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Analysis of an agent-based model for predicting the behavior of bighead carp (*Hypophthalmichthys nobilis*) under the influence of acoustic deterrence

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Abstract

Bighead carp (*Hypophthalmichthys nobilis*) are an invasive, voracious, highly fecund species threatening the ecological integrity of the Great Lakes. This agent-based model and analysis explore bighead carp behavior in response to acoustic deterrence in an effort to discover properties that increase likelihood of deterrence system failure. Results indicate the most significant ($p < 0.05$) influences on barrier failure are the quantity of detritus and plankton behind the barrier, total number of bighead carp successfully deterred by the barrier, and number of native fishes freely moving throughout the simulation. Quantity of resources behind the barrier influence bighead carp to penetrate when populations are resource deprived. When native fish populations are low, an accumulation of phytoplankton can occur, increasing the likelihood of an algal bloom occurrence. Findings of this simulation suggest successful implementation with proper maintenance of an acoustic deterrence system has potential of abating the threat of bighead carp on ecological integrity of the Great Lakes.

Keywords: bighead carp, Great Lakes, acoustic deterrence, agent-based model

1 Introduction

Four aquatic, invasive species labeled as ‘Asian carp’ are currently threatening the ecological integrity of Lake Michigan. Two of these fish, silver carp (*Hypophthalmichthys molitrix*) and bighead carp (*Hypophthalmichthys nobilis*), have been identified as immediate threats warranting research and action [3]. Bighead carp, particularly, are filter-feeding planktivores that consume up to 40% of their own body-weight in food per day and can produce up to 2 million eggs per year [4]. Since these fish out-compete other native species for natural resources and spawn at such dramatic rates, they are classified as an invasive species. This project focuses specifically on the species of Asian carp known as bighead carp, their ecological influence, as well as a method of deterrence to avoid a potentially devastating impact on the Great Lakes. A simulation was constructed in NetLogo [14] to determine barrier effectiveness and integrity.

2 Background

Bighead carp, natives of east Asia, were introduced into U.S. aquaculture in Arkansas for the first time in the

early 1970s, in an effort to control phytoplankton and help wastewater treatment facilities keep retention ponds clean [2]. Throughout the 1990s, a series of floods resulted in the species escaping their contained environment. This invasion propagated in the Mississippi River and stemmed into the Missouri and Illinois Rivers. Currently bighead carp have been spotted as close as the T.J. O’Brien Lock and Dam, 7 miles outside of Lake Michigan.

The only method currently employed to keep these, as well as other, invasive species from entering The Great Lakes is an electric barrier [12]. An unfortunate drawback of this deterrent is that it also prevents native species from entering the Great Lakes. Other methods of deterrence have been researched, but no new methods have been implemented in a real-world environment outside of the current electric barrier [7]. Of these newly researched methods of deterrence, the most successful appears to be acoustic deterrence.

Vetter et al. measured the influence of acoustic deterrence on bighead carp populations [13]. Trials were conducted in which live specimens were subjected to several frequencies of pure tones as well as a broadband sound stimulus. Speakers were placed at either end of the environment and were played over several intervals. Sound was initiated on one side for 30 seconds followed by a one second delay before switching to speakers on the opposite side of the tank. After 10 minutes of conducting a sin-

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gle trial, subjects were given a 15-minute recovery period for pure tone trials and a 30-minute recovery period for broadband trials [13].

Results indicate broadband stimulus is the most effective deterrent to bighead carp while not negatively influencing native fish populations. Unlike most native species, bighead carp are ostariophysans and possess Weberian ossicles¹. These allow for higher frequency hearing and sensitivity to broadband sound where other species of native fish will remain unaffected [13, 1].

3 Behavioral Model

Previous research conducted by Vetter et al. and Zielinski and Sorensen report on live specimen behavior under acoustic trials within a contained environment [13, 15]. This model expands on their results while maintaining assumptions for real-world integration. These assumptions are inclusive of fish behavior in regards to both the barrier and their natural habitat, species dominance, and spawning habits of both native and invasive species.

3.1 Purpose

The purpose of this model is to discover and assess properties that may alter the effectiveness of an acoustic deterrence system. Particularly, it is to be determined if an Asian carp invasion is probable. What levels of population density, population diversity, and reproduction impact barrier integrity and successful deterrence outcomes?

3.2 Entities, state variables, and scales

This model comprises three hierarchical levels: individual, landscape, and population. Individuals are characterized by the the following state variables: energy, cruise-speed, wiggle-angle, and turn-angle. These state variables define both native and invasive fishes. Energy dictates movement, reproduction and death in both fishes (see Table 1).

The landscape is defined by the non-mobile agents: plankton, detritus, and acoustic speakers. Both plankton and detritus are characterized by the state variables “energy-at-spawn” and “location”. Speakers are characterized by “strength-of-wave” and “radius-of-detection”.

The population is composed of species of fishes, native fishes and invasive carp. Populations are characterized by size and number of individuals. Carp and native populations require differing amounts of energy to swim, eat, and reproduce. Carp populations react to the acoustic barrier deterrence, while native populations do not.

¹a series of small bones that form a link between the inner-ear region and the swim bladder, facilitating sound reception

Table 1: Overview of processes, parameters, and default values.

PARAMETER	VALUE
Initial Population Sizes	
Bigheads	33
Natives	66
Detritus to plankton	40 : 60
Initial Energy	
Bighead carp	10
Native fishes	20
Swim & Directional Speeds	
Cruise speed	3
Wiggle angle	5
Turn angle	10
Resource Growth (Spawn) Rates	
Plankton	10
Detritus	8
Energy Allotment	
Plankton	5
Detritus	5
Energy Requirements	
Reproduction	≥ 19
Death	≤ 0
Acoustic Deterrence	
Strength of wave	60
Detection radius	5

The model world has no lateral bounds, but fishes are recorded and removed from the simulation when crossing either end zone, allowing representation of fishes swimming through or across the body of water. Spatial heterogeneity has been included such that both plankton and detritus are spawned in random locations between the bounds of the simulation area upon initialization. Speakers are placed near maximum x -coordinates to represent barrier existence in stream.

3.3 Process overview and scheduling

This model proceeds with ticks. Within each tick, process phases are carried out by carp and native species of fishes. Fishes will swim forward unless they are on top a food resource. The fishes will then consume and absorb the energy of the resource. Carp can eat both plankton and detritus, while native fishes can eat only plankton. After energy is applied to the individual, parameters are

Figure 1: Simulation of fish behavior under the influence of acoustic deterrence.

checked for reproduction. If able, fishes will spawn a new individual and continue swimming. At any point in these processes, if an individual is at or below zero energy, they will expire.

At each tick, immobile speakers will begin to emit a “sound wave” in the form of a mobile agent. These sound waves gradually decrease over time at a rate dependent on the strength of the wave. If a carp swims into or is close enough to the “sound wave”, they will rotate within a 45° angle and continue to swim forward. This will continue to happen until the fish is out of energy or is no longer near the wave.

3.4 Design concepts & Implementations

Emergence Emergent behavior appears to indicate a carrying capacity in the bighead population. When running the simulation, time was truncated to 1000 ticks for the purpose of discretizing the analysis. Upon initialization, populations for both natives and bigheads approach a stable state; however, under certain trials, the bighead population would spike, exceeding the maximum carrying capacity (~ 300). At this point, the bighead carp are “resource-starved” and will puncture the barrier in effort to reach more plankton and detritus. This results with them eventually reaching the yellow “end zone”, indicating that they have invaded the lake.

Sensing When bighead carp travel within the designated radius of the sound projection, movement is halted, a range of specified rotation executed, and movement speed increased for a short period of time as the fish swims away from the deterrence. This behavior matches that reported in previous research in which live trials were conducted [15, 13].

Interaction Native fishes are inherently set to have a greater starting energy than the bighead carp, theoretically giving them an upper-hand in competing for resources. This extra energy does not help the native fish live longer than the bigheads. Due to this competition, bighead carp overcame the native fishes during every trial.

Stochasticity Several behavior parameters are assigned a probability to better demonstrate population-level phenomena. All fishes are assigned an initial energy, e_i , upon spawning, which is uniformly distributed over a pre-specified interval. In an attempt to compensate for the dominant nature of the bighead species, random assignment of e_i for natives is such that $e_i \in (0, 20]$, whereas bighead carp are assigned e_i such that $e_i \in (0, 10]$.

Initial placement of fishes is defined with randomness in the xy -plane. Upon setup, all fishes populate longitudinally 3 patches to the east of the field’s western border. The placement of each individual fish along this line is uniformly distributed along the interval $[y_{\min}, y_{\max}]$.

Native and bighead fishes are assigned a maximum angle of movement of 5° . This allows for analysis of forward-moving swim behavior with respect to the acoustic deterrence. Fishes still move with an element of randomness, as their angular movement is uniformly distributed over the interval $[0, 5]$, where 0° means fish move in a straight line. A turn-angle on the interval $[0, 10]$ is also assigned to both populations to account for fish behavior when interacting with a boundary in the field. Additionally, bigheads are assigned an angle of rotation when coming into contact with the acoustic barrier. As reported by Zielinski, this angle of rotation is uniformly distributed on a $[-45, 45]$ interval [15].

Resources are populated through a scheduling param-

Figure 2: Life history of the model fishes, both native (blue) and invasive (red), showing processes by which resource consumption, spawning behavior, and energy tracking occur. Carp-specific behavior in relation to the acoustic wave is also displayed.

ter referred to as the “growth rate”. At each tick, a random number on a uniformly distributed interval [0,1000] is selected for each non-resource patch. If the random value selected is less than the scheduled growth rate for the associated resource, the non-resource patch becomes the resource under which the condition passes. Default growth rates of 8 and 10 are set for detritus and plankton, respectively.

Observation Data were collected using BehaviorSpace’s built-in functionality in NetLogo [14]. Data were catalogued per simulation completion, output to a SQLite database and fed into a query-based analysis system to assess the output and modify the following batch of simulations. This was completed in effort to save computational power, time, and explore the widest range of significant parameter possibilities.

3.5 Initialization

This model begins with 33 bighead carp and 66 native fishes. These numbers can be modified based on the user’s preference. By default, plankton and detritus spawn randomly at a $\frac{4}{5}$ ratio, detritus to plankton, respectively. Initialization will depend on user-defined variables. Default values are reported in Table 1.

3.6 Sub models

Resource competition Bighead carp have a substantial diet overlap with gizzard shad, bigmouth buffalo, and paddlefish [11]. Bighead carp and gizzard shad are both pump filter feeders, consuming both phytoplankton and zooplankton, similar to bighead carp. Due to sharing limited resources in the form of food and space, there is interspecific competition [11]. This interspecific competition is represented in our model as both “native” fishes and bighead carp consuming the same resources in the same space.

Bighead Carp Interaction with Sound Waves In a previous study of bighead carp behavior in response to broadband stimuli by Zielinski et al., the orientation of carp when encountering stimuli was discovered [15]. Results from this study show that when carp encountered broadband stimuli, they rotate 45° away from the stimuli in either direction and swim away [15]. This is directly implemented in our model as “wiggle”. If any carp agent encounters the sound wave produced by the acoustic speakers, they will rotate randomly left or right at an angle $-45 \leq \theta \leq 45$ and swim away. This consumes a small portion of the fishes energy, allowing us to replicate the extra motion and swift speeds in which they naturally move. This reaction may occur multiple times.

Invasion Parameter An “invasion” occurs in this model when 20 fish pass through the yellow “end zone”, representing the other side of the stream—as we call it “into lake” (see Figure 1). This parameter is based upon establishment calculations by Cuddington [5]. An “established” population, in this case, is a self-sustaining population, which carries the risk of harming the native ecosystems. Cuddington found a 100% establishment probability if 20 adult fish were to enter into the ecosystem [5]. Additionally, there is a 75% chance of establishment if a continual leak of 10 adult fish are introduced in a 20-year period [5].

Speaker placement Sound production by speakers in this simulation is based upon *in vivo* study of interactions between bighead carp and acoustic deterrence methods by Vetter et al. [13]. Speaker placement in a stream environment was created in this simulation by replicating construction proposals for an acoustic deterrence system by the U.S. Army Corps of Engineers, near the T.J. O’Brien lock and Dam [12]. Both of these references include an amount of room to allow for a secondary allocation of preventative measures, including barring the stream system entirely or activating an electric barrier system.

Sound production In an analysis of several forms of acoustic production, it was found that broadband sound has the greatest ability to provoke a response in bighead carp [13]. The specific physics and acoustics of broadband sound is beyond the scope of this model. However, the movement and direction of the sound “waves” in this simulation follow that of those which produce broadband sound in the aforementioned study. The “amplitude” of these waves is controllable via a user input slider, although their relative effectiveness on the fish cannot be compared with actual amplitudes.

Our speakers are red patches. These patches radiate sound agents in 360° (see Figure 1). The agents that are produced from these patches have a set level of amplitude, which decreases as they travel. These “sound waves” interact with the environment and other waves. This is representative of the way sound travels underwater and the refractions that occur between these waves and physical objects.

Comparative species behavior Bighead carp and native species can be distinguished in this model through attributes assigned to both of the fish types [9]. Native fishes are in greater abundance due to there being an already assumed stable population of native fish species in the area. Although natives have a higher starting energy, carp are able to consume more resources—given priority in situations in which both fishes are on the same resource patch. Native fishes are also allowed to swim freely past

and through the barrier. These are the defining parameters that classify a fish as an invasive carp or a native fish [9].

4 Analysis

4.1 Conditional Inference

Conditional inference trees are constructed regression-based trees with recursive partitioning, binary splitting, and early stopping [8]. The incorporation of conditional inference allows us to overcome common problems of traditional trees: over-fitting, selection bias based on co-variables and multiple variable types. When variables are selected for a split point, all decisions are embedded into hypothesis testing and then permutation tests [8].

A conditional inference tree algorithm was produced to determine variable and parameter value combinations, which could influence the invasion likelihood of a simulation. This tree was trained and tested on a 70:30 split of data produced from our BehaviorSpace output. Included in these parameter and variables are: starting number of bighead carp, starting number of native fishes, energy of plankton and detritus, growth rate of plankton and detritus, threshold for birth, strength of the acoustic deterrence waves, detection radius of carp to wave, number of bighead carp back into stream, number of natives into stream, the number of plankton and detritus both behind and in front of the barrier, and the total number of bigheads that encountered the acoustic deterrence waves. Split variables/parameters, split values, and Bonferroni-adjusted P-values were calculated.

4.2 Random Forest

Random forest classifiers are constructed with a great number of individual traditional decision trees operating as an ensemble. This ensemble of trees will predict on subsections of data to determine the best prediction from a set of many [10]. Data was split 70:30, training and testing respectively. Trees ($n = 1000$) were created, with replacement, predicting the number of carp to enter the lake with the parameter and variables specified. Included in these parameter and variables are the following: starting number of bighead carp, starting number of native fishes, energy of plankton and detritus, growth rate of plankton and detritus, threshold for birth, strength of the acoustic deterrence waves, detection radius of carp to wave, number of bighead carp back into stream, number of natives into stream, the number of plankton and detritus both behind and in front of the barrier, and the total number of bigheads that encountered the acoustic deterrence waves. After training, the final algorithm was tested. Accuracy, purity and importance were produced.

5 Results

5.1 Random Forest: Variable Importance

Results from the random forest algorithm showed 99.6% accuracy in prediction of our outcome (Non-invasion, Invasion), based upon the reported literature value of 20 invasive carp passing through the barrier. Variable & parameter importance is plotted in Figure 3, and all values are reported at $p < 0.05$. Parameter and variables found to be significant influences to an invasion outcome are plotted in decreasing order.

5.2 Conditional Inference: Splitting, Outcomes

A conditional inference tree was generated to analyze the importance of specific variable combinations, allowing for identification of variable/parameter levels and combinations that result in an invasion outcome. Figure 4 displays information as a network of nodes and edges. Oval nodes represent variables, numerically ranked from most to least important based on orientation in the random forest. Square nodes display the number of simulations that meet the variable combination traced in the tree and show a (Non-invasion, Invasion) percentage likelihood. Lastly, edges identify split values at which additional variable combinations or barrier success rate is determined. From this output, it can be seen that “Bigheads Deterred Successfully” in conjunction with “Detritus Behind Barrier” have the greatest influence in determining barrier efficacy.

5.3 Model Validation

Several phenomena exist in this model that can be validated by referring to the primary research to support our research question and hypothesis. Operation and deterrence effect of the speakers can be validated by comparing our model to that of the *in vivo* models provided by Vetter et al. and Zielinski [13, 15]. A re-creation of this was constructed in NetLogo to validate carp movement in response to acoustic deterrence (see Figure 5).

Figure 5 models trials conducted by Vetter et al. where the speakers are turned off and the fish are aloud to freely move around the tank, and where fish movement is restricted by the acoustic barrier. This allowed us to validate swim patterns as reported by Vetter et al. and ensures that the speakers are operational, demonstrating the effectiveness of the barrier as reported. Additionally, carp movement in response to the barrier was also validated using research provided by Zielinski.

Percent Importance to Invasion

Figure 3: Conditional inferences are significant at $p < 0.05$. Each parameter or variable's importance independent to that of other parameters to an invasion outcome. Each value indicates its individual influence on an invasion outcome.

Figure 4: Conditional inference tree predicting percent likelihood of invasion.

Figure 5: Bighead swim patterns as influenced by acoustic deterrence.

6 Discussion

This simulation shows that an acoustic deterrence barrier is a valid method of discouraging a bighead carp invasion. Acoustic deterrence has been evaluated in controlled environments. Our model incorporates data collected from those trials and implements them in a simulated real-world environment. Several other variables were also taken into account that weren't included in the prior controlled trials, such as resource availability, intensity of the speaker projection, fish energy levels, and the reproduction & death of bighead carp species. All of these factors have an influence on the integrity of the ecosystem in which the deterrence is to be executed.

Algal Bloom One discovery not initially predicted in the model was the influence of the acoustic barrier on algal bloom. Algal bloom occurs when there is a rapid increase or accumulation in the population of algae in an aquatic system, and is recognized by the discoloration in the water from their pigments [6]. Since bighead carp are unable to consume phytoplankton directly past the barrier, there is a possibility of these resources growing at a more rapid rate than is allowed inside the barrier. Phytoplankton consume oxygen in the water and convert that into a resource for algae; therefore, there is a direct relationship between the population size of the phytoplankton and algae within an aquatic system. Algal bloom will result from this associated increase in the population of algae. This would make the water toxic and unsafe for native species and humans alike. To prevent harmful side effects, an acoustic barrier should not be integrated within a reasonable proximity of water treatment facilities and recreational areas.

7 Conclusions

This simulation only introduces the possibilities of real-world implementation. Future study and projects have the potential to show greater results. Actual real-world testing, outside of a controlled environment, has not yet been conducted. If an acoustic barrier was effectively implemented, this could have several positive implications, not the least of which would include preserving the ecological integrity of the Great Lakes. This could potentially allow for herding of the invasive species to prevent further invasion into other ecosystems.

These results show that acoustic deterrence methods are a practical use case for preventing a bighead carp invasion. Our model simulates the use of an acoustic deterrence method in a real-world environment with various assumptions. This model allows the user the ability to input parameters that could not be realistically evaluated in physical experiments to provide practical evidence in favor of the use of acoustic deterrence methods. If assumptions and scale were to be more accurately evaluated, we could further improve the effectiveness of acoustic deterrence methods in the prevention of bighead carp invasions.

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A Appendix: Netlogo Interface

A.1 Main view window

Simulation view. Turning on or off view updates can help increase performance.

A.2 Graphical Numeric Output

Allows tracking of detritus, plankton, native fishes, and carp populations over time. Under are counts of numbers graphed.

A.3 Real world Simulation

Our core simulation consisting of setup and go as well as addition of more speakers for testing (additional speakers not used in study).

A.4 Replicate Simulation

Used to re-create the Vetter et al. Experiment through simulation. Drawing is to show the paths of the fishes in response to speakers.

A.5 Variable Parameters

Sliders allow for changes of all variables that are modified by the user.

A.6 Code Descriptions

A.6.1 Breeds

Breeds are turtles that are found in the simulation.

Speaker/speakers

bighead/bigheads

native/natives

wave-component/wave-components

A.7 Global

speed-of-sound: constant that controls the speed of sound waves

next-wave-id: counts the id of the wave components

wave-internal: the internal space between the wave appearance in ticks

Figure 6: Simulation User Interface

initial-wave-amplitude: the wave strength of sound waves

into-lake: counter of number of bigheads that made it into the lake

wait-time: number of ticks before the fishes begin to move

bigheads-backwards: counts the number of bigheads that are traveling back from the far left side

natives-backwards: counts the number of native fishes that travel back from the far left side

natives-into-lake: counts the number of native fishes that travel into the lake

bounced: counts the number of bigheads that are hit by the sound waves.

A.11 Grow Resources

Creates the growth factors for green patches and brown patches.

```

to grow-resources
ask patches
[ if pcolor = blue
  [ if random-float 1000 < detritus-grow-rate
    [ set pcolor brown ]
    if random-float 1000 < plankton-grow-rate
    [ set pcolor green ]
  ]
]
end

```

A.8 Setup procedures

Setup clears the field, resizes the world, sets the patch colors, add resources to the field, creates the fishes and speakers.

A.9 Create-additional-speakers

Adds additional speaker rows to the already established speakers (not used in study analysis).

A.10 Runtime Procedures

Main procedures that start the simulation. Bigheads moving, dying and waves moving are run here.

Decreasing Growth prevents the growth of detritus from becoming 'too large'

```

to decrease-growth
ask patches
[ if pcolor = brown
  [ if random-float 300 < detritus-grow-rate
    [ set pcolor blue ]
  ]
]
end

```

A.12 Wave Amplitudes

Sound wave amplitude procedures. Each wave gets an ID and travel speed based on the amplitude and location of other sound waves.

```

    to-report amplitude-here [ids-to-exclude]
    let total-amplitude 0
    let components wave-components-here
    if count components > 0
    [ let wave-ids-here remove-duplicates [ wave-id ] of components
      foreach ids-to-exclude [ id -> set wave-ids-here remove id wave-ids-here
    ]
    foreach wave-ids-here [ id -> set total-amplitude total-amplitude +
      [amplitude] of max-one-of components with [ wave-id = id ]
      [ amplitude ]
    ]
  ]
  report total-amplitude
end

    to emit-wave
    let j 0
    let num-wave-components Strength-of-wave
    hatch-wave-components num-wave-components
    [ set size 1
      set j j + 1
      set amplitude initial-wave-amplitude
      set wave-id next-wave-id
      set heading j * ( 360.0 / num-wave-components )
      if hide-amplitudes? [ hide-turtle ]
    ]
    set next-wave-id next-wave-id + 1
  end

```