish that are fed upon contaminated algae can get contamination as well, which in term accumulate in the human body as they are consumed by humans. The accumulation of mercury in humans causes mercury poisoning and leads to impaired vision, hearing, speech, coordination, and muscle contractions (Borgå, 2013). The phenomenon of this gradual build-up of a chemical in a living organism is called bioaccumulation, which describes the net result of all uptake and loss processes that causes enhancement of contaminants in organisms over time (“Mercury in fish,” 2020). Biomagnification describes the process whereby toxin moves up the food chain in progressively greater concentration due to ingestion by the larger organisms (University of Calgary, 2018). Due to the threat mercury can pose to both wildlife and humans, it is important to understand how mercury accumulates in different organisms and to develop a model that can simulate the effects of different concentrations of mercury in a fish population, as well as predict ecological implications.

Background

<u>Previous works on Mercury Bioaccumulation</u>

Before producing an effective simulation, it is important to critically assess not only the underlying system in an attempt to determine significant variables, but also the available literature which describes previous efforts to study similar phenomena. Johns et al. describe a ternary system where the bioaccumulation of mercury is modelled in an ecosystem of plankton and fish. The species are denoted as population F (plankton), population S (prey fish), and population T (predator fish), each possessing mercury levels which are described as A (plankton mercury level), B (prey fish mercury level), and C (predator fish mercury level), respectively. For each population, the factors which dictate the flux of mercury proceeds as follows:

$$A' = kFI - jA - LAS$$

Rate of bioaccumulation for population F = uptake due to consumption - first order pharmacokinetic elimination - loss due to predation by the next trophic level.

$$B' = LAS - jB - nBT$$

Rate of bioaccumulation for population S = gain due to predation on A (mercury in plankton) - first order pharmacokinetic elimination - loss due to predation by the next trophic level. Where

$$C' = nBT - jC$$

Rate of bioaccumulation for population T = gain due to predation on S - first order pharmacokinetic elimination

Where k is the relative absorption of a given toxin (in this case mercury), j is the relative rate of elimination, L and n describe the population lost from each population due to predation. Of note, this system assumes that each species will uptake and excrete mercury at a given rate, which may vary among species within observable ecosystems.

Methodology

For further instructions on the Bioaccumulation NetLogo program, please refer to the Appendix.

To simulate the system of algae and two species of fish, the NetLogo programming environment was used to model our system because it provides a simple and intuitive approach to modelling population dynamics. Our program uses patches as algae and two breeds for big and small fish. Parameters were adjusted in order to exhibit a stable fluctuation in the population of the 3 species both with and without the presence of mercury. These parameters are set as the default and can be reset using the default button.

Simulating Fish Species

In our attempt to mimic the hunger and overall fitness of an individual fish, each fish has its own energy variable that is capped at 100. Both big and small fish exhibit random motion (i.e. not motivated towards food sources) around the lattice and their energy decreases each time step. If this variable decreases below 0, then the fish will die. In order to increase the energy level, a fish must consume its respective food source. However, they are only able to eat when their energy level drops below a threshold. When a small fish is on an algae patch and is allowed to eat, its energy level increases by 16 units (as defined by the “AlgaeNutrition” slider). When a big fish is on the same patch as a small fish, there is a 40% probability that the small fish is eaten and the big fish’s energy level increases by 50 (as defined by the “SmallFishNutrition”).

For reproduction, a reproduction threshold slider for both fish species controls the reproduction rate. If a fish reproduces, the energy of offspring will be set to 100 and the mercury level starts at 0.

The death rate of fish is a summation of both natural causes and mercury intake. The death rate due to natural causes is proportional to the amount of missing energy from the cap of 100. This is given by $b*(100 - \text{Energy})$ where b is a conversion constant. There is also linear increase in the death rate due to the level of mercury accumulated ($c*[hg]*dt$), where c is another conversion constant and [hg] is the level of mercury in the individual fish.

Mercury concentration change

Mercury occurs naturally within Earth’s crust and is spewed from volcanic eruptions, but release of this substance into the environment is due to human activities, such as mining and fossil fuel combustion. When mercury enters the ocean, it is constantly absorbed by algae, small plankton, and sediments (US EPA, 2014). Fish obtain mercury through the consumption of algae. Additionally, mercury levels constantly increase within fish upon the constant consumption of mercury-containing small plankton and sediment (“Mercury in fish,” 2020). Therefore, in our model, we will make the initial concentration for each fish species to be zero. Algae begins with a mercury level of 1 and live algae increases in mercury over time to simulate the absorption of mercury in the water. The small fish will obtain mercury through the consumption of the affected algae and the big fish will get mercury from eating the small fish. Because mercury also attaches to sediments and plankton and they are constantly engulfed by fish species, both living fish species will increase in mercury level overtime as well. When the algae and small fish are eaten by the small fish and big fish respectively, the mercury level of the food source is passed on completely. This assumption is made as mercury is fat soluble and does not break down easily in fish.

Results

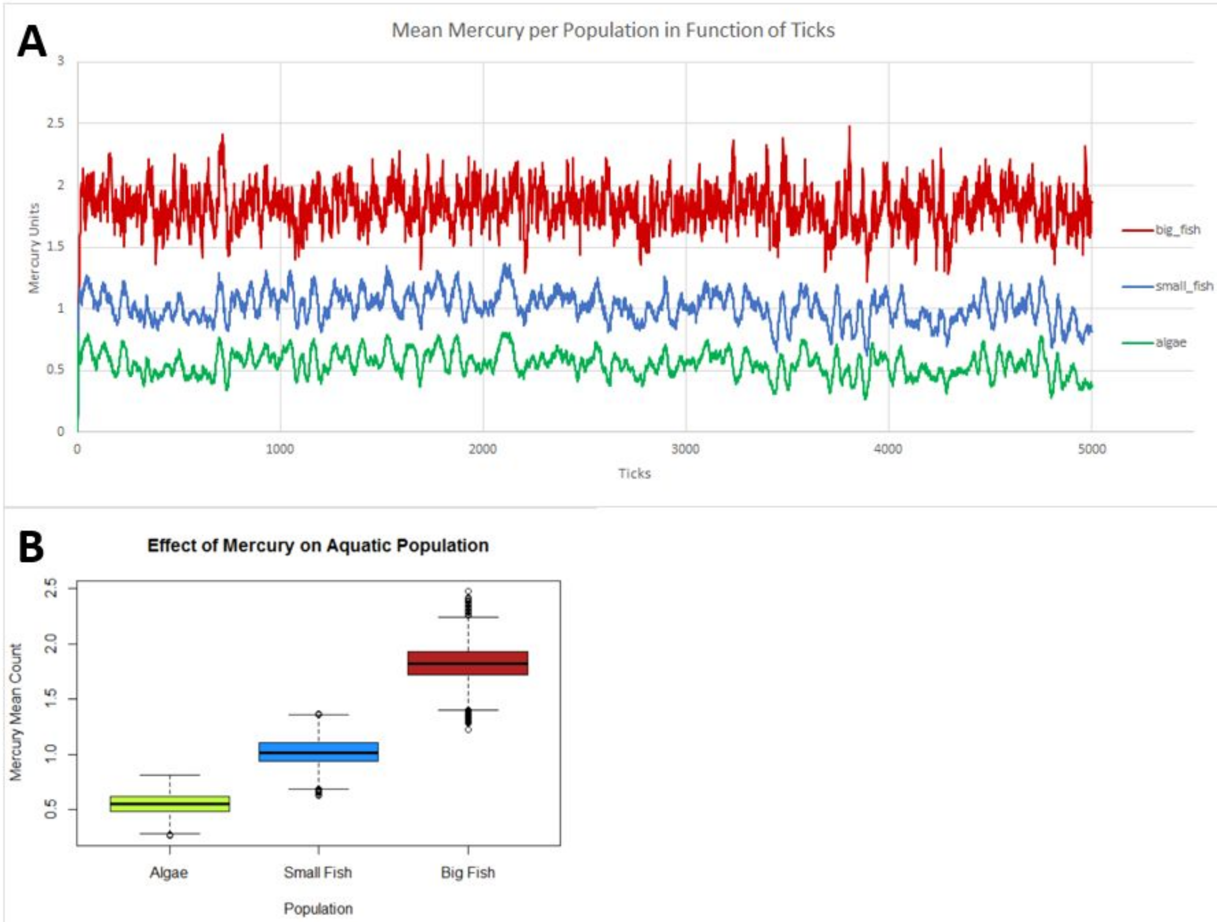

Figure 1. Mercury level fluctuation in ternary ecosystem A) Mean Mercury per Population in Function of Ticks over time. Big fish (red), small fish (blue), and algae (green) average mercury units within each population for each time tick. For each population, N = 5000. B) Box plot of the mean mercury. The average level of mercury over time for algae, small fish and big fish is 0.55, 1.01 and 1.83 respectively. For each population, N = 4500.

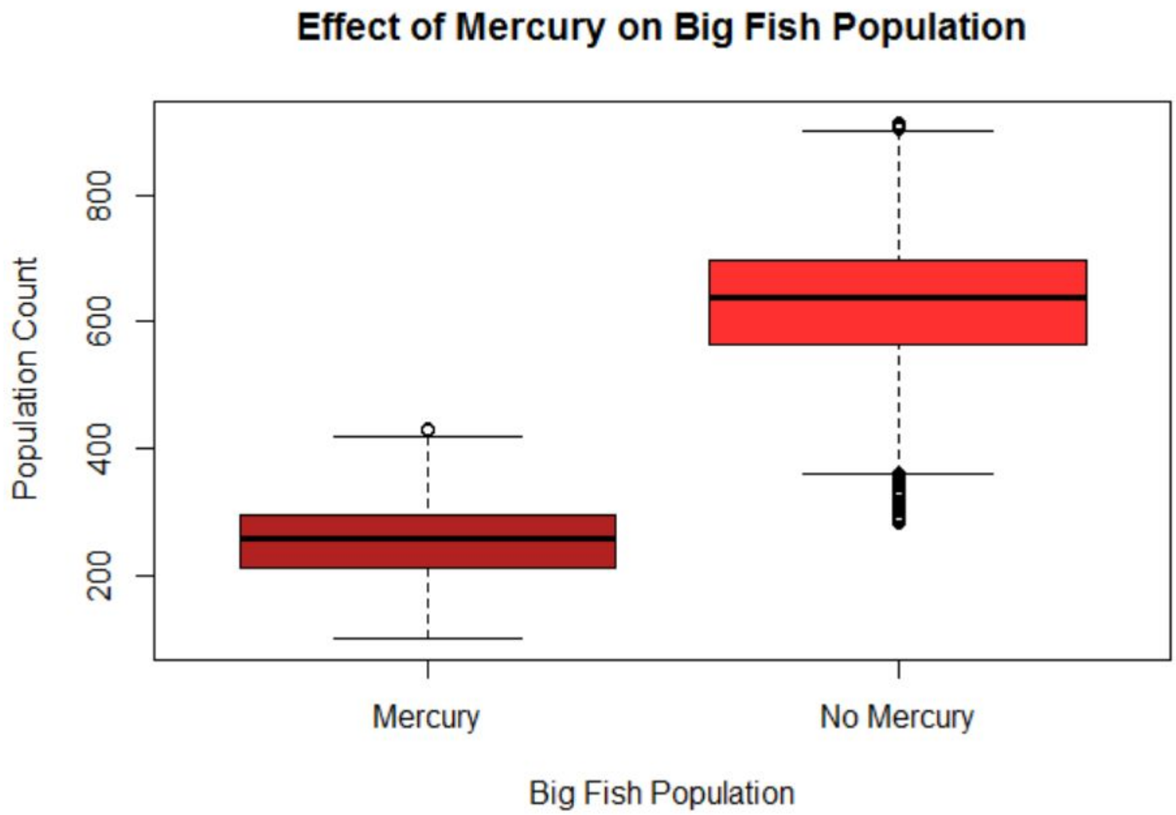

Figure 2. Effect of Mercury on Big Fish Population. Box plot of big fish population at each time tick. “Mercury” category denotes population snapshots where mercury was present in the simulation. “No Mercury” category denotes population snapshots where mercury was not present in the simulation. The mean population for mercury and no mercury is 256 and 626 respectively. For each category, N= 4500. Error bars are 1.5*IQR. Anova, p = 2.01e-08.

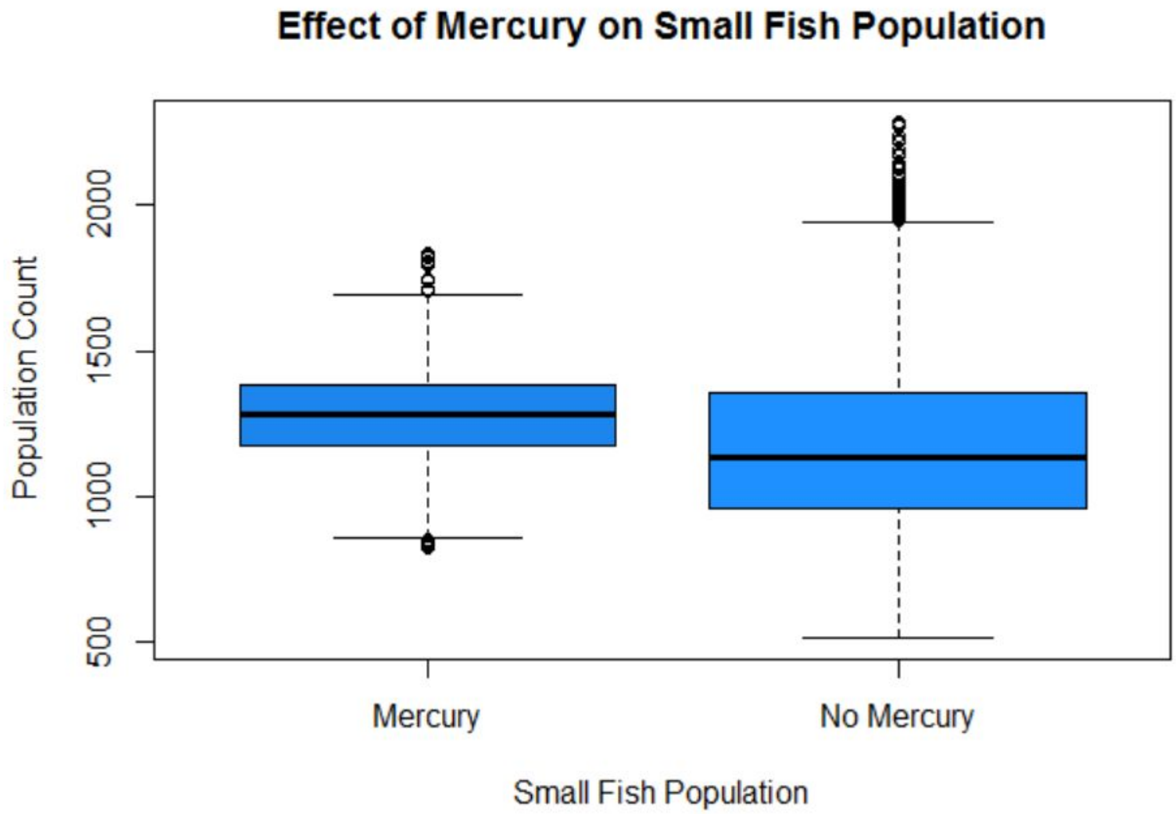

Figure 3. Effect of Mercury on Small Fish Population. Box plot of big fish population at each time tick. “Mercury” category denotes population snapshots where mercury was present in the simulation. “No Mercury” category denotes population snapshots where mercury was not present in the simulation. The mean population for mercury and no mercury is 1276 and 1181 respectively. For each category, N= 4500. Error bars are 1.5*IQR. Anova, p = 0.026.

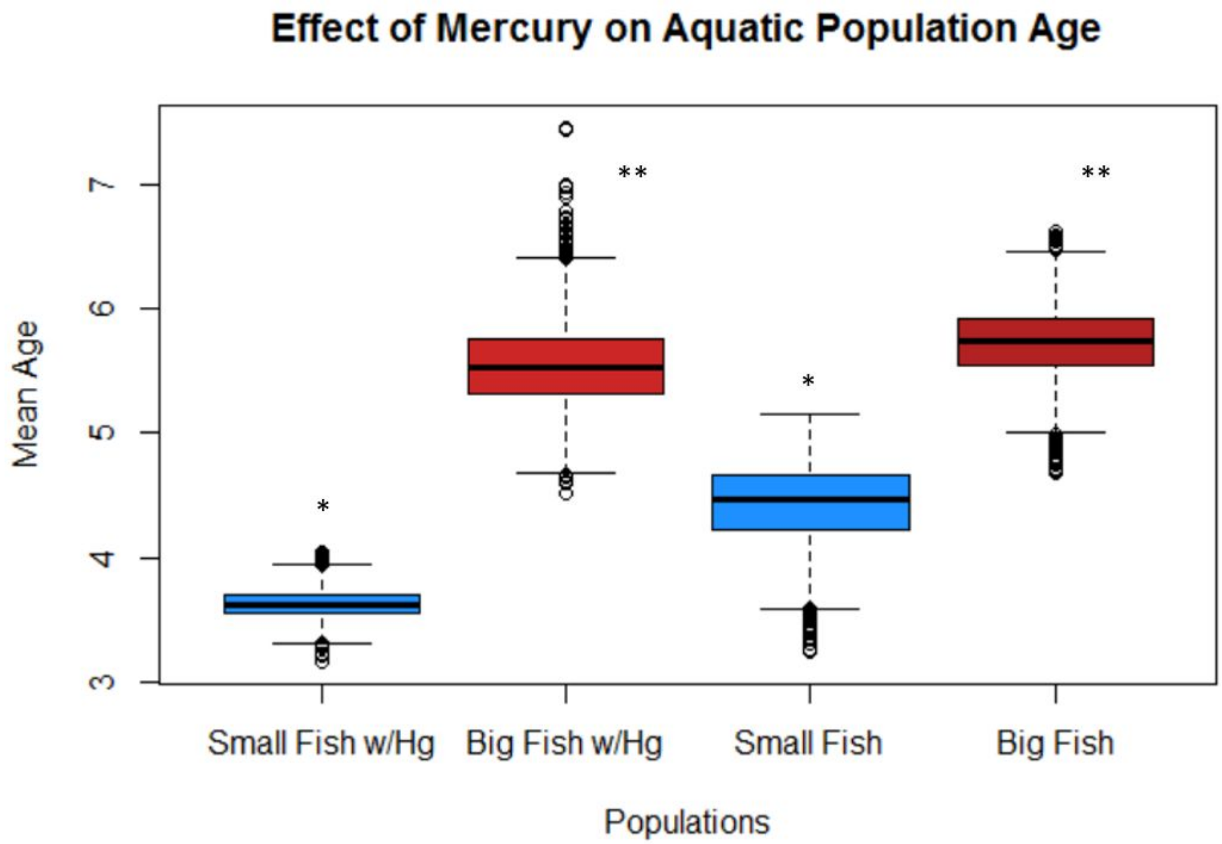

Figure 4. Effect of Mercury on Aquatic Population Age. Box plot of mean age among small fish and bigh fish, with and without mercury in the environment. The average age of small and big fish in the presence of mercury is 3.64 and 5.59 respectively. The average age of small and big fish without the presence of mercury is 4.5 and 5.72 respectively. For each population, N = 4500. Error bars are 1.5*IQR. Anova, *p = 0.00219, **p = 2.67e-07

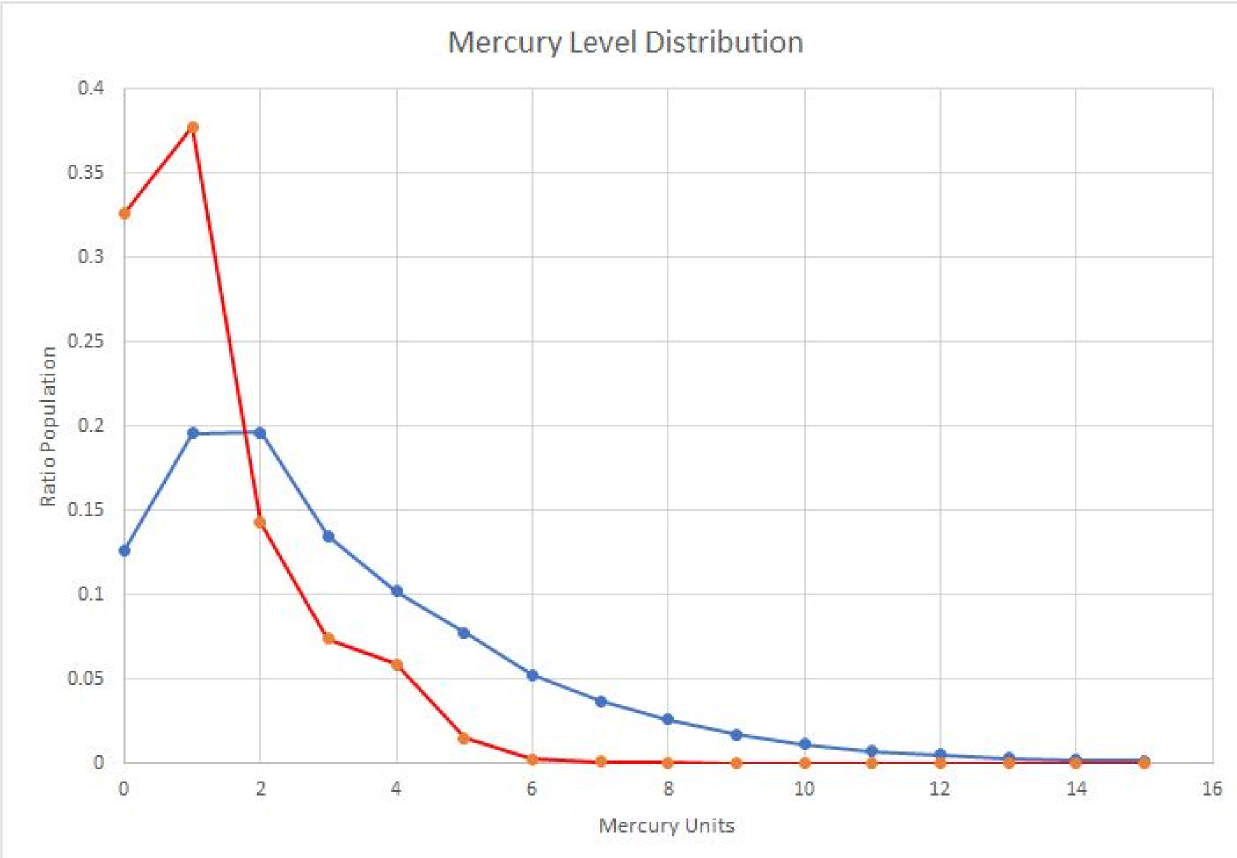

Figure 5. Mercury Level Distribution. Average mercury units for each small fish (blue) and big fish (red). N = 4000. Small fish standard deviation is 0.062. Big fish standard deviation is 0.116.

This simulation manages to model stable population dynamics during a prolonged period of time steps which provides a basis for our investigation on the effects of a bioaccumulating toxin, namely mercury. Our results show that mean mercury concentration within each species increases until equilibrium is reached. Interestingly, equilibrium mercury values are at their highest for the big fish, with algae having the lowest mercury value, therefore showing evidence for bioaccumulation in our model (Figure 1). Furthermore, our model reports mercury having a greater detrimental effect on the big fish (Figure 2.) population than on small fish (Figure 3.), which might be indicative of bioaccumulation, since higher levels of mercury in the big fish will do it more harm. Interestingly, this is further emphasised in Figure 4 which shows that both species of fish are negatively affected by mercury through a decreased lifespan, which is consistent with observations in literature that show a decreased lifespan and reproductivity in fish species in the presence of sub-lethal mercury concentrations (Shao et al., 2016). Interestingly, most small fish tend to have a narrow accumulation of mercury in comparison to the big fish (Figure 5). This shows that small fish aren't able to accumulate high levels of mercury before dying, while the big fish have a higher probability to live long, thus allowing greater time for the accumulation of mercury to occur.

Discussion

Mercury contamination has put wildlife and human health in danger since the 1950s when the ocean in Minamata Bay, Japan, was found highly contaminated by mercury. Governments started to pay attention to this issue and scientists have studied intensely to find a strategy to reduce the effects of mercury contamination. On October 19th, 2010, Environmental Canada and Health Canada published the Risk Management Strategy for Mercury. Thus, more and more Canadians put in their efforts to minimize mercury releases and advocate for less human activities involving mercury release (Government of Canada, 2017). By constructing a model that mimics the mercury accumulation in aquatic organisms, we are able to show the severity mercury can pose to wildlifes and the ecosystem.

Our model allowed us to investigate the effects mercury has towards other organisms that are within the same food chain. We were able to control the “mercury release” using a “on/off” switch to compare the effects of mercury. We plotted the population density for big- and small-fish and algae, and the mean mercury level for all three populations. In addition, histograms of mercury level and age were plotted to provide distribution of each fish population. The average age and the average eat count of each fish population were also plotted.

There are three main implications from our results. First, our ecosystem is too fragile to remain stable when a pollutant is introduced. As can be seen in our model, when turning on the mercury switch, the population density for all three species are disrupted and try to re-establish the steady state, causing the loss of “predator-prey” interactions. Secondly, toxins are easier to accumulate in a bigger organism, which leads to more severe adverse effects. Our results support this statement. As can be seen in Figure 1, the mercury concentration is the highest in the big fish than in the small fish. In Figure 2, it also suggested that mercury largely decreased the big fish population compared to no mercury. Humans can be involved in this fish-fish-algae food chain as humans consume contaminated fish. Due to bioaccumulation and biomagnification, toxin is in a higher concentration in the human body than in other smaller organisms, which elicits adverse effects in humans, including the harm to brain, heart and immune system, and impairment in vision, speech and muscle contractions (WHO, 2017). Lastly, we were able to show the reduction of big fish abundance affected the small fish population. It is shown in Figure 3 a slight increase in the small fish population can be observed when mercury presents, which is due to bioaccumulation of the toxin in big fish, reducing the big fish abundance and releasing more small fish from predation. The counterintuitive effect was well explained by Huang et al. (2015), where they modeled the predator-prey dynamics under different toxin levels and showed a similar result when they introduced lower concentration of toxin in their model.

It is difficult to simulate out the real world case due to the complexity of it. Therefore, our model has limitations because we might omit some aspects of real life. For example, we set the fish to move randomly (i.e. not motivated by food). In reality, it is definitely more complex due to the tendency to escape from predation or seek for food. Improving and optimizing a model to make it is an ongoing project, which requires efforts from academia and governments.

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Appendix

<u>Bioaccumulation NetLogo Program Guide</u>

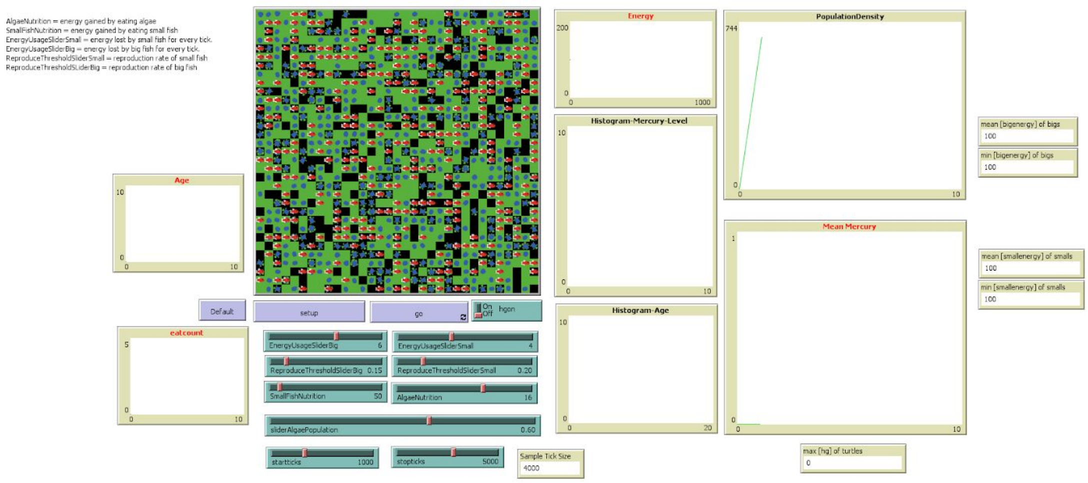

Figure 6. Bioaccumulation NetLogo Interface

When the bioaccumulation NetLogo program is opened, the user is introduced to several parameters in the form of sliders and switches, and several plots of different measurements. Please refer to the methods section for explanation of parameter sliders. Mercury in the system can be controlled using the hgon switch. The system is stable with the parameters when the program is opened. A Default button is added to return to the stabilizing parameters. The bottom two sliders are used to control the sample size for ticks. Because the model is stochastic and the measurements fluctuate over time (age, hg, population), an average is measured across the sample ticks between startticks and stopticks. Upon reaching stopticks, the simulation ends and the averaged measurements are printed in the command center. The user should press on the setup button at the beginning of each simulation before pressing go. During the simulation, the algae, small fish and big fish are color coded as green, blue and red respectively in the lattice and plots.