A Letter to a Farmer: An Agricultural Model

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Problem Title: 2025 ICM Problem E: Making Room for Agriculture

Contents

1 Project Summary

Problem E of the 2025 ICM tasks us with developing a model that captures the agricultural evolution of a farm established on newly cleared forest land. The problem directs us to incorporate both natural ecological processes and human interventions, like the use of pesticides and fertilizers, which support crop growth but negatively impact insect and bird populations. It also suggests two routes for building a model: either we could find an environment that has experienced forest-to-farm habitat change and collect data based on this, or start from scratch. We chose to start from scratch.

After making this decision, we structured our model into three distinct stages, guided by relevant research and our understanding of how the ecosystem would likely behave in this scenario.

1. Stage 1: Early Development – Here, the ecosystem is unstable. The soil requires fertilization, crops depend on pesticides to avoid destruction by insects, and birds are the only natural predators of insects.

2. Stage 2: Transitional Phase – The land begins to recover, allowing the return of native species such as bats, which also prey on insects. During this stage, we continue to use pesticides and the introduction of bat species brings bat guano into the system.

3. Stage 3: Going Green – We fully transition to eco-friendly methods, or "going green." This step eliminates all pesticide and fertilizer use. At this point, the farm ecosystem is allowed to develop naturally.

We model this by using a discrete logistic growth model with a one-year time step and a time/ resource dependent carrying capacity to mimic resource dependence. To ensure there is some continuity between stages, we use the final population numbers from the end of one stage as the initial in the next. This continuity models the natural progression of the environment. The examination of the long-term behavior in each stage is key to determine which stage meets the farms goals best. By including parameters for predation, pesticide use, fertilizer removal, and addition of bat guano, we determined that Stage 2 would have the highest average crop yield for the farmer while maintaining a bio-diverse ecosystem.

2 Letter to a Farmer

Dear Farmer,

As members of the Consideration of Mature Agricultural Practices (COMAP) group, we're excited to share some insights and suggestions to support you as you begin your farming journey. We've developed a model that tracks describes how your land can transition from forest to farmland, and we hope the information we provide will help guide your decisions in both economically and environmentally responsible ways.

To start, it's important to know that the 200 acres you've received were previously part of a nearby forest. As a result, the land is currently somewhat unstable. The soil is nutrient-deficient, and the local insect population has recently lost its natural food source due to deforestation. Applying fertilizer to your soil will help it regain some of its nutrients; to address the insect issue, using a basic pesticide will help control the insect population. This, in turn, will reduce crop damage. In addition, we suggest reintroducing a native bat species to the surrounding edge habitat. Bats are a keystone species in this environment. They play a vital role in controlling insect populations, and their guano serves as a valuable natural fertilizer. Their reintroduction will help you in your farming efforts and improve the local ecosystem's biodiversity, which has been suffering since the land was cleared.

We understand that adopting all of these new practices may be fiscally difficult. The cost of fertilizers and pesticides have risen in recent years, while the market prices for staple crops like corn, wheat, and soy have remained relatively stagnant. If you're unable to afford both fertilizers and pesticides, we recommend using only pesticides. On average, pesticides are cheaper than fertilizers and have more of an effect on crop yield. Our model indicates that pesticides alone will offer more of an immediate benefit in addition to being more cost-effective.

Recently, there has been an increase in demand of organic goods. If you're considering an organic farming approach that excludes both fertilizer and pesticide use, it's important to recognize that your crop yield would decline significantly according to our model. While bat guano meets the USDA's standard for organic fertilizer, but it alone is not enough to make up for the loss in crop yield that will come from removing pesticides. Pesticides are responsibly for controlling a large portion of the insect population. Nonetheless, supporting the return of the native bat population remains beneficial, and we encourage habitat restoration. Their presence in this ecosystem will have a beneficial effect on your farm no matter what.

Whichever approach you choose, we encourage you to collect and record data from your farm. Your input will help us refine our model and improve future recommendations for you and other farmers. We wish you the best in your farming endeavors!

Sincerely,

Manna, Shelby, Josie, Bridget, and Sophie of COMAP

3 Introduction and Other Background

3.1 Introduction

Croplands use about 1.57 billion hectares of land out of the total 13 billion hectares of available land on Earth, meaning around 12% of Earth's land surface is used for crop production. [1, 2] To meet the growing demands of a rising global population, forests are increasingly being cleared for agricultural expansion. In fact, agricultural development is responsible for nearly 90% of global deforestation. [3] This transition from forest to farmland disrupts ecosystems, removes biodiversity, and introduces human-driven processes such as chemical usage. With this is mind, in this project we construct a mathematical model to simulate the transformation of a forested area into an agricultural ecosystem. Our analysis focuses on crop yield and interactions between bird, bat, and insect populations. We examine three stages: freshly cleared land, the reintroduction of bats, and then switching to organic farming techniques. By integrating ecological interactions with seasonal and behavioral patterns, the model aims to provide insights into long-term ecosystem stability and sustainable farming practices.

In their study *Deforestation Impacts on Bat Functional Diversity in Tropical Landscapes* Rodrigo García-Morales and Claudia E. Moreno found that species richness, abundance and functional richness per night are positively related with forest cover [4]. This suggests that forest degradation would negatively impact species richness in agricultural areas. These studies, as well as many others, outline the way that deforestation for agricultural use disrupts the surrounding ecosystem. Our model acknowledges this fact in Stage 1, where we assume that the environment is unstable.

3.2 Mathematical Background

We decided to make the model discrete so it can better represent changes on a year to year basis, as we we replant crops every year. We initially tried a Lotka-Voltera population model but it did not represent our system well because the crops fluctuate on an annual basis. We also struggled to find a realistic parameter which modeled the resource dependence of our consumers (i.e., how bats depended on the insect population). We then found consumer-resource models that are better designed for predator-prey interactions. We derived a discrete logistic growth model from the continuous consumer-resource model. However, this equation did not fit our parameter requirements because it was difficult to find data for the Holling Type II functional response term parameters.

The basis of our model ended up being a discrete logistic growth model, inspired a similar model we found in the notes on a course at SDSU. We decided this would be the simplest way to discretely model the complex system[5].

For the crop equations on the graphs, we decided to input a normal distribution to incorporate the crop variation on an annual basis. This allowed the crops to fluctuate so we could see the impact of bats and pesticides.

We include pesticides as a factor that negatively impacts insects and positively impacts crops. The effect of pesticides on crops is implicit as most small farms use pesticides in the US, and therefore the average crop yield in the normal equation is with the use of pesticides. To find the rest of our constants, we researched the average rate of prey consumption, death rate, and birth rate for birds, bats, and insects. The carrying capacity of each species is a function of time instead of a constant. We did this because we recognized that the carrying capacity of each species would change over time because our environment was changing overtime. This goes back to our problem set up that it is a deforested ecosystem that is gradually regaining species over time, so the carrying capacity does not remain constant.

4 Our Model

4.1 Some Assumptions

Since this problem's instructions were vague, we needed to make a lot of assumptions in order to have a functioning model. We will split up between the assumptions made for simplicity and the ones that have some basis in reality.

For simplicity:

- The land we are modeling is being converted into a small 200-acre farm located somewhere in the United States. This farm is evenly divided among three cereal crops: corn, wheat, and soy. Any changes to the ecosystem are assumed to affect all three crops equally. We also assume that they benefit from fertilizers, pesticides, and other external factors at the same rate. This uniformity allows us to justify using parameters derived from studies on individual crops—such as wheat or soy—within the same equation. We made this assumption primarily due to limitations in data availability. It was often difficult to find consistent data sets pertaining to the same crop across all variables. For example, we found one study describing how bat guano improves corn yields, but not wheat or soy. In other cases, we found generalized data referring only to "cereal crops" without specifying a particular type. As a result, we used any data relevant to cereal crops—or to corn, wheat, or soy specifically—where applicable, under the assumption that the findings could reasonably extend to the others.

- Our farm is fortunate, so we don't experience any droughts, famines, or other natural disasters.

- We don't include an explicit parameter for the positive effects of pesticides and fertilizers on crop yield. Our average yield is based on the expected per-acre output from farms that already use both. We instead included parameters that capture the impact of removing fertilizers and pesticides from the system.

- We assume that our birds and insects have a lifespan of roughly one year.
- We have an average expected crop yield, which will be harmed or improved by whatever is going on during that stage.
- We don't distinguish between gmo or non-gmo plants.
- We assume pesticide effect and natural death are separate and distinct. Thus pesticides affect the portion of insects who did not die of natural deaths.
- For insects and birds, we chose to focus on two species specifically: barn swallows and grasshoppers. This was again due to data availability. We found grasshoppers were decently detrimental to cereal crops, and that barn swallows were often found near farmland and are insectivorous. We were able to find consumption rates, reproduction rates, and death rates for our chosen species. Without this assumption, we wouldn't have been able to make our model accurate in real life.
- We made the opposite assumption for bats: rather than focusing on a specific species, we assumed the presence of a general bat population on our farm. This decision was based on the fact that most of the data we found referred broadly to "bats" as a group, rather than distinguishing between individual species.
- The birds and bats on our farm are purely insectivorous. They will not eat our crops.
- We use "pesticides" as an umbrella term that includes herbicides, insecticides, and fungicides. We found that the removal of pesticides as a whole had more of an effect on the ecosystem than herbicides alone, as was suggested in the problem.
- When we first approached this problem, we expected to find data supporting the inclusion of a bird death rate caused by pesticide exposure. However, we ultimately chose to omit this parameter for several reasons. Most of the available data addressing this issue focused on dichloro-diphenyl-trichloroethane (DDT), an insecticide infamous for its severe environmental impact. Since DDT has been banned in the United States since the 1970s, we considered data related to its effects to be outdated and not relevant to our model. Furthermore, studies on more commonly used modern pesticides suggest that their impact on bird populations is not immediate but instead manifests over multiple generations. While adult birds may not experience immediate effects, the reproductive success of their offspring and their offspring's offspring could be affected. This generational aspect to this parameter seemed better described by a Leslie Matrix model (for the bird population alone), which is something we didn't incorporate.
- Lastly, we assume all insects are bad: we don't distinguish between insects that are beneficial to the ecosystem (pollinators, like bees) and those that are harmful to our crops.

Based in Reality:

- We don't explicitly model any competition between the bird and bat species. Instead, any potential competition is implicitly captured through the carrying capacity function, which accounts for the availability of their shared food resource and any indirect effects the two species may have on it. This approach reflects real-world behavior as well, since there isn't much direct interaction between bats and birds. Bats are nocturnal and feed at night, while birds are diurnal and feed during the day, effectively reducing the likelihood of direct competition.
- Our time steps are one year. Corn, wheat, and soy are all harvested one year after being planted.
- Assume there is a minimum population and the populations cannot go to zero. This is realistic since populations which are very small for insects would be much more difficult to find for predators and would then result in a lower level of predation. For small bird and bat populations, a smaller population would imply more resource per animal, which would make surviving and reproducing easier. We could not make dynamic predation rates, so instead we used a population minimum to mimic this.

4.2 A Basic Food Web

Figure 1: Food web for Stage 1. Here, we have the use of fertilizer and pesticides, and the only natural predator of insects are birds.

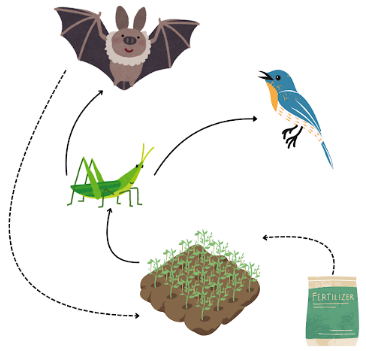

Figure 2: Food web for Stage 2. We've reintroduced the bat species back into our ecosystem and another predator of insects.

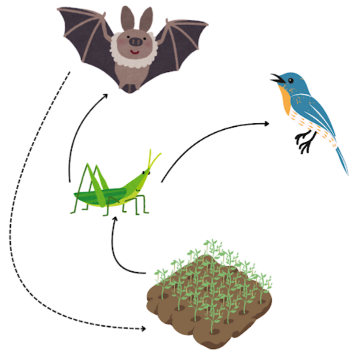

Figure 3: Food web for Stage 3. Here, everything is the same as Stage 2, but we've removed fertilizers and pesticides.

4.3 The Model and Analysis

We began developing our model by formulating a word equation for each population. We anticipated that most populations would follow a general pattern: $G(t+1) = G(t) + (\text{births} - \text{natural deaths} - \text{unnatural deaths}) * G(t) + (\text{external factors helping or hurting the population, such as predation})$ where $G(t)$ is a population at time t, and $G(t+1)$ represents the population one year later. After some discussion and the rejection of several models that didn't intuitively make sense, we ultimately settled on a system of consumer equations resembling a discrete version of the continuous logistic growth model: $G(t+1) = G(t) + rG(t)(1 - \frac{G(t)}{K})$. From our prior research and testing a few iterations of different models, we settled on incorporating the effects of the current available food resource on the consumer population as a dynamic carrying capacity.

4.3.1 Stage 1: Early Development

As mentioned earlier, our model is divided into three stages, each described by a series of discrete equations. The first stage represents newly cleared forest land that has been converted into a small farm. At this point, the ecosystem is relatively unstable. Clearing the land has removed a primary food source for local insects which have now turned to feeding on our crops. To ensure reasonable crop growth and yield, we rely on the use of fertilizers and pesticides. While pesticides help promote crop growth by reducing the number of insects preying on crops, they come with significant drawbacks. Pesticides often harm non-target organisms, including beneficial insects like pollinators, as well as the natural predators of pests, such as birds. In particular, pesticide exposure can negatively affect the reproductive rates of bird populations. This stage of the model focuses on the interaction between these three populations: crops, insects, and birds.

Population Dynamics:

$$P(t+1) = \mathcal{N}(618, 10) - \alpha_{IP} \cdot I(t)$$

$$I(t+1) = I(t) + (\mu_I - d_I - p_I) \cdot I(t) \cdot \left(1 - \frac{I(t)}{K_I(t)}\right) - \alpha_{Bi-I} \cdot Bi(t)$$

$$Bi(t+1) = Bi(t) + (\mu_{Bi} - d_{Bi}) \cdot Bi(t) \cdot \left(1 - \frac{Bi(t)}{K_{Bi}(t)}\right)$$

Carrying Capacity Updates:

$$\boxed{\begin{aligned} K_I(t+1) &= \frac{1}{2} \cdot \left(\frac{P(t)}{\alpha_{IP}} + K_I(t)\right) \\ K_{Bi}(t+1) &= \frac{1}{2} \cdot \left(\frac{I(t)}{\alpha_{Bi-I}} + K_{Bi}(t)\right) \end{aligned}}$$

We begin our analysis with the first equation in our model, which describes the crop yield, denoted by $P(t+1)$. We have a resource and expect the insect population to diminish it. For simplicity's sake, we decided not to model how much the crops would grow from a starting amount of seed, but rather work with a constant representing the expected yield a plot of our size would typically produce. In our case, to account for weather or yearly fluctuations, we chose this constant from a normal distribution $\mathcal{N}$ with a mean of 618 and a standard deviation of 10 (in thousands). This number was calculated by multiplying the total area of the farm by the average cereal crop yield per acre, measured in tonnes. This value represents the average potential crop yield under ideal conditions. According to the USDA 2017 Census for Agriculture, the majority of farms in the US are small family farms that produce cereal grains. Thus, we focus on cereal grain production on small farms that averaged around 200 acres [6]. To utilize real data, we found a weighted average of the yields (in bushels) of wheat, oat, and barley to find an average yield of 52.93 bushels per acre which is around 3,087.85 lbs [7, 8].

$$\text{Weighted Average Yield (lbs/acre)} = \frac{\sum_i (\text{yield}_i \times \text{area}_i \times \text{lbs per bushel}_i)}{\sum_i \text{area}_i}$$

In this first stage, we have taken into account the benefit of fertilizers in this sample from the normal distribution. This can currently be thought of as a factor of 1 in front of the normal distribution term.
Conceptually, this reflects a realistic agricultural process: each year, the farm begins with a fixed planting capacity, but the actual yield is reduced by natural causes and insect activity. Thus, while the potential number of crops planted each year remains constant, the realized crop population is influenced by the variable insect population.

The next equation, $I(t+1)$, describes the insect population. Here, following our discrete logistic growth model approach, insects are the consumers of the crops. Within the factor of $(\mu_I - d_I - p_I)$, μ_I, d_I, and p_I represent the intrinsic birth rate, natural death rate, and pesticide death rate respectively. This is multiplied by the previous year's population $I(t)$, as well as our carrying capacity term, $(1 - \frac{I(t)}{K_I(t)})$. The dynamic carrying capacity's full equation is listed by the insect population model. The dynamic carrying capacity is responsible for enforcing the effects of the current available food resource (crops) into the consumer population (insects). The $\frac{P(t)}{\alpha_{IP}}$ term is the crop yield divided by rate at which insects eat the crops. Thus, this term reflects how many insects the current plant biomass can support given the insect feeding rate. In order to prevent the change in carrying capacities from being too drastic across time steps, we average $\frac{P(t)}{\alpha_{IP}}$ with the previous year's carrying capacity. This results in our carrying capacity function. Finally, the subtraction of α_{Bi-I} corresponds to the number of insects lost annually due to predation by birds. Our bird population model is similar to that of the insect's, but it does not include a pesticide death rate term or a death to predation term.

4.3.2 Stage 2: Transition Phase

This stage serves as a buffer between Stages 1 and 3. The newly cleared land has had some time to adjust to our agricultural practices, enough that a crucial species has returned to the ecosystem: bats. Bats are a keystone species that positively impact most ecosystems they are a part of. They prey on a wide variety of insects, and their guano (bat droppings) are a nutrient-rich, natural alternative to chemical fertilizers. Guano contains essential nutrients like nitrogen, phosphorus, and potassium, all of which promote plant health without the synthetic additives found in conventional fertilizers. We have δ as a parameter for the rate that bat guano helps improve our crop yield. In this stage, we begin to see the beneficial effects of bats on the ecosystem in addition to the fertilizers and pesticides we've had in previous stages, making this a transition phase.

Population Dynamics:

$$P(t+1) = \delta \cdot \mathcal{N}(618, 10) - \alpha_{IP} \cdot I(t)$$

$$I(t+1) = I(t) + (\mu_I - d_I - p_I) \cdot I(t) \cdot \left(1 - \frac{I(t)}{K_I(t)}\right) - \alpha_{Bi-I} \cdot Bi(t) - \alpha_{Ba-I} \cdot Ba(t)$$

$$Bi(t+1) = Bi(t) + (\mu_{Bi} - d_{Bi}) \cdot Bi(t) \cdot \left(1 - \frac{Bi(t)}{K_{Bi}(t)}\right)$$

$$Ba(t+1) = Ba(t) + (\mu_{Ba} - d_{Ba}) \cdot Ba(t) \cdot \left(1 - \frac{Ba(t)}{K_{Ba}(t)}\right)$$

Carrying Capacity Updates:

$$K_I(t+1) = \frac{1}{2} \cdot \left(\frac{P(t)}{\alpha_{IP}} + K_I(t) \right)$$
$$K_{Bi}(t+1) = \frac{1}{2} \cdot \left(\frac{I(t)}{\alpha_{Bi-I}} + K_{Bi}(t) \right)$$
$$K_{Ba}(t+1) = \frac{1}{2} \cdot \left(\frac{I(t)}{\alpha_{Ba-i}} + K_{Ba}(t) \right)$$

4.3.3 Stage 3: Sustainable Farming

In this section, we've fully "gone green." Our agricultural practices are now eco-friendly, meaning we no longer use pesticides, herbicides, or fertilizers on our crops. Initially, we expect this change to harm our plant population for two reasons. First, the removal of fertilizers will have a damaging effect on our crops. According to a study [9], we expect some loss in our crop yield. We have γ as a parameter that models the expected decrease in our crops. Secondly, the absence of pesticides will lead to an increase in the insect population and a resulting decrease in plant matter. This will be slightly managed by the increase in the bat/ bird populations, as their carrying capacities will increase slightly with the increase of availability of their food resource.

Population Dynamics:

$$P(t+1) = \gamma \cdot \mathcal{N}(618, 10) - \alpha_{IP} \cdot I(t)$$
$$I(t+1) = I(t) + (\mu_I - d_I) \cdot I(t) \cdot \left(1 - \frac{I(t)}{K_I(t)}\right) - \alpha_{Bi-I} \cdot Bi(t) - \alpha_{Ba-I} \cdot Ba(t)$$
$$Bi(t+1) = Bi(t) + (\mu_{Bi} - d_{Bi}) \cdot Bi(t) \cdot \left(1 - \frac{Bi(t)}{K_{Bi}(t)}\right)$$
$$Ba(t+1) = Ba(t) + (\mu_{Ba} - d_{Ba}) \cdot Ba(t) \cdot \left(1 - \frac{Ba(t)}{K_{Ba}(t)}\right)$$

Carrying Capacity Updates:

$$K_I(t+1) = \frac{1}{2} \cdot \left(\frac{P(t)}{\alpha_{IP}} + K_I(t) \right)$$
$$K_{Bi}(t+1) = \frac{1}{2} \cdot \left(\frac{I(t)}{\alpha_{Bi-I}} + K_{Bi}(t) \right)$$
$$K_{Ba}(t+1) = \frac{1}{2} \cdot \left(\frac{I(t)}{\alpha_{Ba-i}} + K_{Ba}(t) \right)$$

4.4 On the Formation of Parameters

Intrinsic Birth Rates

μ_I : In a laboratory, population parameters of the *Ronderosia bergi* grasshopper found that over an 18 week period between 5 cohorts there was an intrinsic rate of population increase on average of 1.24. Expanding this over a year long period we obtain [10]:

$$3.72 \pm 0.025 \text{ SE}$$

μ_{Bi} : A pair of Barn Swallows will produce 2 broods every year, with an average clutch size of 4-5 eggs per season. Eggs have a hatch rate of 90% and fledglings have a survival rate of 80% [11, p. 4]. Dividing by 2 to account for each adult and then multiplying by 2 to account for 2 broods per season, we get

$$\text{birds born each year per adult} = 4.5 \cdot 0.9 \cdot 0.8 = 3.24 \text{ birds}$$

μ_{Ba} : Most bat species have one pup per year, assuming that half the population is female, according to [12]. We are making the assumption that the bat population on our farm is one of these general species.

Natural Death Rates

d_I : In a controlled environment it was found that grasshoppers had a death rate of approximately 24 percent, largely account for by diseases [13]

$$0.24$$

d_{Bi} : In a study conducted on a large colony of barn swallows in Nebraska, the probability of average survival rate within the adult population was roughly 0.35. Converting this to a mortality rate, we obtain an average death rate of 0.65 with a standard deviation of 0.054 [14].

$$0.65 \pm 0.054 \text{ SE}$$

d_{Ba} : To estimate the death rate of the bat population, we made some necessary generalizations due to limited data on natural mortality in bats. While direct sources on bat deaths from natural causes were scarce, we found an article discussing multiple mortality events (MMEs) in bats [15]. These events include deaths from human activity, biological factors, and accidents. To determine the proportion of bats that die, we compared this data to the estimated global bat population of approximately 5.4 billion individuals [16]. The total number of deaths reported from MMEs is about 55 million. Thus, the estimated mortality rate is calculated as

$$\frac{\text{total bat death from MMEs}}{\text{total estimated bat population}} = \frac{55,331,000}{5,406,791,300} = 0.0102$$

We actually expect a low death rate for bats, as they have long lifespans.

Pesticide Effect Rates

p_I : In a laboratory setting, 60%-70% of the insects were killed by the use of five common pesticides in tandem [17]. We chose the lower end of the results due to the lack of laboratory control on a farm. We consider that pesticides effect insects which do not die of natural causes thus we take 60% of the surviving 76%.

Consumption Rates

α_{IP}: It is estimated that grasshoppers consume 30 to 250 percent of their body weight on a daily basis [18]. Multiplying by their body weight and 365 we obtain the biomass consumed per insect on an annual basis [19]. Finally, we convert units from milligrams to pounds.

$$100 \text{ mg} * 0.30 * \frac{365 \text{ days}}{1 \text{ year}} * \frac{2.20462e^{-6} \text{ lbs}}{1 \text{ mg}} \approx 0.024 \frac{\text{lb}}{\text{year}}$$

α_{Bi-I}: The average farm bird will eat around 850 insects per day which is 310 thousand per year. This also applies to barn swallows, our chosen bird [20].

α_{Ba-I}: The average bat will feed for 4 hours per night and can consume on average 600 insects per hour, which totals 876,000 insects eaten per bat per year on average [21, 22].

Extra Parameters

δ: This parameter captures the beneficial effect that bat guano has on plants. Bat guano is a nutrient-rich fertilizer and is often considered a superior natural alternative to commonly used synthetic fertilizers. In ecosystems where bats are present, we assume their guano contributes to plant growth in addition to any applied fertilizer. This effect is quantified using results from a study that found bat guano improved corn yield [23] (based on information from the abstract).

$$\frac{\text{Final yield} - \text{Initial yield}}{\text{Initial yield}} = \frac{3.85 - 3.17}{3.17} = 0.2145$$

The study conducted experiments across three different sites, each producing similar results, suggesting that bat guano consistently improves crop yield. Relative increases from the other two sites were calculated as 0.4269 and 0.165, respectively. We chose the smallest of these numbers for teh sake of simplicity. It is important to note that although all measurements were reported in megagrams per hectare (Mg/ha), the rate of increase doesn't change when converted to pounds per acre. Therefore, we define as $\delta = 1.165$, representing a 16.5% increase in yield attributable to bat guano.

γ: This parameter accounts for the relative loss in crop biomass yield due to the removal of pesticides and fertilizer. This assumes that bat guano alone is less effective than conventional fertilizer. According to a study [9], the removal of pesticides alone can result in a 32% decrease in cereal crop yield. We therefore assume that the removal of pesticides, combined with the use of bat guano, will have the following calculated effect on our crops: $\delta \cdot 0.68 = 0.7922$, indicating a 20% loss in crop yield. This suggests that while bat guano is beneficial, it is not sufficient on its own to fully compensate for the absence of traditional fertilizers.

4.5 GitHub Repository

- View our GitHub Repository

5 Results and Analysis: Go Green or Go Home?

Running our models for Stages 1, 2, and 3 with the above parameters gives the following results. In Stage 1, we started with initial conditions of 100,000,000 insects and 600 birds. In Stage 2, we started with 20 bats. Between stages, we carried over the ending population counts of all animal species, in order to simulate a realistic transition between stages, as if these were implemented in succession on a real farm.

5.1 Stage 1 Results

Table 1: Stage 1 summary statistics for each population category.

Category	Mean	Standard Deviation	Max
Birds	90.08	284.63	1.80×10^3
Insects	8.41e+06	7.81e+06	5.62×10^7
Crops	4.24e+05	1.23e+05	5.98×10^5

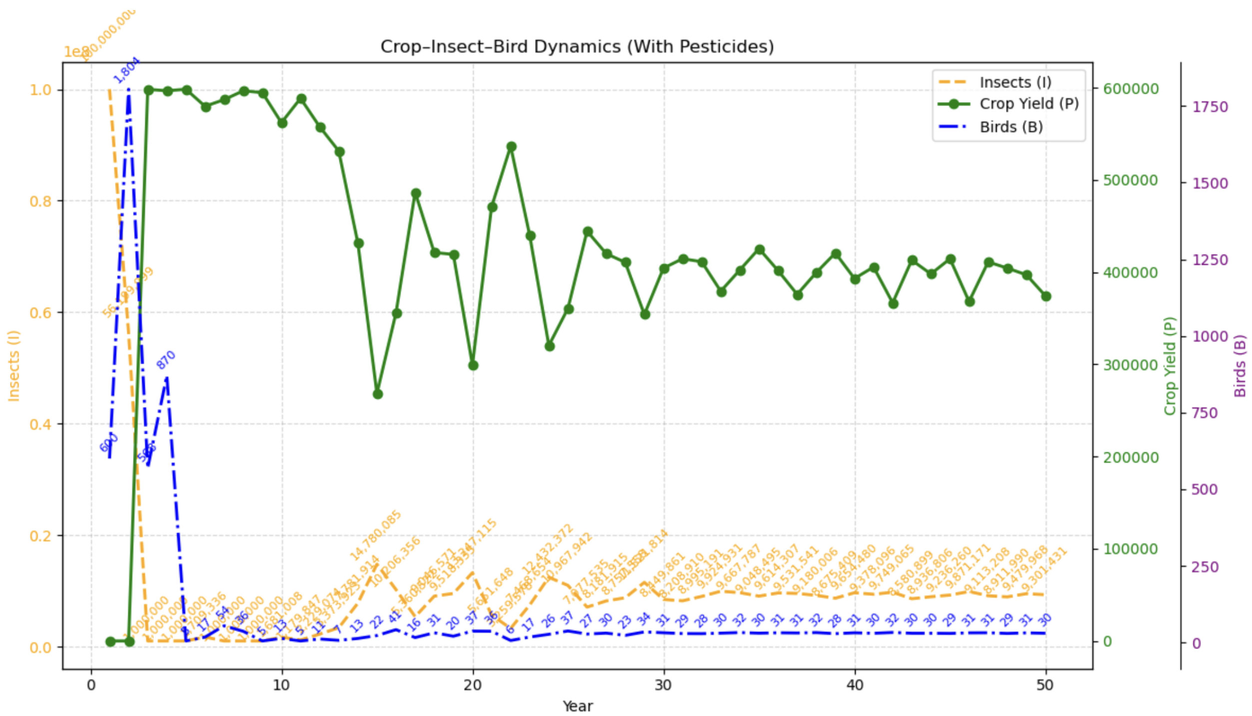

Figure 4: Stage 1 results showing crop yield and insect and bird populations over 50 years.

In Stage 1, we obtain our second largest crop yield average, and the smallest standard deviation among the three stages. This lack of variability in our data output implies that crop yield within this stage will overall be more consistent relative to others. In other words, the use of fertilizers, pesticides, and the absence of bats in our simulation indicates larger predictive abilities in crop yield.

5.2 Stage 2 Results

Table 2: Stage 2 summary statistics for each population category.

Category	Mean	Standard Deviation	Max
Birds	47.50	123.69	8.06×10^2
Bats	23.24	40.60	2.24×10^2
Insects	6.77e+06	7.92e+06	2.35×10^7
Crops	5.40e+05	2.05e+05	7.14×10^5

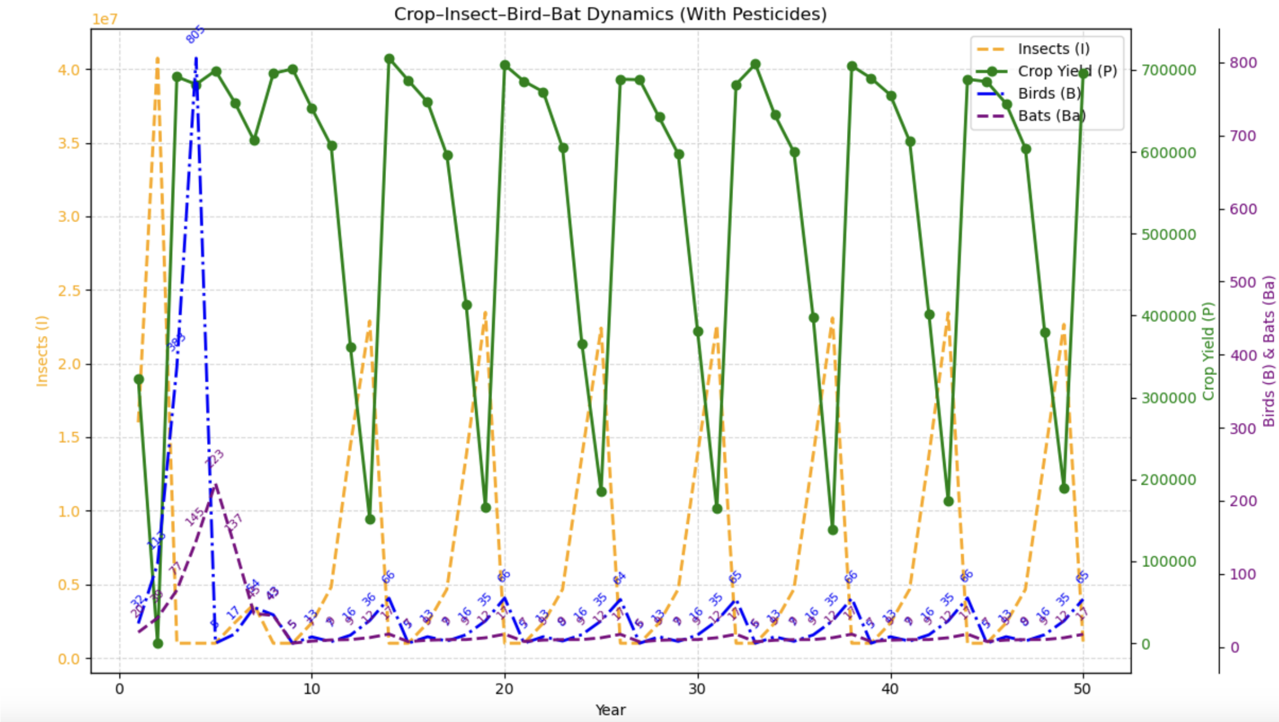

Figure 5: Stage 2 results showing crop yield and insect, bird, and bat populations over 50 years.

In Stage 2, our average crop yield is significantly higher than in other stages. However, our standard deviation is at a peak. Although this simulation may generate a larger yield in crop biomass, it will fluctuate greatly. This is apparent from the range of our crop yields. Our maximums reach nearly seventy thousand pounds, and our minimums roughly twenty pounds approximately every six years. We generate more crops overall.

5.3 Stage 3 Results

Table 3: Stage 3 summary statistics for each population category.

Category	Mean	Standard Deviation	Max
Birds	42.11	122.73	8.03×10^2
Bats	18.90	31.15	1.60×10^2
Insects	5.19e+06	6.57e+06	3.68×10^7
Crops	3.70e+05	1.27e+05	4.74×10^5

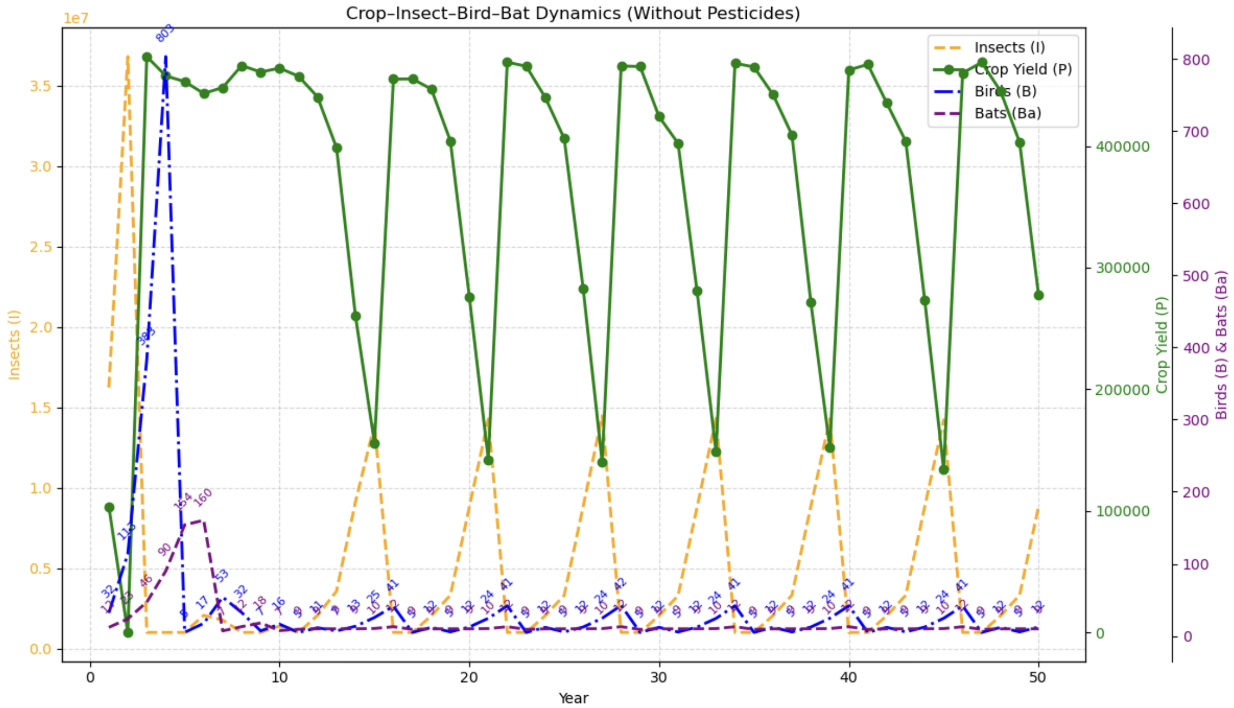

Figure 6: Stage 3 results showing crop yield and insect, bird, and bat populations over 50 years.

Stage 3 had the lowest average crop yield and a similar standard deviation to Stage 1. In general, "going green" seems to reduce yield significantly.

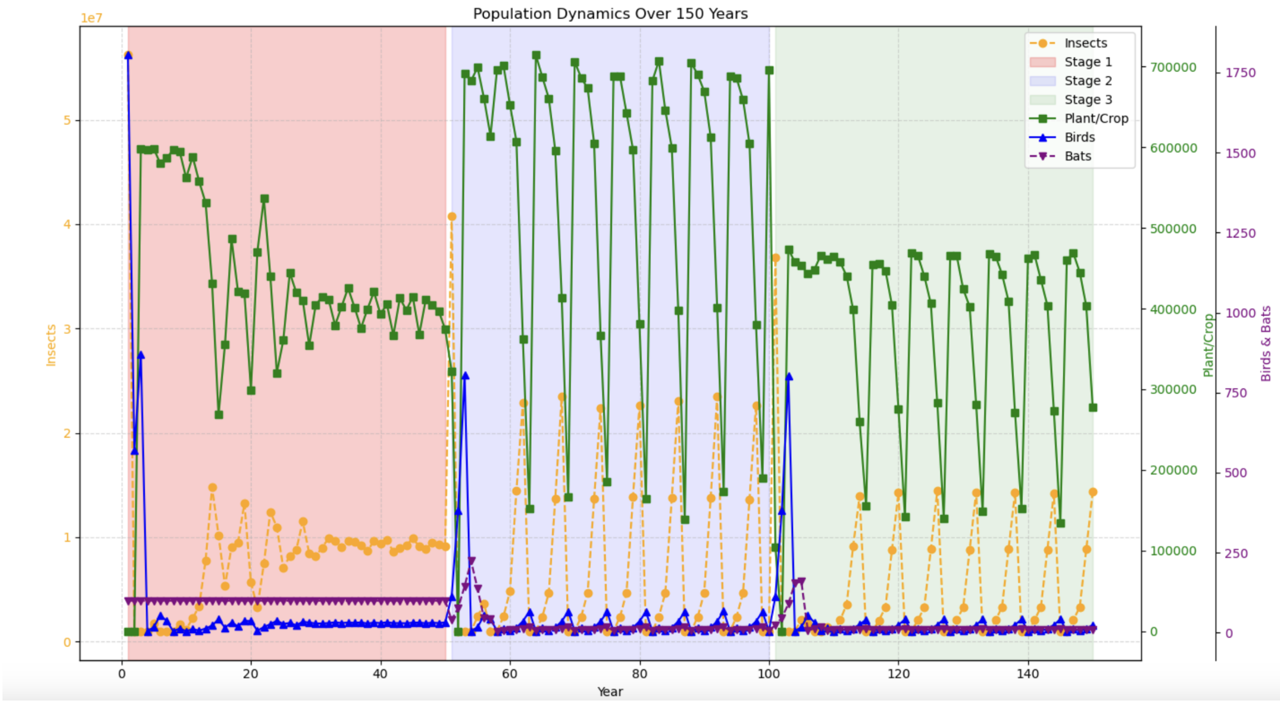

Figure 7: Compilation of all three stages throughout the 150 year period.

The aim of this compilation is to act as a visual aid in interpreting crop yield throughout our simulation period. The consistent yield in Stage 1 represents our smallest standard deviation. The large oscillations in crop yield within Stage 2 reveal our largest standard deviation. Finally, Stage 3 shows a notable decline in annual biomass yield, an indicator that going green may not be a viable option.

6 Conclusions and Discussion

According to our model, going green is not better because the average crop yield is greater in Stage 1 with pesticides and no bats than Stage 3 with bats and no pesticides. This suggests that the farmer should continue using pesticides, and bats would be helpful too if they can reintroduce some of the bat population. Stage 2 is the overall best scenario because it results in the greatest average crop yield of approximately 540,155 pounds per year. The environment is also more stable due to the reintroduction of bats, a keystone species, which help control the insect population and reduce crop loss. The average crop yield varies more once bats are added during Stage 2 because of the periodic behavior of the bat, bird, and insect populations. Stage 1 provides the benefit of a stable crop yield and has the second greatest average crop yield due to the use of pesticides. This is what we originally hypothesized because we assume that pesticides have made farming more profitable which is why they are so widely used. Note that the numbers are low for a 200 acre farm, which is potentially an issue with our parameters and initial populations.

The carrying capacities are generally adjusted to a lower number and form a periodic oscillation which follows the oscillation of the resource population. All of the carrying capacities decreased from the initial inputs for Birds and Bats. The speed of adjustment was high likely due to the form of the equation. This made it so that averaging over long periods of time eliminates the effect of the initial carrying capacity. The implementation of a minimum carrying capacity to avoid absurd behavior was discrete at each step. This helped prevent a division by 0 error if the population became too small. Interestingly, the populations of Birds and Bats within the 50-year time frames which we chose converged to numbers similar to their carrying capacities. For insects the carrying capacities were one order larger. This shows that even with the variable carrying capacity, the populations still converged to their capacities and then the two followed the same pattern of oscillation in long-term behavior.

The following is a graph of the carrying capacities of birds and insects during Stage 1 based on our model. This figure demonstrates that the insect and bird carrying capacity level out during Stage 1 within the first 5

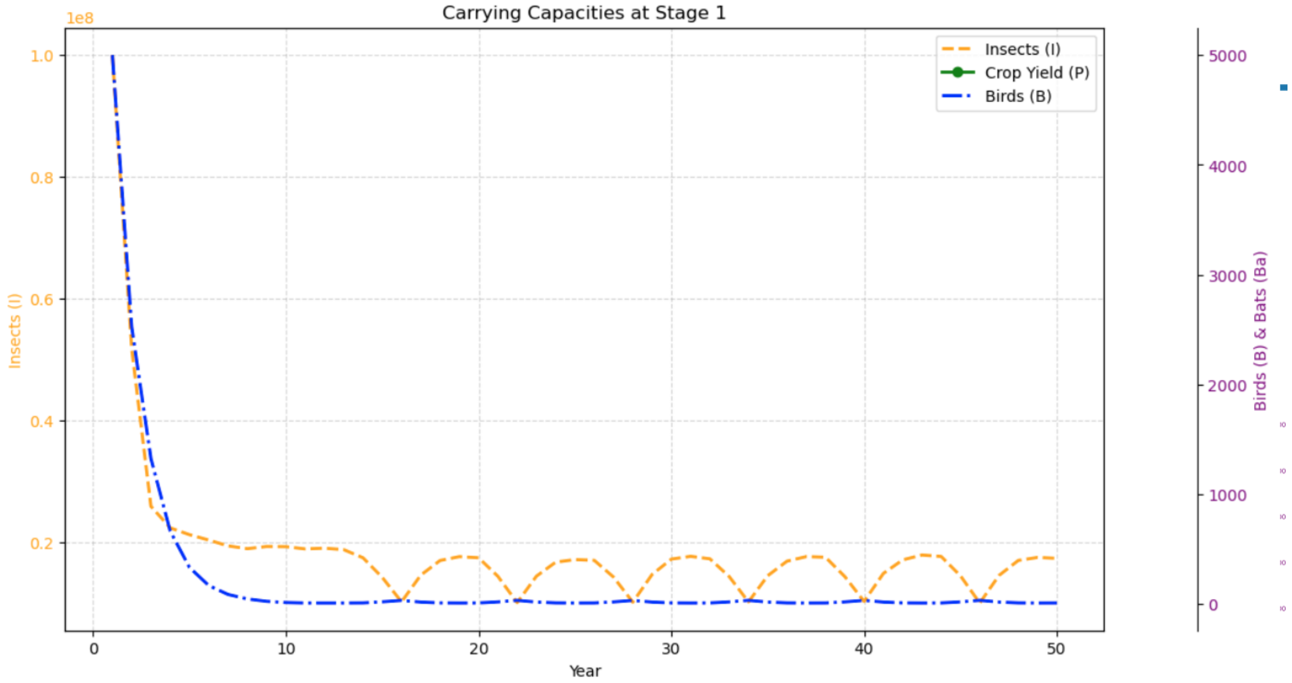

Figure 8: Stage 1 carrying capacity results

years. The insect carrying capacity also steeply declines, but it reaches more of an oscillation minimum instead of the flat line.

Below are the graphs of the carrying capacities of Stage 2 and Stage 3. They show that the bat carrying capacity behaves in a similar way as bird carrying capacity. The insects continue to oscillate at a minimum carrying capacity. If we had more time, we would research more accurate ways to implement the carrying capacity function. We suggest finding a way to weight the initial K_0 more so that it does not immediately periodically oscillate around a smaller number with the insect population or level out at the minimum after only 5 to 10 years for the bat and bird populations. Our model assumed that there was an equal amount of fertile

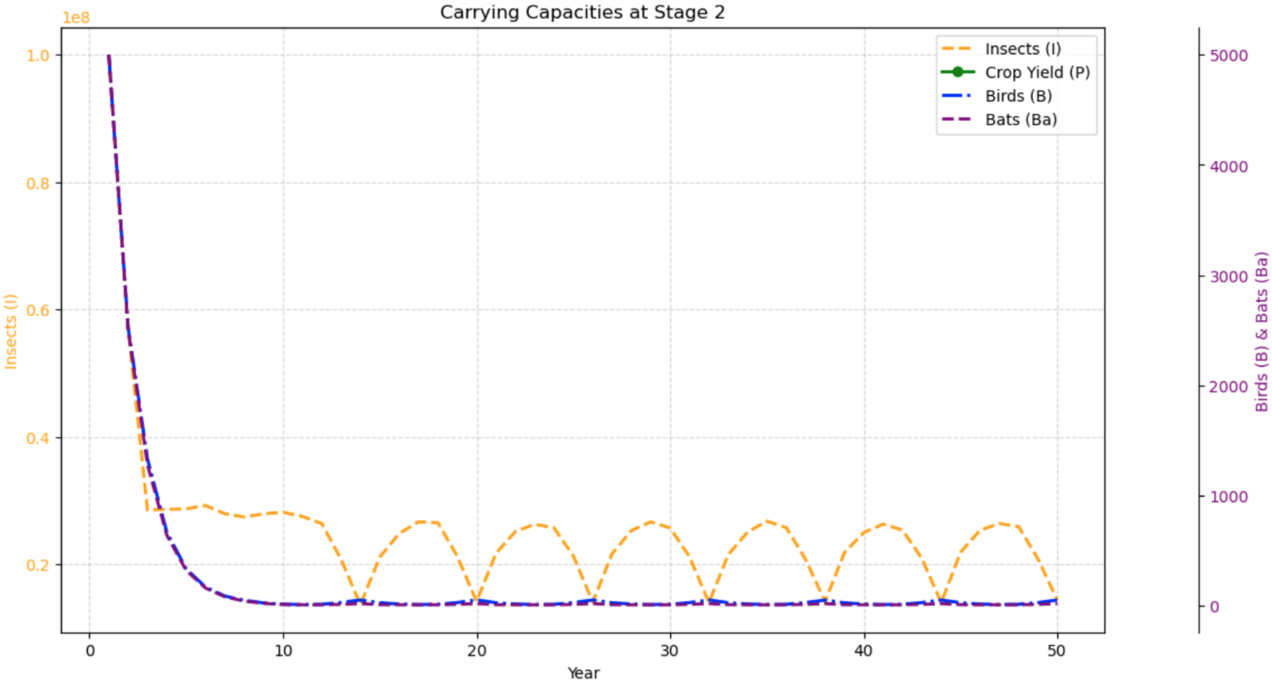

Figure 9: Stage 2 carrying capacity results

land for crops to grow on each year, but this is not realistic because we are transitioning from a cleared forest to an agrarian ecosystem, so the land fertility will change over time. Therefore, finding a way to implement a changing carrying capacity of fertile land for cereal crops would more accurately represent the scenario.

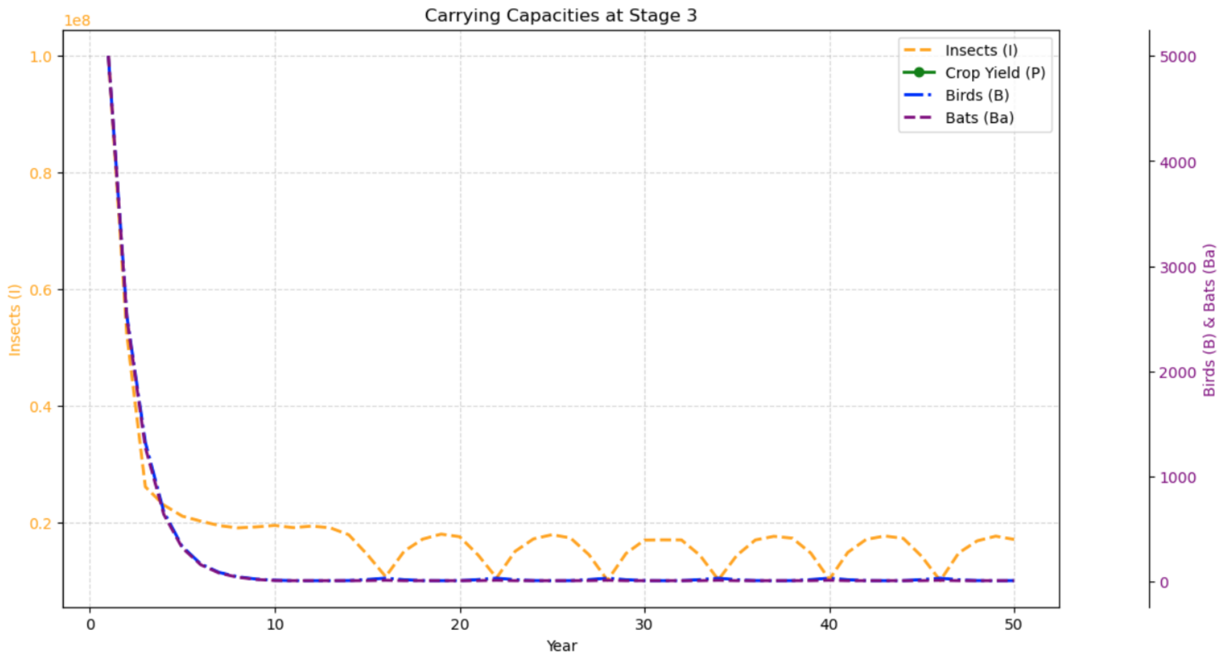

Figure 10: Stage 3 carrying capacity results

As for the limitations of our project, our model did not account for all of the intricate relationships of the different trophic levels. The impacts of decomposers and birds and bats on crops should be more carefully evaluated. For example, some birds eat crops, so they should be included into the harm factor. Finding all of the parameters within the same system would increase the accuracy of the model because it would be a more controlled setting. For populations that can have multiple generations within one time step, like insects, we could run a Leslie Matrix model. This would be an improvement because for simplicity we assumed that insects only reproduce once a year, but this true in real life. Therefore, a Leslie Matrix model may more accurately represent the dynamic changes within species populations. We also implemented a minimum population and carrying capacity at discrete steps to simulate more realistic predator-prey behavior due to limitations in what data and parameters we could find. If possible, parameters which are accurate and more suitable to create predation/feeding rates which are resource dependent would improve the model, potentially allow for the use of the consumer-resource model and likely eliminate the need for a population minimum. A final improvement we would recommend is using a smaller time step so that we can accommodate for seasons and incorporate the consumer-resource model's handling time and efficiency rate. Another benefit of using a smaller time step is that it would be more relevant to the single lifetime of a farmer, because our current model stretches over 150 years.

7 Author Contributions

- Manna Adhanom contributed to the models, project summary, parameter formation, assumptions, model analysis, and the letter to a farmer.
- Shelby Jackson contributed to the models, graphs, parameter formation, assumptions, summary statistics, and model analysis (thanks to shelby for the github!!).
- Josie Goodson contributed to the models, graphs, math background, letter to a farmer, and discussion sections.
- Bridget Bidwell contributed to the models, model analysis, introduction, food web, parameter formation, and the letter to a farmer.
- Sophie Kogan contributed to the models, dynamic carrying capacity equation, parameter formation, assumptions, and discusson.

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We would like to acknowledge our Professor Mason Porter and our TA Haoyang Lyu for guiding us through the math modeling process this quarter and giving us feedback on our models. We would also like to acknowledge the USDA crop database website for helping us find the parameters.

9 Formatting and AI Use Report

We used ChatGPT to help create and edit our python code to represent our models graphically. We also used AI to help us search for different sources for the parameters of bat death rate, etc. It often helped in giving us texts to look up, but these were not always reliable. We double checked the sources to confirm they existed and were helpful after using AI to find them. We used it because it was an efficient way to graph our model and find relevant sources with parameters. Lastly, we used ChatGPT to do some basic maintenance on our text. We ran through some of our text blocks through to double check for spelling errors, grammatical errors, and to make sure our statements were clear. We often had to edit whatever AI gave back to us, as it often missed the main point of the text.

References

[1] Food and Agriculture Organization of the United Nations. Land use statistics and indicators 2000–2021. global, regional and country trends, 2023.

[2] Food and Agriculture Organization of the United Nations. Cropland area – fao [dataset], 2024. With major processing by Our World in Data. Original data from FAO's "Land, Inputs and Sustainability: Land Use".

[3] Food and Agriculture Organization of the United Nations. Fra 2020 remote sensing survey, 2022.

[4] Rodrigo García-Morales, Claudia E. Moreno, Ernesto I. Badano, Iriana Zuria, Jorge Galindo-González, Alberto E. Rojas-Martínez, and Eva S. Ávila Gómez. Deforestation impacts on bat functional diversity in tropical landscapes. https://doi.org/10.1371/journal.pone.0166765, 2016. PLOS ONE, Accessed: 2025-06-10.

[5] Joseph M. Mahaffy. Math 121 - calculus for biology i: Logistic growth and nonlinear dynamical systems, 2009. Lecture slides, San Diego State University, Last updated: May 11, 2009.

[6] U.S. Department of Agriculture. 2021 Farm Typology Report. https://www.nass.usda.gov/Publications/Highlights/2021/census-typology.pdf, 2021. Accessed: 2025-06-04.

[7] Michigan State University Extension. Test weight in small grains. https://www.canr.msu.edu/news/test_weight_in_small_grains, n.d. Accessed: 2025-06-04.

[8] U.S. Department of Agriculture. Small grains 2024 summary. https://downloads.usda.library.cornell.edu/usda-esmis/files/5t34sj573/w08944064/3x818d810/smgr0924.pdf, September 2024. National Agricultural Statistics Service (NASS), Accessed: 2025-06-04.

[9] Muyesaier Tudi, Hong Yang, Peiling Wang, Abat birth ratedul Qadir, Jitendra P. Srivastava, David L. Scott, Muhammad Yaqub, Fahad A. Alsharif, Hailin Wang, Pedro M. F. J. Costa, Nabil A. M. Belgacem, Jose Luis G. Rodriguez, Ademola Braimoh, Saleem A. Shaikh, Intikhab Alam, Muhammad Adeel, and Muhammad A. R. Bhutta. Agriculture development, pesticide application and its impact on the environment. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7908628/, 2021. International Journal of Environmental Research and Public Health, Vol. 18, No. 3, Article 1112. Accessed: 2025-06-04.

[10] Walter de Freitas Lemos, Maria Aparecida Castellani, João Carlos da Silva, and Ana Gabriela Lemos. Biological aspects and population parameters of the grasshopper ronderosia bergi (stål) (orthoptera: Acrididae). *Journal of Insect Science*, 10(1):92, 2010.

[11] Angela Turner and Chris Rose. *A Handbook to the Swallows and Martins of the World*. Christopher Helm Publishers, London, 1989.

[12] Paul Hormick. Bat pups, 2023. Accessed: 2025-06-05.

[13] Anthony Joern and Kyle A. Benedix. How often are ecosystems top-down controlled? experiments in grassland grasshopper and bird systems over time and space. *Ecological Monographs*, 84(4):559–576, 2014.

[14] The Committee on the Status of Endangered Wildlife in Canada(COSEWIC). Cosweic assessment and status report on the barn swallow hirundo rustica in canada. *COSWEIC*, 2011.

[15] Eva M Bernhard, Merritt R Turetsky, et al. Consequences of permafrost thaw for boreal forests. *Nature Communications*, 9(1):1–11, 2018.

[16] Wikipedia contributors. List of bats by population. https://en.wikipedia.org/wiki/List_of_bats_by_population, 2025. Accessed: 2025-06-07.

[17] Abida Nasreen, Muhammad Ashfaq, Ghulam Mustafa, and Rashad Khan. Mortality rates of five commercial insecticides on chrysoperla carnea (stephens) (chrysopidae: Neuroptera). *Pak J Agr Sci*, 44, 01 2007.

[18] Tom Getts and Tracy Schohr. Grasshoppers. Fact sheet, University of California Agriculture and Natural Resources, May 2022.

[19] USDA Agricultural Research Service. Bigheaded grasshopper (*Aulocara elliotti*) fact sheet. https://www.ars.usda.gov/ARSUserFiles/30320505/grasshopper/Extras/PDFs/Species%20Fact%20Sheets/Bighead.pdf, 2002. Accessed: 2025-06-10.

[20] Linda deKort. Barn swallow – bird of the month. Flathead Audubon Society Website, November 2014. Accessed: 2025-06-14.

[21] United States Department of Agriculture. Bats. The People's Garden – Importance of Pollinators, 2025. Accessed: 2025-05-28.

[22] Bill Dowd. North york wildlife: How long do bats stay out at night? Skedaddle Wildlife Control North York Blog, September 2019. Accessed: 2025-06-14.

[23] Stefan Hauser, Dominique Mulumba Munkendi, Robert Mukendi Kamambo, and Germaine Vangu Paka. Maize, soybean and cassava yield response to bat manure in congo democratic republic. In [if available] Georg, editor, *Resilience of Agricultural Systems Against Crises*, page Abstract, Göttingen – Kassel/Witzenhausen, Germany, September 2012. Tropentag. Tropentag, September 19–21, 2012.