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An Agent-Based Modeling Approach to Determine Overwintering Habits of American Robins and Eastern Bluebirds

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Abstract

American Robins (*Turdus migratorius*) and Eastern Bluebirds (*Sialia Sialis*) are two species of migratory thrushes that breed in Northwest Indiana but historically are uncommonly present during the winter season (November 1 - March 1). These trends have changed recently, and both species are seen more abundantly during the winter. Recently invaded non-native fruiting plants continue to provide nutrients for the birds throughout the winter and may contribute to the increased avian populations during that time. To measure the effect these food sources contribute to thrush wintering habits, we created an agent-based computer model to simulate the birds' movement in Northwest Indiana along with their food consumption over the course of the winter season. The model incorporates availability of food sources, foraging and roosting behavior, bio-energetics, and starvation, with parameter values informed by the literature. Ultimately, this model will yield a survival rate that could explain changes in the birds' migratory patterns.

Contents

1 Introduction

American Robins (*Turdus migratorius*) and Eastern Bluebirds (*Sialia sialis*) are common migratory birds in Northwest Indiana. Nearby, it has been found that although most Eastern Bluebirds in Iowa migrated for the winter, some of the birds remained and depended on fleshy, invasive fruits as a food source [6]. With a comparable winter climate, we have focused this project in Northwest Indiana, where there are six main invasive fruiting plants that continue to provide nourishment to the birds over the course of the winter months, including Autumn Olive (*Elaeagnus umbellata*), Amur Bush Honeysuckle (*Lonicera maackii*), Multiflora Rose (*Rosa multiflora*), Highbush Cranberry (*Viburnum opulus*), Bittersweet (*Celastrus orbiculatus*), and Bittersweet Nightshade (*Solanum dulcamara*) [1]. Across the nation, the flowering periods of the species vary; however, in Illinois the blooming season of Bittersweet Nightshade begins in early May and the plant is usually in full bloom by October. Research shows that these surviving plants, then, remain a food source for American Robins and Eastern Bluebirds alike over the winter months [4]. This raises the question of the winter survival rates of these birds in Northwest Indiana. Given the amount of fruit on November 1, how many birds can survive with the amount of fruit that the invasive plants are sustaining and providing over the winter months? How many birds can survive given that there is a limited amount of fruit that depletes as the winter proceeds? To answer these questions, factors such as basal metabolic rate, foraging patterns, roosting behavior, realistic range sizes, and different habitats in Northwest Indiana were taken into consideration to create an Agent-based model (ABM).

ABMs are a helpful tool that are often used to model and determine various emergent patterns or behaviors when dealing with populations over time. The agent-based modeling technique provides a well-suited structure to modeling foraging and roosting patterns for birds, as it can model an entire bird population's movements and behavior, and at the same time track and record the data of a single bird within the flock. ABMs are flexible and provide an easy way to manipulate population and resource sizes, thus allowing for simulation of specific environments.

In this project, we have used Netlogo to develop an ABM that models the foraging and roosting patterns of American Robins (*Turdus migratorius*) and Eastern Bluebirds (*Sialia sialis*) during the winter months (November 1 - March 1) [1] in Northwest Indiana. To create this model, we had to make various simplifying assumptions, however this project provides insight into the birds' general behavior in the winter months, and provides a foundation for future research to be performed.

2 Agent Based Modeling

2.1 Purpose

The purpose of this agent-based model is to simulate the behavior and survival of American Robins and Eastern Bluebirds in Northwest Indiana over winter months. To this end, we considered various aspects known about thrush foraging behavior, thrush roosting behavior, and the environment of Northwest Indiana. The simulation results indicate the overarching characteristics of thrush behavior in this setting and how it changes with factors such as food availability and population density.

2.2 State Variables and Scales

This agent-based model is comprised of two primary components — bird agents and a landscape composed of various patches. Each bird agent represents either a robin or a bluebird. The landscape is a grid of patches representing the region of Northwest Indiana. These patches correspond to different habitat types with varying amounts of available food. These agents and patches correspond to those in the NetLogo program.

2.2.1 Bird agents

Robins and bluebird agents appear as brown and blue agents on the Netlogo interface, however they are identically coded, meaning the only distinction between the species is their color. Biologically, the species have comparable foraging, roosting, and migratory behavior, and so homogeneity was assumed among them in the model.

Each bird agent keeps track of its own energy level in kilocalories over the course of a simulation. At the beginning of the simulation, every bird agent has the same amount of energy at 300 kcal. This level is depleted over time according to the field metabolic rate of American Robins. Additional energy is expending when the birds actively fly to a new location, while less energy is expended when they are sleeping. This energy level is increased when the bird agent consumes fruit from the patch where it is located. When this energy level reaches zero the agent is deleted and the bird is considered to have died.

Every bird agent also keeps track of the roosting site that it slept at the previous night. Birds' initial starting location is always a roosting site. The birds have a preference to return to the previous roosting site, however once food sources become depleted and birds have further to travel, other roosting sites also become attractive.

2.2.2 Patches

The model's representation of Northwest Indiana consists of a 31×31 grid of patches (for a total of 961 patches). The edges of this grid wrap so that the topology of landscape is a torus. Each patch represents a 25 hectare (0.25km^2) square area. This makes the entire model a $15.5\text{km} \times 15.5\text{km}$ square region.

There are four different habitat types represented by patches in the model. Each habitat type contains a different concentration of food and is represented by a differently colored patch. Within each habitat type, patches are assigned an initial amount of food based on a normal distribution. Negative and non-integer values for the amount of fruit are not allowed. This fruit is depleted only when it is consumed by bird agents and there is no way for the amount of fruit in a patch to increase during the simulation.

Some patches in the modelled landscape serve as roosting sites to which bird agents must return to sleep for the night. Each patch has an equal probability of being a roosting site upon initialization. Roosting sites are represented by a darker colored patch. The number of roosting sites can easily be altered from one run of the model to the next using a slider bar on the Netlogo interface. However, we only used 15 roosting sites in our large-scale simulations.

2.3 Process Overview

The model proceeds in time steps of 30 minutes. For each time step, every bird agent takes action to meet its needs according to a predetermined decision making process, which incorporates stochasticity. (See Figure 1)

2.3.1 Bird Subroutines

The "Starve" subroutine checks to see if the energy level of the bird agent is less than or equal to zero. The bird agent is deleted and is said to have died if it does not have a positive energy value. If the bird agent has a positive energy value, then it simply continues in its decision-making process. This subroutine is implemented every time that a bird agent expends energy.

One of the first values that each bird checks in its decision making process is the time of day. If it is earlier than 6:00 am then the birds go about the "Sleep" subroutine. If it is between 6:00 am and 10:00 pm then the birds go about their decision process when they are awake. After 10:00 pm, the birds also go about the "Sleep" subroutine. These times of day were arbitrarily estimated.

The "Sleep" subroutine first checks to see if the bird agent is in a roost. If the bird is in a roost, then bird simply expends the amount of energy calculated based on the bird's BMR over a 30 minute period. If the bird is not in a roost, then the bird flies either to its previous roost or to the nearest roost based on a probability comparing the bird's distance from each roost. After arriving at a roost the bird sleeps for that time-step.

The "Move" subroutine is the first action that a bird agent takes every time-step that it is awake. This subroutine compares the patch where the bird is currently located to the surrounding patches visible to the bird agent. The bird then chooses the most attractive visible patch based on food quantity and distance from the birds current location. The bird then chooses whether or not to actually travel to this attractive patch based on a probability comparing it to its current patch based on these same values for each patch. In the case that all patches within the bird's visible range have very little food, then the bird will choose a random direction to fly (taxi) in search of patches with more food. If a bird must taxi to a new location it travels a distance determined by a normal distribution with an average of 5 patches (2.5km) and a standard deviation of 1 patch (0.5 km). After the Move subroutine, the "Starve" subroutine is run because the birds have expended energy if they flew from one patch to another.

After a bird has decided how it will move, then it goes through the "Eat" subroutine. This subroutine determines how much food a bird agent will eat from its current patch and makes the bird eat it. The amount of food that a bird eats is determined by a type II functional response equation based on the amount of food in the current patch. The value of this functional response equation is added to a normal distribution with an average of 0 fruits and a standard deviation of 2 fruits. This value is then rounded to the nearest integer to give the number of fruits that the bird then eats. After the bird eats then its energy value is updated before the timestep then ends.

The patch agents do not change by themselves over time. They are only impacted by their interactions with the bird agents. As bird agents eat fruit, the amount of fruit in the patch is depleted accordingly.

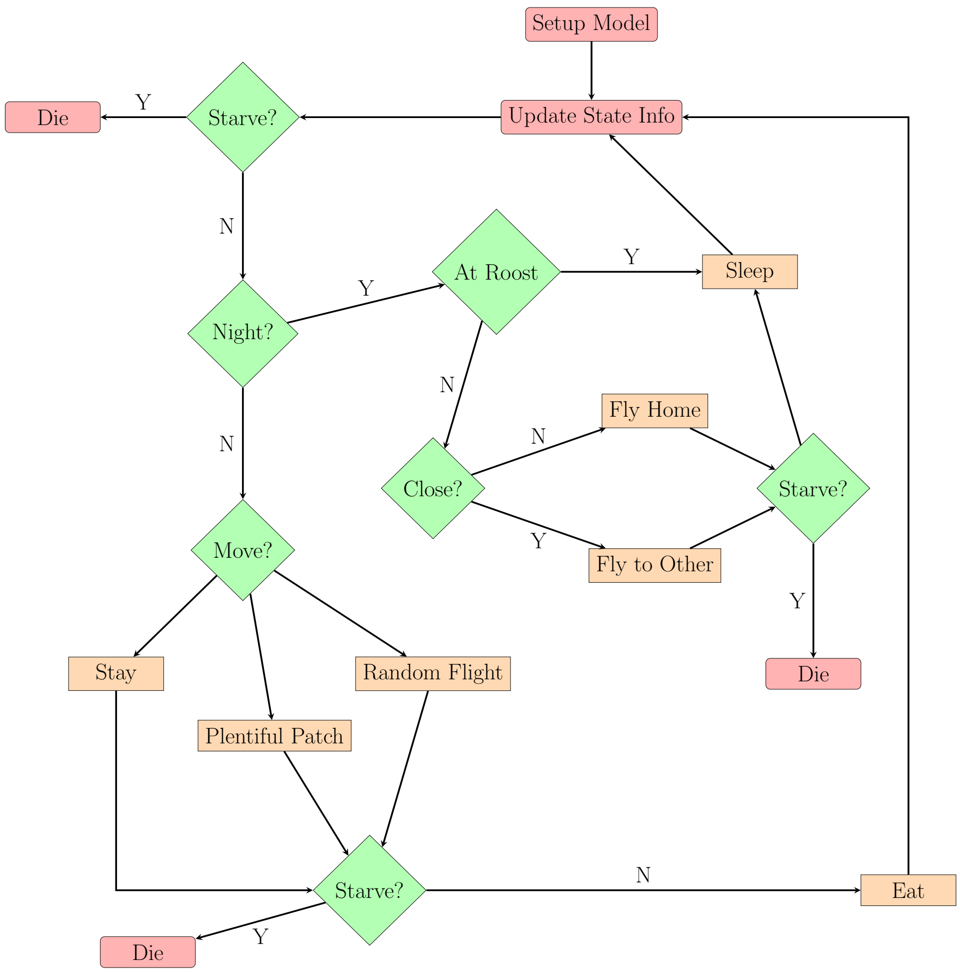

Figure 1: This decision tree describes a bird's decision-making process for each timestep in the ABM.

2.4 Design Concepts

Emergence

Some aspects of the model such as the bird's survivability, the amount of fruit that they eat, and any tendencies to group together or disperse emerged from the behavior of the individual birds and their interaction with the environment. Although the birds' general decision making process is strictly defined, many of their actions and most of their choices incorporate some degree of stochastisity.

Fitness

In the model, each bird tries to survive the winter as best it can by consuming as much fruit as it can, while limiting its energy expenditures from moving. This is accomplished primarily through the "Move" subroutine which determines if, where, and how birds move to meet this goal.

Sensing

During a simulation bird agents are assumed to be aware of their environment within a radius of 5 patches (2.5km). Within this radius, a bird agent is aware of the various patches along with their amount of food as well as the other birds in this area. A distance of 5 patches was chosen rather arbitrarily. This distance was decided on because a bird was assumed to be able to fly quickly and be roughly familiar with its territory — enough to be fully aware of its environment within a 5 patch radius. This distance was also sufficiently small to reasonably limit the number of patches that a bird agent will have consider when deciding where to move.

Stochasticity

Many aspects of the model incorporate stochastic processes. Within the environment, the locations of and thus the distribution of the roosts was completely random. Additionally, the initial amount of food in a given patch was determined by a normal distribution with an average determined by the type of patch. The type of each patch was also determined randomly so that each patch had an equal likelihood of being any particular type.

For the bird agents, the starting location of each bird was a randomly chosen roosting site. Many of the bird agents' decisions involved stochastic processes. For instance, when a bird must fly to a roost for the night, it decides whether or not to fly to its previous roost or another one based on a probability related to the agent's relative distance to the unfamiliar roost. Also, when bird agents eat fruit, the amount of fruit is determined by a type II functional response equation added to a normal distribution with an average of 0.

Finally, the "Move" method includes stochasiticity in two ways. First, a bird agent will decide to move to the most attractive patch that it can sense based on a probability determined by comparing the prospective patch to the bird's current patch. Second, in the event that a bird chooses to taxi because there are no observable patches with a certain amount of food, then the bird randomly chooses a direction to fly in and flies a distance determined by a normal distribution.

2.5 Initialization

At the beginning of each run of the simulation, the initial number of robins, bluebirds, and roosts is set by the observer using the slider bars on the Netlogo interface. Runs can be performed individually, by pressing go on the Netlogo interface, or batch runs can be performed. The observer can select what data to output, and the Netlogo software outputs the desired information into an Excel spreadsheet. The data was then processed and evaluated in Matlab.

2.6 Inputs

2.6.1 Patches

There are four basic types of patches, each containing a different amount of food relative to the other types. Patches of type 1 have a 30% "concentration" of fruit. Patches of type 2 have a 60% "concentration" of fruit. Patches of type 3 have a 85% "concentration" of fruit. Patches of type 4 have a 0% "concentration" of fruit. The initial amount of fruit in a given patch is 10 times the value given a normal distribution with an average of the fruit "concentration" (so for type 1, 30 as opposed to 0.3). This normal distribution has a standard deviation of 10. This value is then multiplied by the Food Abundance Percent and rounded to the nearest whole non-negative number to yield the number of fruits in the patch. The Food Abundance Percent is a variable that the user can adjust to scale the total amount of fruit in the simulation. For a bird agent, consuming one of these fruits increases its energy level by 3 kcal. Because of lack of suitable literature on the total amounts of fruit or on the energy contained in the different types of available fruits, these values were estimated. However, since the total amount of food was one of the values that we varied in our simulations by modifying the Food Abundance Percent, the results for various values were considered in that way.

2.6.2 Energy Expenditure

The basal metabolic rate (BMR) we calculated for the birds is $\frac{0.003644256 \text{ kcal}}{\text{grams of bird} \cdot 30 \text{ min}}$. We calculated this using thermodynamic values and stoichiometry found in a general chemistry textbook. This value was used to determine the bird's energy expenditure while sleeping.

The field metabolic rate (FMR) we calculated for the bird agents is 1.11536 kcal per 30 min timestep. This value was calculated from the regression equation relating FMR to mass in passerines found by Kenneth Nagy in his study on FMR in different types of animals based on mass [5]. The average weight of the robins was used to calculate the FMR for the bird agents. This gave us a value of approximately 225 kj per day, which was then converted to 1.11536 kcal per half-hour. This was the value that was used as an energy cost for the bird agents per timestep while they were awake.

The mass of the birds was calculated using data from two studies that included a variety of birds, one of which was the American Robin. A study performed by Christopher Guglielmo and had the average body mass of 18 American Robins from Ontario, Canada [3]. Another study performed by Alexander Gerson had a mean pre-flight mass of 6 robins [2]. We used these body mass values and the given standard deviations to obtain an average body mass for our study. This averaged to 77.0808 grams, which was the mass utilized in the Netlogo model. This mass was used for the American Robins and Eastern Bluebirds .

The energy cost for the flight of the bird agents was 8.167 kcal per half kilometer (patch) flown. The study performed by Alexander Gerson provided values for the energy content of lean mass and fat mass used for robins. We also used Gerson's experimentally determined average values for the amount of lean mass and fat mass consumed per minute of flight [2]. These values were used to calculate an energy expenditure per minute of flight. Then a reasonable flight speed for the American robin was obtained from the book *The American Robin* by Roland Wauer. We took the middle of the range of flight speeds specified by Wauer, giving us a flight speed of 24.5 mph for robins [7]. This speed was used to convert our energy cost per minute to energy cost per half kilometer (patch) flown. Our final value of 8.167 kcal per half kilometer (patch) flown was used as the energy cost for the bird agents' movement between patches.

2.6.3 Equations

Within the "Move" subroutine, the bird agents need a way of ranking the surrounding patches based on their food density and distance away. A value for the bird's attraction to every observable patch was determined by the following expression where D represents the distance (in patches) from the bird agent to other patch being considered:

$$\frac{25 * \text{fruit at other patch}/(\text{fruit here} + 0.001) - 0.8167 * D}{25 * \text{fruit at other patch}/(\text{fruit here} + 0.001) + 0.8167 * D + 0.001}$$

Only the patch with the highest value was considered. This value was then used as the probability that the bird agent would fly to the new patch versus stay at its current patch. The addition of 0.001 in various places prevents the computer from trying to divide by zero in certain scenarios. This method of evaluating the patches makes the bird agents balance both their ability to find fruit with their desire to not unnecessarily expend energy.

The equation determining how much fruit a bird agent eats in a particular timestep is a type II function response equation (aka Holling Type II equation). The following equation was used to determine the base number of fruits to be eaten based on the local fruit density.

$$\text{Base number of fruits} = \frac{5 \cdot \text{total number of fruits in the patch}}{400 + \text{total number of fruits in the patch}}$$

This equation was chosen because it reflects the property that even under very high food densities, there is a maximum amount of food that can be processed based on how quickly the agent can eat the food. Additionally, the equation yields lower quantities of fruit when the overall fruit density is lower. This aspect reflects the idea that a bird agent will be able to find less food when it is more scarce. The base number of fruits from this equation was added to a normal distribution with an average of 0 and a standard deviation of 2. This new value was rounded to the nearest integer to give the amount of fruits that the bird agent would eat that timestep.

The bird agents must have a decision distribution for deciding what roost to go to. The value of the following expression is the probability that a bird would choose to fly to a roosting site other than its previous one. Note: negative values correspond to a zero probability.

$$\frac{\text{distance to previous roost} - \text{distance to other roost}}{\text{distance to previous roost} + \text{distance to other roost}}$$

This equation was chosen because it causes the bird agent to be more likely to sleep at the unfamiliar roost the closer that it is to that roost relative to its previous roost. For instance, in the case that a bird agent is already in the same patch as the unfamiliar roost, then there is a 100% chance that it will simply stay there. However, this equation also causes the bird to always return to its previous roost if that happens to be closer. Although, this relationship does not have an experimental basis, it was chosen for its reasonable and desirably properties within the model.

3 Results

We ran two large-scale simulations. For each simulation, we looked at bird survivability in terms of another variable. The first simulation was run varying food availability (see Figure 2). Initial population in this simulation was 20 birds, with 15 available roosts. Survival increased with greater food availability, although not linearly.

The second simulation was run varying initial bird population (see Figure 3). In this simulation, food availability was 25, with 15 available roosts. Survival percentage decreased with a greater initial population.

Each data point is the average of 30 runs of the model. Standard deviations were small and, thus, not graphed.

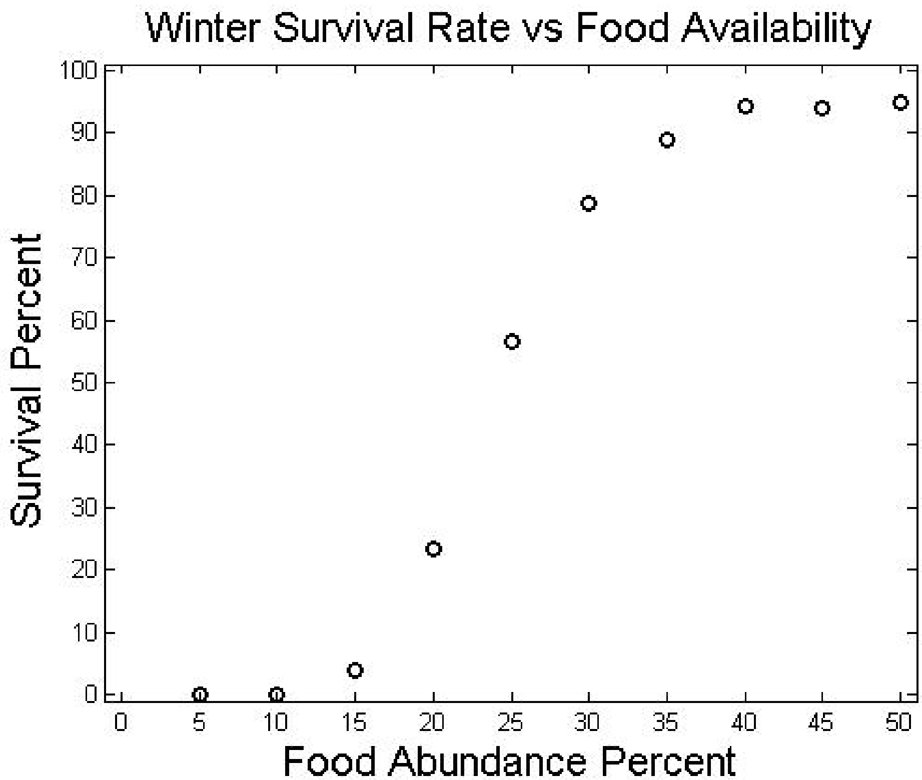

Figure 2: Number of birds alive at the end of the winter months versus food availability. n=30.

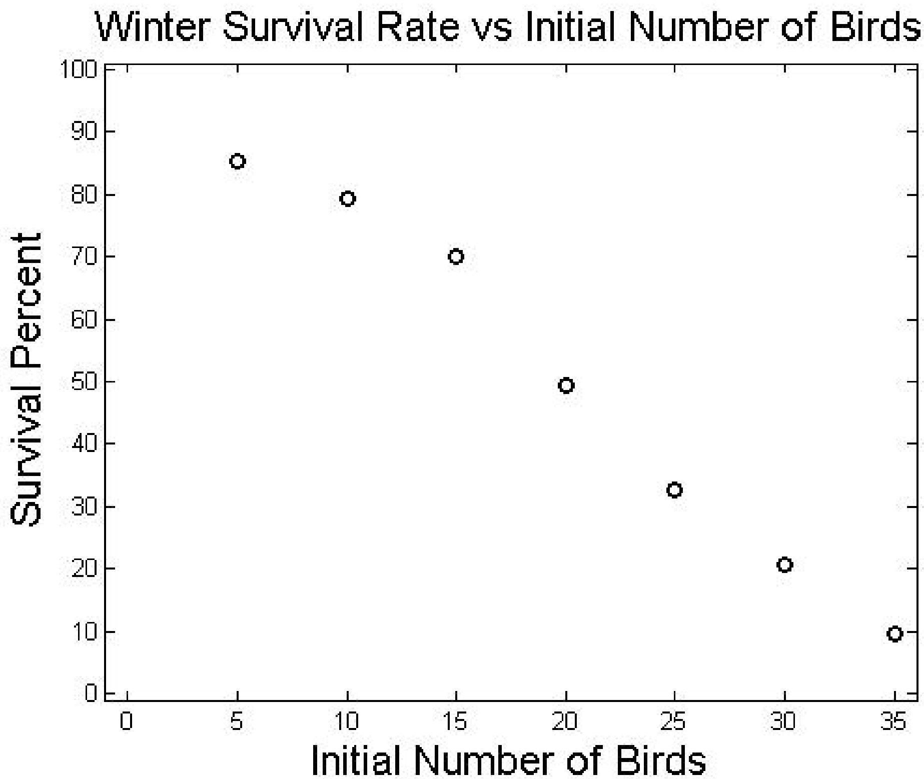

Figure 3: Percentage of birds alive at the end of the winter months versus initial population. n=30.

4 Discussion

The results confirm what is to be expected biologically. In the first simulation we ran, we varied the amount of food that was available for consumption. As the food abundance increased, the number of birds also increased. Since the number of birds is a fixed value, one would expect that with more food available, more birds will be able to survive due to competition between birds. The results from this simulation verify that with more food available, more birds survive. Although we did not perform a statistical analysis on the data, the graph appears to generally follow a logistic function.

In the second simulation we varied the number of birds and held the amount of food constant. The results tended to verify the biological intuition that with competition, less birds survived when the initial bird population was high rather than when the bird population was low. This also follows from the reality of competition for resources. If there were large amounts of birds foraging for some amount of food, it would be less probable that a bird would survive compared to if there were only a few birds foraging for the same amount of food.

5 Future Work

The research performed for this project has many potential areas for future development and investigation. While the model we have constructed acts as a foundation, there are many biological factors that have yet to be included. The model is set up in such a way that the bird populations and food resources can be altered according to the realistic sizes, however these numbers are yet to be determined.

Furthermore, this model was initially an investigation of migratory patterns and behaviors of American Robins. Due to a reconstruction of the research question, the research we conducted dealt more with survival rates. However, the model could be extended to include migratory behavior and patterns of both American Robins and Eastern Bluebirds alike. We speculate that this would require some rigorous biological study due to the difficulty in distinguishing birds that migrated into the area, from the birds that remained in the area for the winter season.

Some simplifying assumptions were made due to time restrictions on our research, however further research could include collecting biological data to input where simplifying assumptions were made when creating the model. Currently, as stated in Section 2.2.1, the only difference between the American Robin and Eastern Bluebird is the color of the agent in the Netlogo interface. While the birds do have similar roosting and migration patterns, they surely have differences that would become apparent with further investigation. These differences could then be included in the model to create a more accurate simulation of their respective behavior.

We also made the simplifying assumption that the only way the food resource decreased was via bird interaction. This is not an accurate representation, as there are natural causes that contribute to food depletion, one of which includes competition for resources within the environment. With further biological investigation, a more realistic representation of biological competition for food resources could be included in the model.

Natural causes of food depletion could also be included. For example, Northwest Indiana is known to experience harsh winters, oftentimes with blizzards and lake effect winter conditions, which could affect the food availability over the course of the winter. Likewise, these harsh conditions could cause death of the birds themselves, and such factors are not included in the current model. Further research could be conducted to include data of meteorological trends and biological consequences regarding the realistic ability a bird has to survive during such conditions.

In the same way, these conditions most likely affect the foraging and roosting behavior of the birds. Since a meteorological homogeneity was assumed, further investigation could provide a clearer and more accurate depiction of the effect the severe weather conditions have on birds' foraging patterns as well as their energy expenditure and roosting patterns.

Acknowledgements

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