

Modeling Eastern Equine Encephalitis in Massachusetts

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The Spread of EEE

Research Goals

This study proposes an interactive multi-species SIR system of equations to model the spread of Eastern Equine Encephalitis over the time period of one summer or 90 days. This is achieved via three distinct SIR equations for the Bird, Mosquito, and Human species.

- Understand the spread of EEE across different species
- Develop a graphical analysis of disease outcomes in humans

The Three Species Model

Corresponding Compartment Diagrams (Right) for species-dependent equations (Left). Depicted in descending order: Bird, Mosquito, and Human species.

Birds:

$$\dot{S} = -b_B S_B \left(\frac{I_M}{N_M} \right)$$
$$\dot{I} = b_B S_B \left(\frac{I_M}{N_M} \right)$$

F1 is the rate at which birds are becoming infected.

Mosquitoes:

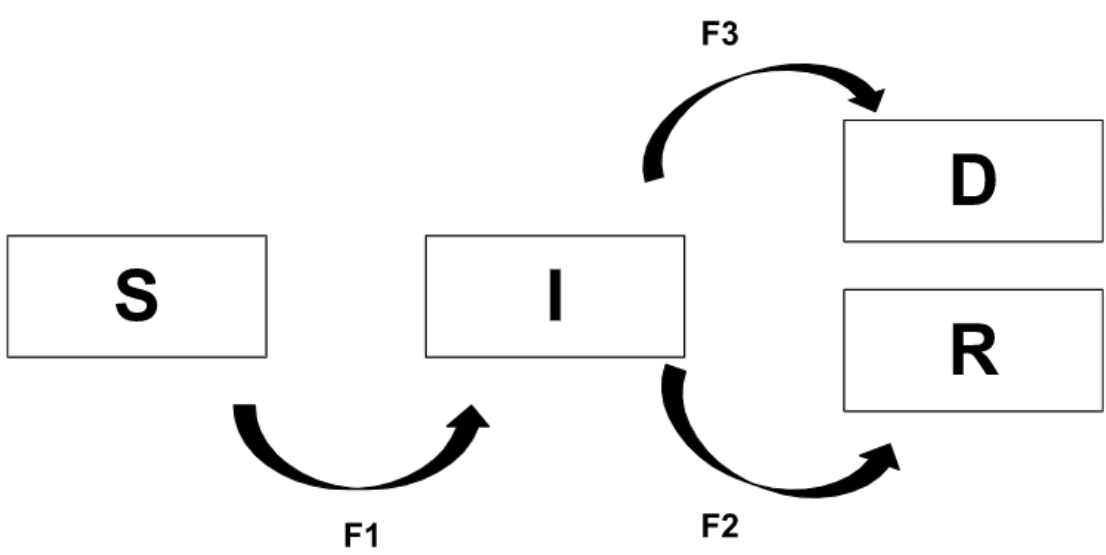
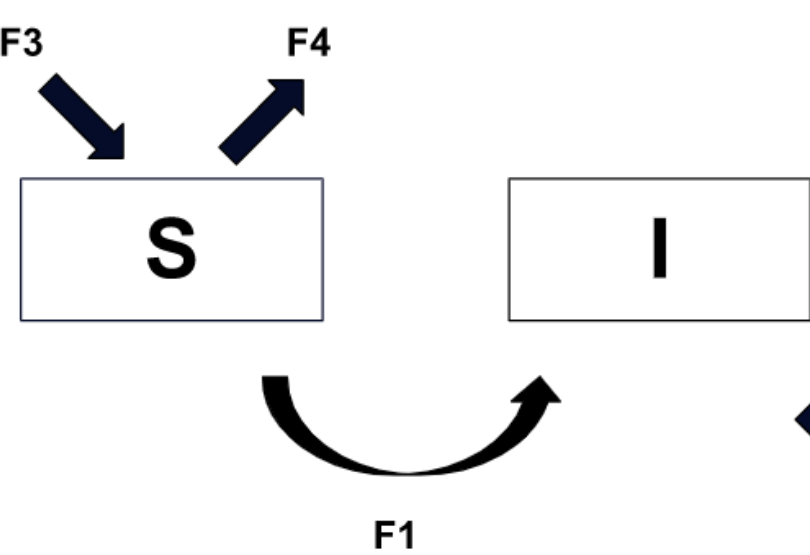
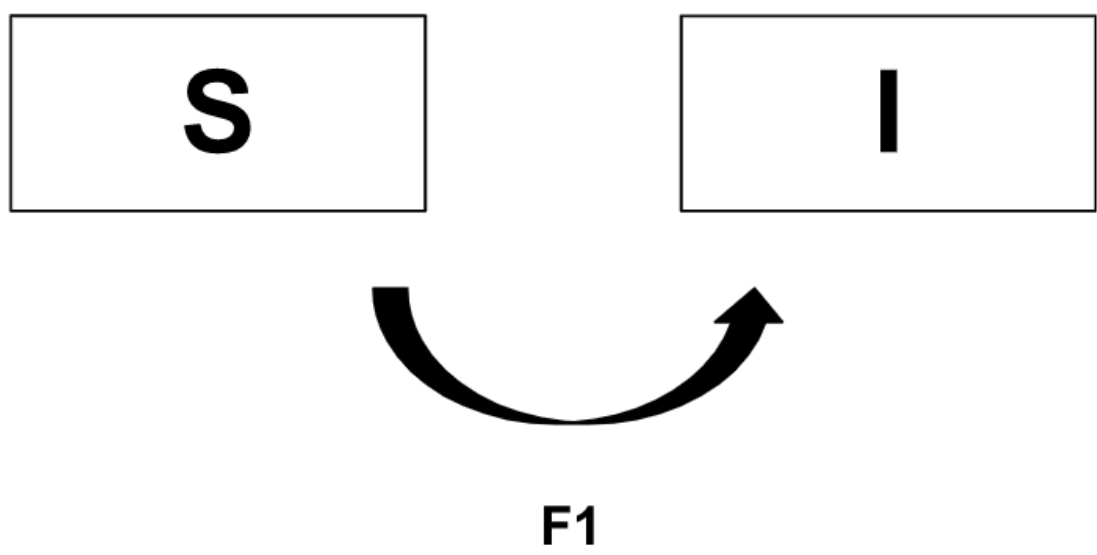
$$\dot{S} = -b_B S_M \left(\frac{I_B}{N_B} \right) + N_M \rho - S_M \nu$$
$$\dot{I} = b_B S_M \left(\frac{I_B}{N_B} \right) - I_M \nu$$

F1 is the rate at which mosquitoes are biting infected birds. **F2** is the rate at which infected mosquitoes die. **F3** is the rate at which new mosquitoes are born. **F4** is the rate at which susceptible mosquitoes die.

Humans:

$$\dot{S} = -b_H S_H \left(\frac{I_M}{N_M} \right)$$
$$\dot{I} = b_H S_H \left(\frac{I_M}{N_M} \right) - \gamma_H I_H$$
$$\dot{R} = 0.59 \gamma_H I_H$$
$$\dot{D} = 0.41 \gamma_H I_H$$

F1 is the rate at which infected mosquitoes bite susceptible humans. **F2** is the rate at which infected humans recover. **F3** is the rate at which infected humans die.



Most Important Model Assumptions for Disease Transfer to Humans:

- No natural births or deaths for human or bird populations, but mosquito populations are subject to change due to short lifespan
- EEE is only fatal for humans, not birds
- Only Humans are capable of recovery
- EEE is exclusively vectored by mosquitoes
- Mosquitoes are continually vectors after biting infected birds
- The mosquito population grows by 120% every day (see justifications)

Initial Conditions and Variable Values

b_b	Rate birds are bitten	4
b_h	Rate humans are bitten	0.25
ρ	Birth rate of mosquitoes	2.2
ν	Death rate of mosquitoes	0.33
γ	Fractional recoveries per day	0.095
B_S	Initial susceptible bird pop.	$1.64 * 10^8$
B_I	Initial infected bird pop.	1
M_S	Initial susceptible mosquito pop.	$1.12 * 10^8$
M_I	Initial infected mosquito pop.	0
H_S	Initial susceptible Human pop.	$7 * 10^6$

Table 1. Values of variables and initial populations used to estimate the model's behavior

Justifications of parameter values

- Mosquitoes bite about four birds a day. Mosquitoes bite about one human every four days. [3]
- Mosquitoes lay 100 eggs twice a season, which is averaged over 90 days [4]
- A mosquito has a life span of three days which implies that a third of the population dies per day [4]
- The average time spent infected for humans is 10.59 days. $\gamma = 1/10.59$ [2]
- There are 7 million people in Massachusetts with the estimated ratio of mosquitoes to humans being 16000 : 1 [1]. We estimated that the Black Tailed mosquito population is only 0.2% of the total global mosquito population, and only females bite. Females make up half of the Black Tailed mosquito population.
- The ratio of all mosquitoes to all birds is about 680 : 1. [5]

Results

- Runge-Kutta 4 approximation of the three populations over a period of 90 days with a step size of 0.1.

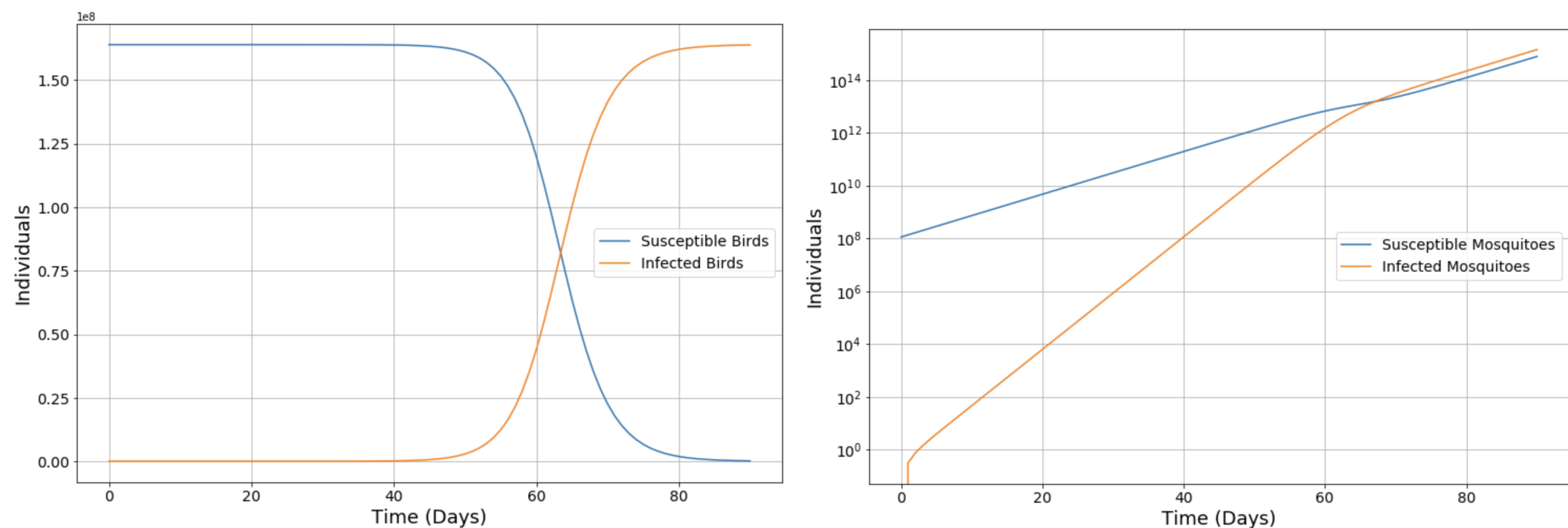


Figure 1. Approximation of the Bird population (Left) and the Mosquito population (Right), with the y-axis shown in Log scale, over 90 days

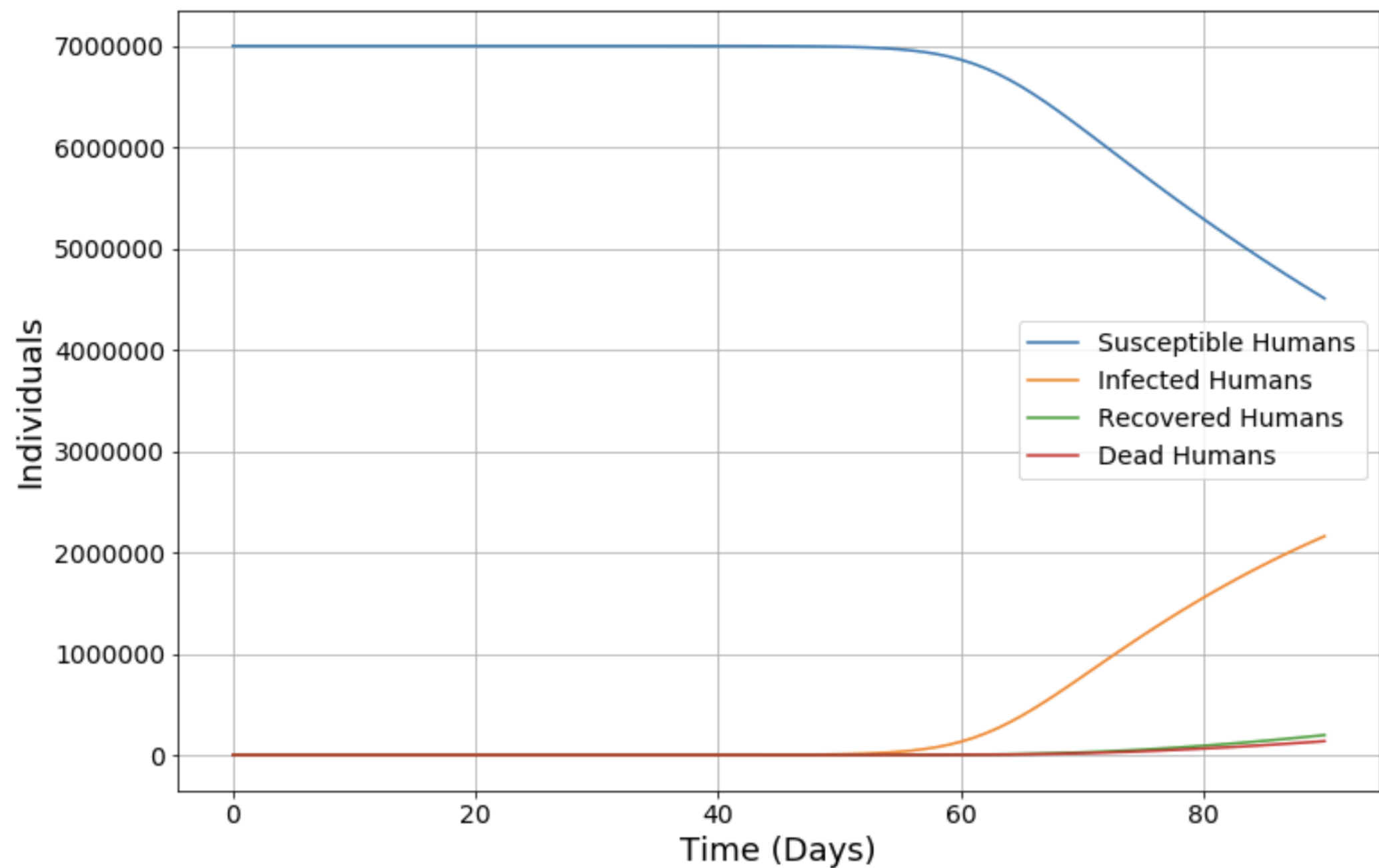


Figure 2. Approximation of the Human Population over 90 days ($b_H = 0.25$). Just over 4.5 Million remain susceptible, just over 2 Million become infected, just under 200, 000 recover, and just under 140, 000 die after 90 days.

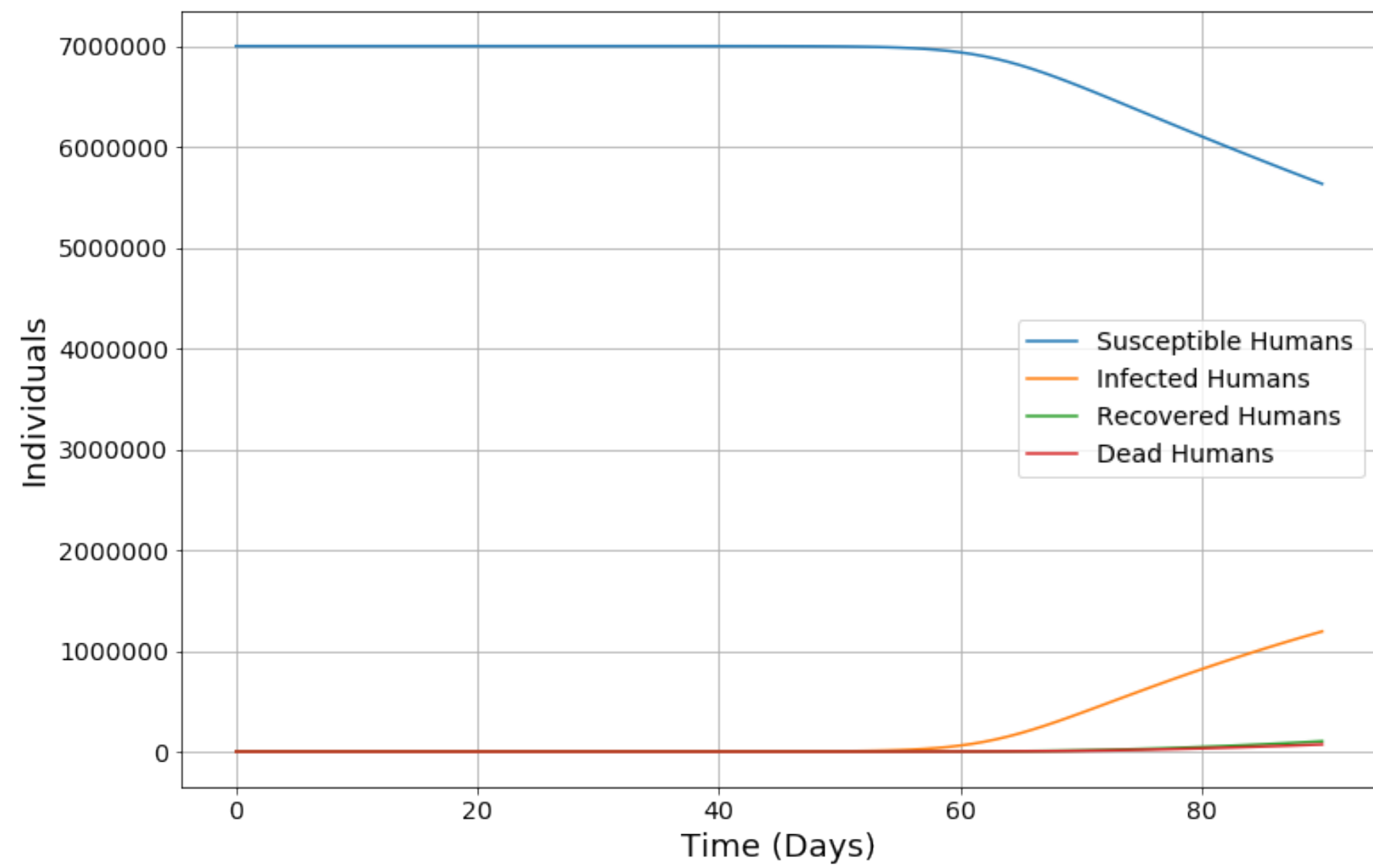


Figure 3. Approximation of the Human Population over 90 days ($b_H = 0.125$). Just over 5.6 Million remain susceptible, just under 1.2 Million become infected, just over 100, 000 recover, and just over 70, 000 die after 90 days.

Conclusions

- Over a third of the population contracts EEE in our model, significantly larger than the average of 5 reported cases per year in Massachusetts [2].
- Number of infections among humans stays near zero for most of the summer until an outbreak around day 60.
- A rise in bird infections is the most accurate predictor of human infections and mortality.
- The interaction between species and the difference in the mosquito population at the end of the summer compared to the beginning explain why the peak of the outbreak is later than what is typically seen in single species SIR models where population growth is not a factor.
- Figures 2 and 3 exemplify that actions should be taken to decrease human-mosquito interaction and thereby lessen the effect of the disease.

Next Steps

Implement a carrying capacity and natural birth rates for the mosquitoes, so the mosquito population does not grow without bound. Our predicted mosquito population had a magnitude of about 2^{14} individuals for this single specific species only in the state of Massachusetts, compared to about 2^{14} mosquitoes worldwide.

We generalized research about mosquito feeding preferences from another species to the species that transmits EEE. However, this species does not bite humans as much as some others, so future models should have a lower value for the parameter b.

Add a recovered compartment to our model of the bird population so the population of infected birds stabilizes leading to a less severe outbreak among humans.

Vaccines for birds are available, so we could incorporate vaccination for birds into our model and look at the change in infection rates among all populations.

References

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- [5] Main, Douglas. "How Many Birds Are There in the World?" National Geographic, National Geographic, 17 May 2021, www.nationalgeographic.com/animals/article/how-many-birds-are-there-in-the-world-science-estimates, Accessed 8 May 2023