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Simulating Foodborne Pathogens in Poultry Production and Processing to Defend Against Intentional Contamination

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Running Title: Simulating Pathogens in Poultry Production

Abstract

There is a lack of data in recent history of food terrorism attacks, and as such, it is difficult to predict its impact. The food supply industry is one of the most vulnerable industries for terrorist threats while the poultry industry is one of the largest food industries in the United States. A small food terrorism attack against a single poultry processing center has the potential to affect a much larger human population than its immediate consumers. In this work, the spread of foodborne pathogens is simulated in a poultry production and processing system to defend against intentional contamination. An agent-based simulated environment that represents the farm, processing plant, homes, and restaurants is developed, which contains both poultry and human agents that move through the system and possibly infect each other. The simulation is run by varying several parameters that include probability of infection if exposed for both poultry and humans. The simulation predicts the number of infected poultry and humans over time.

Introduction

Often overlooked as a contingency, the food supply sector represents a substantial risk in human safety and healthy lifestyles. While safe transportation and regulation is being pursued heavily after the events of September 11, 2001, there is considerable uncertainty in the ability to prevent or halt food terrorism, defined as "an act or threat of deliberate contamination of food for human consumption with biological, chemical, and physical agents or radionuclear materials for the purpose of causing injury or death to civilian populations and/or disrupting social, economic, or political stability" (Setola and Maggio 2009). Tommy Thompson, the Secretary of the Department of Health and Human Services, even hinted toward the unpreparedness of the United States in regard to food terrorism when he resigned, stating, "I, for the life of me, cannot understand why the terrorists have not . . . attacked our food supply because it is so easy to do" (Roberts 2006).

There is a lack of data for intentional contamination and possible outcomes due to lack of actual attacks making it past the initial target; however, a biological attack has potential to affect a larger population as a whole. This lack of data makes preparing for food terrorism difficult (Layfield *et al.* 2008).

The top three most important foodborne outbreaks of 2016 include *Salmonella* linked to poultry, *Listeria* linked to frozen vegetables, and hepatitis A from raw scallops (Flynn 2016). CDC's FoodNet monitors foodborne diseases from ten United States cities and in 2016 identified 24,029 infections, 5,512 hospitalizations, and 98 deaths caused by foodborne pathogens (Marder *et al.* 2017). The FoodNet surveillance network does not track all cases in the United States (CDC 2017) and the most recent estimate of the total number of cases is from a 2011 study (Scallan *et al.* 2011). Foodborne morbidity and mortality associated with pathogen contamination of the United States food supply results in an estimated 48 million cases, of which 128,000 are hospitalized and 3,000 are fatal (Handley *et al.* 2015; Scallan *et al.* 2011). This estimation means that approximately 15% of the United States population is affected with a foodborne illness every year. Of all these illnesses, salmonellosis is one of the most common, costing $3.3 billion annually in medical bills and productivity loss in the United States (Handley *et al.* 2015). These are most likely not intentional contaminations, but it begins to shine some light on how vulnerable the industry could be if an intentional attack slipped through the cracks.

Poultry products rank in the upper echelon of commonly consumed foods, globally, and in the United States, poultry began surpassing beef consumption after 2010 (Handley *et al*. 2015). In 2013, the United States

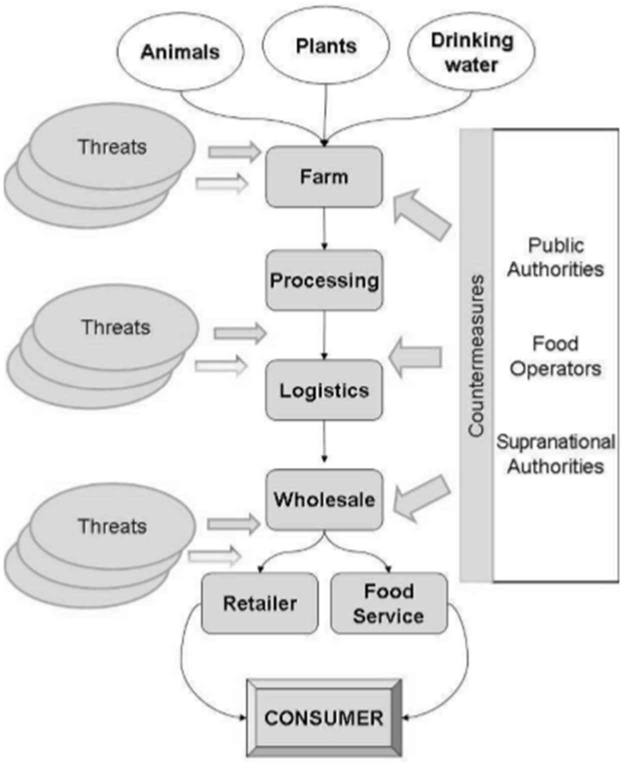

Figure 1: The general poultry food supply chain (Setola and Maggio 2009).

measured in at 639.6 million pounds of broiler meat shipped (Handley *et al*. 2015). As one of the largest sources of food in the United States, poultry is a top contender for possible food terrorism targets. There are also many vulnerable entry points for threats between each processing step as shown in Figure 1.

Even if a foodborne illness threat is neutralized quickly, traced back to the source, and taken off the shelves, if there were some people affected, there is still the possibility for contagious varieties of pathogens to be passed around to other people.

Methods

Overview

The approach taken in this project is to simulate the spread of foodborne pathogens among poultry and humans using an agent-based simulation model. The simulation steps are: use a focused software suite specifically for agent-based simulation, choose common and substantial pathogens to simulate, and determine agents such as chickens and humans.

The software suite chosen for this project is NetLogo, a robust modeling environment for designing agent-based simulations (Wilensky 1999). In NetLogo, each agent is programmed with a set of rules for actions such as movement around patches and interactions with other agents. It comes with disease models (Rand and Wilensky 2008) and has been used for modeling the immune system (Chiacchio *et al*. 2014).

In the United States, it is estimated that 31 different pathogens end up causing 37.2 million morbidity and mortality with 9.4 million of them being foodborne. *Salmonella* is one of the most common pathogens in the United States at 1 million estimated annual morbidity and mortality cases, 19,000 estimated annual hospitalizations, and 380 estimated annual fatal cases (Scallan *et al*. 2011). As prominent as it is, *Salmonella* was chosen as a starting point for gathering meaningful simulation data. The Center for Disease Control and Prevention (CDC) would be considered a good primary resource for further pathogen selection.

Having a software suite and pathogen to study is only half of the simulation: the simulation also requires the interacting agents, for example, poultry and humans in the current case. The simulation distinguishes different demographics in the humans, as there are varying susceptibilities to *Salmonella* and other pathogens. For example, the age of a given population will affect how easily the illness affects the agent. In addition to the varying demographic, the project manipulates the infection rate based on how much exposure to the food pathogen sources occurs when they are being consumed. For example, it is necessary to consider a specific population's frequency in eating out of home to adjust the exposure of certain pathogens. Human agents were divided into three age groups: young, middle, and old based on differing susceptibility to the given pathogen, *Salmonella*.

During the different parts of production, as shown in Figure 1, the poultry have multiple opportunities to encounter the pathogen. As they get further along the supply chain, through processing, logistics, and consumption, the poultry are moved around in groups (not autonomously roaming) and may come into contact with other poultry who in turn may also become infected. As the poultry are moved to wholesalers, stores, or restaurants, they may come in contact and infect humans based on exposure to the infected poultry.

NetLogo Overview

NetLogo identifies various groups of agents with their individual behaviors and frees them to disperse and engage in an interactive environment (Wilensky 1999). Simulations are comprised of turtles, the moving and acting agents in the simulation, and patches, the space in which the turtles move and interact.

The turtles are sectioned into differing breeds that have different rules and variables to act under. These different breeds then move around and can be set to behave in specified ways depending on what breed with which they are interacting.

The patches act as a grid that the turtles are set to move around and possibly interact with other turtles. Each patch can have different properties that affect turtles and perhaps other patches.

Every time tick, there is a loop that goes through each turtle and tells them to do their next step in the simulation. The ticks can represent any appropriate unit of time such as seconds, minutes, hours, or days. Ticks can be slowed down or sped up to focus on specific areas of the simulation or to generally speed things up to gather a greater quantity of data.

Breeds, Patch Types, and Customizable Properties

For this project, there are 2 different breeds of turtles and 4 different kinds of patches. Turtles can be either poultry (plural poultry) or person (plural people) as shown in Figure 2. Both breeds may also be gray, signifying a pathogen infection, or black, indicating no infection. There are four different kinds of patches representing the farm, processing plan, restaurants, and houses.

Both the person breed and poultry breed have a member variable for infection. When true, the person or poultry will change from its normal color variation (black) to its infected color (gray). There is also an infection modifier variable set upon turtle creation that can manipulate the probability for that person/poultry to be infected. The infection modifier mostly comes into play for differing age groups of people since there are varying susceptibilities to pathogens.

The poultry breed has properties to help identify which part of the supply chain it should be in currently. There is a counter variable to keep track of how long it has been in its current section. There are also two Boolean properties, alive and processed, to identify which sections the poultry have already visited. If the poultry are not alive, then they have already been slaughtered, etc.

The person breed has four separate properties: age group, infection timer, house number, and restaurant timer. The age group property determines the turtle property infection modifier. People have an adjustable infection timer to specify how long they are infected with pathogens such as *Salmonella* that are typically fought off after a week's time. The house number is the number of the house to which each person is assigned. The restaurant timer is for counting down how long a person has been in a restaurant.

Figure 2: Poultry and persons colored black indicate no infection, while poultry and persons colored gray represent a pathogen infection

The four different patch types do not act by themselves, but they do affect the actions of the turtles on them. Turtles check the kind of patch they are on and act accordingly. For instance, when on the farm patch, the poultry breed roams around randomly. While on the processing patch, the poultry stay in the position they are assigned. Both breeds stay stationary on the restaurant patch. The person breed stays stationary while on the house type. The farm patch type includes a large area to allow the poultry to move around freely. The processing patch type also includes an area, although it is much smaller than the farm type. The restaurant and house patches are setup to be individual patches that count the number of people currently in that patch.

In addition to all the specific properties for turtles, there are a variety of sliders easily changed in the user interface. These sliders include the following: setting the number of people in the simulation, the number of houses and restaurants, the frequency people visit restaurants, the infection duration, the probability of poultry infecting people on the same patch or poultry on the same patch, the initial number of poultry, and the spawn rate of poultry.

Workflow

The simulation is loosely based off Figure 1 and the simulation flow diagram is shown in Figure 3, with the poultry trickling down through steps where threats can be inserted, finally landing in a patch with the consumers. Prior to the simulation starting, or any time during the simulation, the user can select poultry to "get-infected". This is how intentional contamination is simulated.

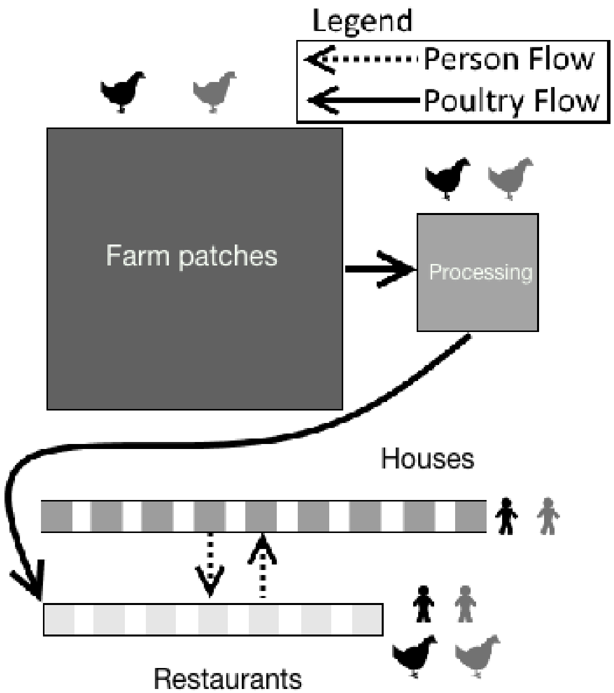

Figure 3: Simulation flow diagram of the flow of poultry and persons in the simulated environment consisting of the farm, processing plant, restaurants, and houses. See Figure 2 for legend.

When the simulation is initiated, there is a set number of poultry provided by a slider. These poultry are placed in the large farm patch section. There is also a spawn rate for poultry to be continuously added to the farm patch section to simulate continual poultry breeding. Each poultry has a timer and, when it reaches a threshold, it moves to the next section. This timer is meant to simulate a poultry's growth cycle before being butchered. During its time in the farm patch section, each simulation tick, poultry randomly select a direction around them in a 360-degree radius and move forward one patch. If there is an infected poultry on a given patch, there is a probability, modified by slider, for other poultry on the given patch to also become infected.

The second section poultry move to after their counter is expired is the smaller processing patch section. Unlike the farm patch section, once a poultry is assigned a specific patch in the processing plant patch section, the poultry does not move. Multiple poultry can be placed on one patch. This is meant to represent groups of poultry being close together during the processing stage while not really being in contact with some other groups. If there is a poultry on a given patch that is infected, there is a probability of infecting other poultry on the same patch at each simulation tick. A new counter is started for each poultry when moved to the processing patch section.

The third and final section for poultry is the restaurant. After a poultry's processing plant section timer reaches a threshold, the poultry is moved to a randomly selected restaurant. A final countdown is started once moved to a restaurant, and the poultry is deleted at the end of this timer to simulate the poultry being consumed. If there is an infected poultry in a restaurant patch, there is a probability every tick that any poultry or person in that restaurant patch will also become infected.

The person turtles simply alternate between the house patches and the restaurant patches. An initial number of people is set before the simulation setup and the number of people never changes throughout the simulation. When a person is created, it is assigned a house patch to which it will always return. While on a house patch, people can be set to have a chance to infect the other people in the house, or the slider can be moved all the way to make 0% of people infecting each other.

Every tick, there is a probability, set by slider, that each person will go to a randomly selected restaurant patch. These are the same restaurants that poultry can be sent to during their final step. If there is an infected poultry in a restaurant, it has a probability of infecting the person that has arrived at the restaurant. This is the driving interaction of people becoming infected from the infected food supply. If people are set to be able to infect each other, a person may become infected by another person visiting the restaurant. The amount of time that people stay in restaurants can be set by slider and adjusted to better simulate the shorter duration of restaurant visit and longer duration of staying at home.

Results

The developed simulations can visualize and quantify multiple scenarios with varying parameters. For example, a plot that shows the number of uninfected (healthy) people along with the number of infected people with three infection rates is shown in Figure 4 and a plot that shows the number of uninfected poultry along with the number of infected poultry with three infection rates is shown in Figure 5. Both plots update every tick in the simulation and can easily be exported to a spreadsheet to conduct further analysis.

Figure 4 shows three different sections of time that had differing infection probabilities in people. The section with the line labeled with a “1” shows a 0.1% poultry-to-people infection probability per tick, section “2” shows a 2.5% infection probability, and section “3” shows a 5.0% infection probability. The data changes in real time as adjustments are made to the simulation sliders. It is clear to see that the difference between 1% and higher percentages is strong while the doubling from 2.5% to 5.0% makes a much smaller difference

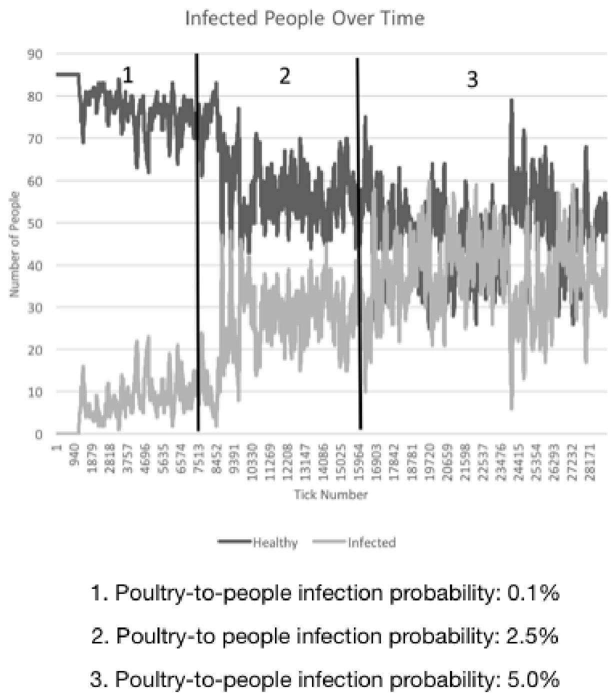

Figure 4: Number of infected people over time with different poultry-to-people infection probabilities

Figure 5 shows the number of poultry at three different periods of time that had differing poultry-to-poultry infection probabilities. Section “1” shows a poultry-to-poultry infection probability of 5.1%, section 2 shows a 10% probability, and section 3 shows a 30.05% probability. The sections over 5.1% show a significant increase in infection. While 10% and 30.05% probabilities do not differ much in terms of maximum amount of poultry infected at one time, 30.05% probability shows a much less varied graph.

Conclusions and Future Work

A food supply chain intentional pathogen injection simulation was built using the NetLogo agent-based modeling simulation software for a poultry production and processing system. These simulations can help

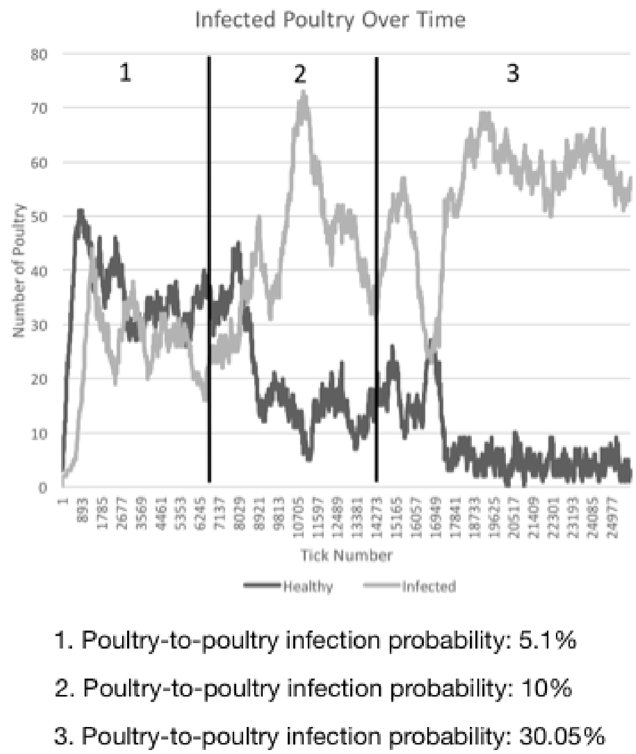

Figure 5: Number of infected poultry over time with different poultry-to-poultry infection probabilities

prevent food terrorism by predicting the spread and effect of foodborne pathogens including the number of infected poultry and the number of infected people over time with varying probabilities of infection. The simulation is loosely based on the poultry food supply chain, but it can be improved in the future by adding more stages in the production and processing, simulating the use of antibiotics and cleaning methods, and by using more accurate epidemiological models to create a more realistic simulation of the system. In addition, another category of highly susceptible people such as cancer patients on chemotherapy could be added. It would be interesting to compare and contrast an actual paired set of demographics for example a suburban Florida community with more retirees compared to an inner-city area with younger people. Finally, once a more detailed model is developed, it could be validated by comparing it with an actual well-documented outbreak.

Acknowledgements

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