# Simulating Foot-and-Mouth Disease in the United States using the Animal Disease Spread Model

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## ABSTRACT

The United States Department of Agriculture, Animal and Plant Health Inspection Service, Veterinary Services, Center for Epidemiology and Animal Health (USDA–APHIS–VS–CEAH) addresses questions related to minimizing the consequences of animal disease outbreaks while protecting our nation's livestock, food supply, and the environment. Using a variety of modeling tools, analysts evaluate alternative control strategies, provide recommendations on planning and effective use of resources, develop surveillance strategies, and estimate the economic impacts of disease control options. The Animal Disease Spread Model is a stochastic, spatially explicit compartmental model that simulates herd-to-herd spread of a highly contagious animal disease. An example of the use of this model to explore control options for a hypothetical outbreak of foot-and-mouth disease will be presented to highlight how simulation methods can provide information for decision-makers.

## ABOUT THE AUTHORS

**Melissa Schoenbaum** is a biological scientist with the USDA–APHIS–VS–CEAH-Monitoring and Modeling unit. She received her BS in biological sciences from East Texas State University and her MS in computer information technology from Regis University. She serves as the modeling team's data management specialist.

**Dawit Assefa** is a Program Analyst with the USDA–APHIS–VS–CEAH-Monitoring and Modeling unit. He received a BA in economics and an MS in computer information system from Colorado State University, with an emphasis on business intelligence. He performs data visualization, validation and cleaning functions using a multitude of software.

**Josiah Seaman** is a software developer working in bioinformatics with a specialty in data visualization. He has a BS from Colorado State University in computer science and is working on a PhD in genetics at Kew Royal Botanical Gardens. Josiah designed a genome visualization program called DNASkittle and founded Newline Technical Innovations. He works with others at Newline on science and automation tools.

**Lindsey Holmstrom** is a veterinary epidemiologist with the USDA–APHIS–VS–CEAH-Monitoring and Modeling unit. She received her BS in economics from Baylor University, her doctorate of veterinary medicine (DVM) degree from the College of Veterinary Medicine at Texas A&M University, and her Ph.D. in veterinary epidemiology from the University of California, Davis (awarded March 2017). As part of the modeling team, she helps advance and apply epidemiologic models to develop scenarios involving disease spread, alternative control strategies, and associated impacts.

**Amy Delgado** currently serves as the director of the Monitoring and Modeling Unit of the USDA–CEAH in Fort Collins, CO. Her work focuses on providing scientific support for emergency response planning for trans-boundary animal diseases. Dr. Delgado received a B.S. degrees in animal science prior to receiving her DVM and Ph.D. in epidemiology from Texas A&M University.

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## SIMULATING ANIMAL DISEASE OUTBREAKS

When a disease is absent from a population, modeling offers a useful method to simulate the spread of disease and evaluate control measures to manage an outbreak. The Animal Disease Spread Model (ADSM) is a stochastic, spatially-explicit compartmental software application that simulates herd-to-herd spread of a highly contagious animal disease. Models such as ADSM allow decision-makers to compare strategies based on their costs and effectiveness in controlling disease.

The recently developed ADSM is based on the North American Animal Disease Spread Model (NAADSM), which was developed as a collaboration between USDA, the Canadian Food Inspection Agency, the University of Guelph, and Colorado State University (Harvey, et al 2007). ADSM shares the same code with NAADSM but with several added functionalities. Like NAADSM, ADSM is flexible enough to simulate a variety of disease conditions, with an emphasis on highly contagious diseases that spread through some form of contact. The user can apply a variety of control measures, such as vaccination or depopulation of infected farms, to influence the outbreak. For the purposes of this example, we used a previously developed NAADSM scenario, implemented in ADSM, in order to demonstrate a mature proof-of-concept in the new application. This paper presents a description of the application and an example of the use of ADSM to evaluate a control strategy for a severe, hypothetical outbreak of foot-and-mouth disease (FMD) in the United States. At this time, ADSM is in beta testing with an expected release in fall 2017.

## OVERVIEW OF ADSM TECHNOLOGY

The ADSM software architecture is divided into several components. The core simulation logic is referred to as the "C Engine". The C Engine has been supporting NAADSM since its release in 2006 and has been exercised extensively by researchers around the world. This component is the shared layer of code between ADSM and NAADSM. It is written in C and highly optimized for running large batch simulations. As implemented in ADSM, the C Engine takes as input a SQLite database file containing all the parameters for the scenario. As it runs, the simulation adds outputs to the database file, ensuring results are never separated from the parameters that created them. Scenarios exported from NAADSM as XML files can be imported into ADSM, so that projects can be converted and will continue to work on the new platform.

The front-end user interface is built from the ground up on web technology to run on all platforms. Django web framework and Python were used for the interface. The application is presented in a browser window. When the user has an internet connection, a linked glossary defining parameter inputs is accessible. The interface provides visual cues as users parameterize the scenario. Parameters are broken up by topic: population, disease, and controls. Details of each section are also divided into reusable pieces. A major difference from the earlier NAADSM user interface is that users now create a block of parameters, named with a context appropriate name, and then assign where those parameters apply.

Users can run one or many iterations of a scenario. While a batch of iterations is running, the interface provides live statistics on the current results. Results can be accessed is several different ways. Immediately upon completion, users can view and browse detailed outputs from the user interface showing the distribution of all tracked variables across all iterations. SQL queries can be used to access the raw data from the tables in the SQLite database. Several supplemental outputs can be created as .csv files if the user selects those options.

ADSM user interface is built on web technology to enable easy maintenance and upgrades in the future as well as opening up a number of new usage options. The ADSM server is compiled for Windows and Linux machines. The server can be run locally on a single computer, or hosted on a supercomputer on the same LAN. ADSM uses multithreading to maximize system utilization and get results back promptly. The Chrome browser can be used on any desktop computer to run simulations on the server. For example, an epidemiologist may use a Windows machine to run simulations on a Linux supercomputer without any issue.

Currently everyone with access to a specific server shares a single file store. User logins and permissions systems are planned for a future release of ADSM. The current architecture is poised to be used as a cloud-based service after user separation is implemented. This would enable a central parameter library, contributed by experts in their subject areas, which could be quickly queried in order to assemble scenarios. For studies of how parameters affect outcomes, variants can be built from existing scenarios.

## WHY FOOT-AND-MOUTH DISEASE IS IMPORTANT

FMD is an economically important disease due to anticipated response program costs that can range from millions to billions of dollars and market effects, namely trade embargoes on meat and livestock by international trade partners that can bring anticipated economy losses into the tens of billions of dollars (Thompson et al., 2002; Carpenter et al., 2011). The effects of an event would be distributed among many parties domestically including producers, consumers, service providers, and the government. Generally trade bans are expected to be a major driver of total economic loss associated with FMD (Paarlberg et al., 2003). A confirmed outbreak would trigger border closure for U.S. exports until such time as disease-free status was regained, although bilateral trade relations would determine the actual speed of markets reopening. For a country that sells a great deal of meat and livestock to international markets, the economic damage from FMD can be marked.

The United States' last experience with FMD was in 1929, leaving little available data to reference in dealing with an outbreak. Traditional emergency response has focused on strict movement restrictions and the rapid slaughter of infected and exposed livestock (Gibbens et al., 2001; McLaws and Ribble, 2007). In the case of FMD, the application of vaccination, with or without the subsequent destruction of vaccinates, has also been applied or explored in many countries (Bates et al., 2003; Perez et al., 2004; Kitching et al., 2007; Barasa et al., 2008; Estrada et al., 2008). Emergency response exercises have recognized issues associated with a traditional stamping out (S-O) response to FMD in large feedlots, as depopulating and disposing of large numbers of animals is logistically and environmentally challenging. Alternative methods are needed for minimizing disease spread while allowing animals to reach their intended purpose. As such, modeling applications such as ADSM provide useful tools to decision-makers to evaluate different control strategies and plan for response before an outbreak occurs.

## USING ADSM TO MODEL FMD

The example presented in this paper is based on a previous analysis which used NAADSM in combination with the Paarlberg model (Paarlberg, et al 2008) to estimate economic impacts of disease (Delgado et al., 2015) under a variety of strategies. The spread and control of FMD within a 7-state region of the United States was simulated for a variety of strategies. For the purposes of this paper, a single scenario was selected and imported into ADSM. A synthetic population file was generated using the Farm Location and Animal Population Simulator (FLAPS) program, which disaggregated Census of Agriculture data from Texas and surrounding states' livestock operations to simulate their locations (FLAPS, 2013).

For the purposes of this example, the starting location of the outbreak was changed so that disease was introduced in multiple locations on the same day to provide output data from large outbreaks so as to demonstrate ADSM's capabilities for evaluating control options. The resulting simulated outbreaks were often severe with impacts on the agricultural and broader economy. The remainder of the parameters used are consistent with those used by Delgado et al. (2015), which characterize the disease progression, the geo-spatial distribution of the susceptible population, the spatio-temporal interactions of farms within the population, and the control measures applied to the different farm types.

## OVERVIEW OF ADSM

ADSM manages the 3 components necessary to simulate an animal disease outbreak: the susceptible population and their interactions, the progression of disease and subsequent transmission, and options for disease detection and control. First, the group of domestic livestock or poultry farms that are susceptible to the specific disease must be organized. Called a “population” in ADSM, these data are provided as a file, including the species and management practice for the animals, the count of animals in the herd/flock, and their geographic coordinates. The application uses “production Types” to define both a species and a purpose for groups of animals, as differences in management practices affect disease spread.

Second, the application uses a set of parameters defining disease progression and transmission. These inputs often vary by production type. Third, the application can simulate control activities, organized into “protocols” that address the specific production types. Parameters may include movement restrictions, contact tracing, zone-based surveillance, euthanasia of infected herds/flocks, and vaccination of specified herds/flocks.

### Population

The population of animals used in this example were from a simulated dataset representing a 7-state region within the United States as shown in figure 1. The full population file contained 363,989 farms. The farms can be loaded into ADSM in the format exported from NAADSM (XML) or loaded as a comma-separated value file. Within the application, the population is visualized on a map and presented in tabular form. Filters and sorting functions are available, which allow users to navigate and explore the population data. Edits to individual farms, such as changing the disease state, can be applied from the population module of the ADSM application.

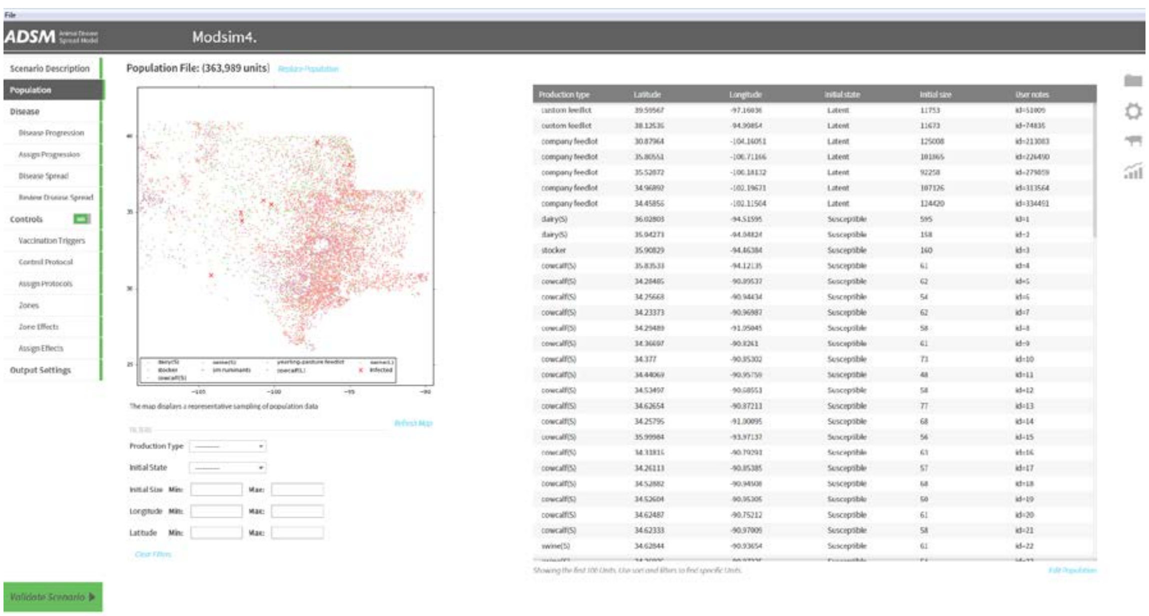


**Figure 1. Population Module**

### Disease

The disease portion of the application is flexible, allowing ADSM to represent several different highly contagious animal diseases. ADSM is a transition state model, meaning farms move between disease states. The disease states include susceptible, latent infection, subclinical infection, and clinical infection. The farm can also be in an immune state, either naturally immune or vaccine-induced immune. Parameters describing the disease states, such as how long a farm may be in a latent disease state, are represented using probability density functions in order to capture the inherent variability in biological processes.

Parameters around transmissibility of the disease are also included. These parameters describe the probability that disease moves between farms that share a contact. ADSM allows these parameters to be built into blocks which are given a user-defined, easily readable name, such as "dairy to dairy direct contact". This parameter block is then assigned to a source production type and a potentially exposed production type- for this example, dairy cattle contacting other dairy cattle.

In creating a matrix of disease spread, developing both the correct set of disease spread parameters and assigning how those parameters allow contact from the source farms to the potential destination farms is complex. In the Review Disease Spread Module shown in figure 2, users are able to visualize the complete matrix of disease spread across all available production types and all disease spread methods. This quick visual reference allows users to quickly identify gaps or errors in the disease spread matrix.


**Figure 2. Review Disease Spread Module**

**Controls**

ADSM provides multiple control measures that are generally used in managing animal disease outbreaks. As with the disease parameters, control parameters are built in blocks with a user-defined, easily readable name. This parameter block is then assigned to one or more production types. These controls describe how disease is detected in the absence of an outbreak, and how surveillance and tracing activities are carried out once the outbreak response process starts. The controls can account for imperfect diagnostic tests, as well as clinical examination of the animals by an owner or veterinarian. Farms may be depopulated in order to control the disease, and parameter settings define the time required for depopulation activities to be completed for each production type. In a large outbreak, delays in control activities are possible, resulting in prioritized waitlists for farms that need activities carried out. Radial, zone-based control measures are also available, and control options in combination with zone enforcement can be applied at the production-type level. Movement controls can be implemented to stop all or specific types of contact between production types. Figure 3 shows the Control Protocol Module with one control measure selected.

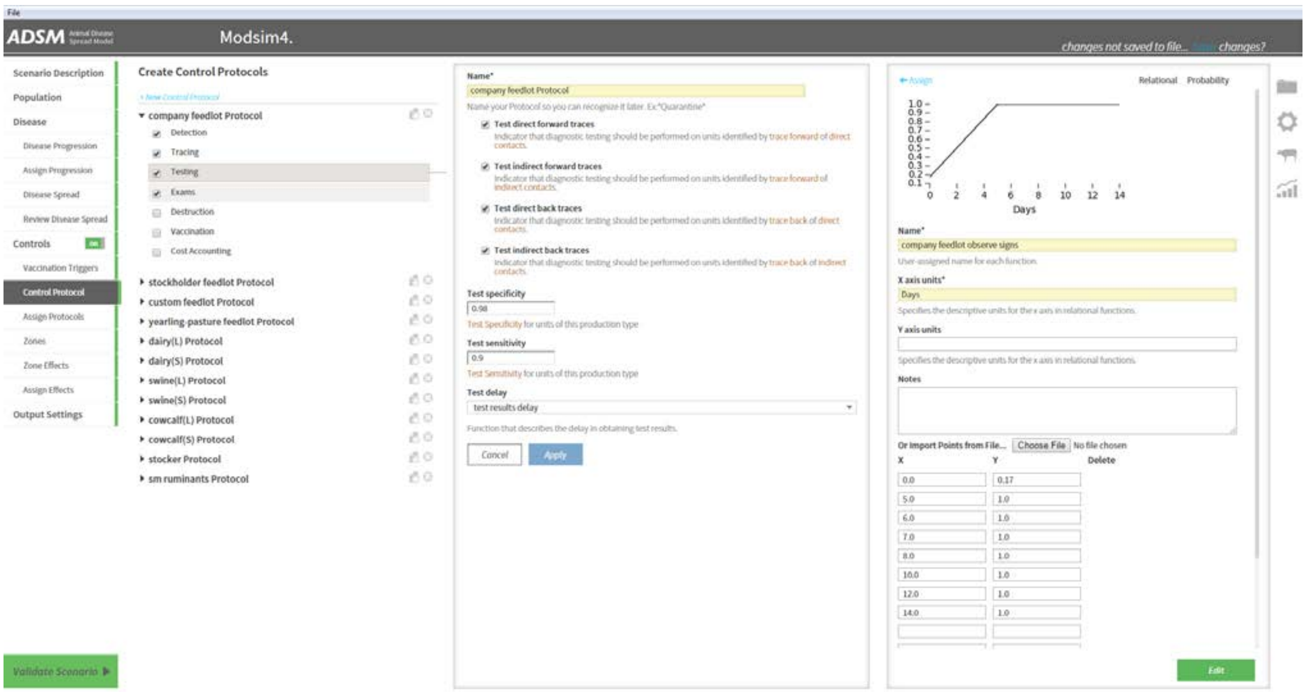


**Figure 3. Example of a Control Protocol with a relational function**

**IMPLEMENTATION AND EXECUTION OF THE FMD MODEL**

In this example, a single scenario was exported from NAADSM and imported into ADSM. The small changes to the starting locations were made (see above), and 500 iterations of the scenario were run. The complete scenario run was completed in 13 hours, with approximately 100 seconds per iteration on a laptop computer.

The summary statistics of the 500 iterations are shown in table 1. Outbreak size ranged from 3 to 86 herds, with an outbreak duration of 24 to 49 days. The number of animals depopulated ranged from 563,189 to 1,722,720. This range in outcomes reflects the stochastic nature of the application and the inherent uncertainty of complex systems. A full dataset is available in the sqlite3 database supporting the application, which can allow users to run statistical summaries and comparisons between scenarios when a variety of strategies are planned for analysis.

**Table 1. Summary Statistics**

| | **Median Value** |
|---|---|
| **Infected Farms** | 25 |
| **Infected Animals** | 338,100 |
| **Infected Farms at First Detection** | 13 |
| **Infected Farms at First Detection** | 199,020 |
| **Depopulated Farms** | 34 |
| **Depopulated Animals** | 946,403 |
| **Duration of Outbreak in days** | 31 |
| **Day of First Detection** | 6 |
| **Total Control Zone Area (km2)** | 25,418 |
| **Total Surveillance Area (km2)** | 61,355 |
| **Number of Control Zones** | 67 |
| **Number of Surveillance Zones** | 41 |

Immediate feedback for the user is available from within the application, providing a high-level overview of the scenario. Dynamic feedback is given as iterations are completed, and once all iterations have finished, a summary map is presented in figure 4. A subset of select, summarized variables is displayed, such as the median number of infected units and the median outbreak duration across all iterations.

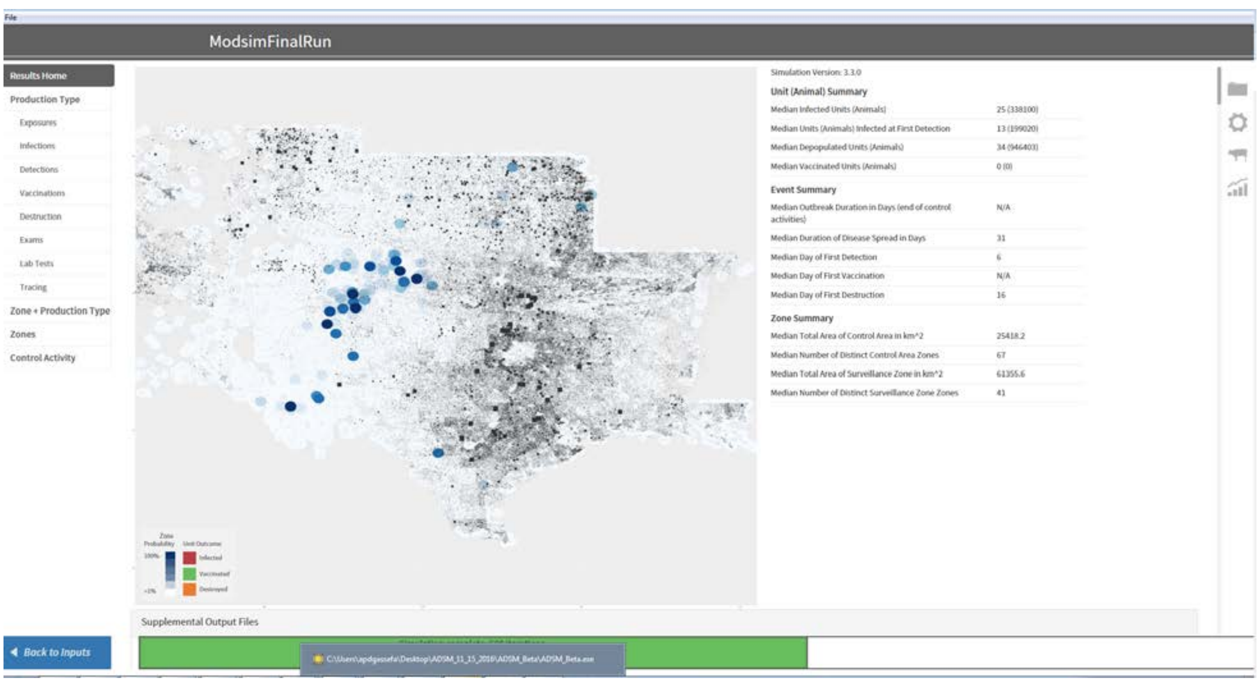


**Figure 4. Map Output and Summary Results**

Users may also drill in to individual variables by navigating down the left menu shown in figure 4. The number of variables presented and graphed individually is dependent on how the scenario was parameterized. They can be viewed as single iteration values or summarized across all iterations, depending on the level of detail needed by the user. This single iteration view can be valuable in exploring an extreme or unexpected simulated outbreak. figure 5 shows the graph within ADSM from one iteration, by production type, with the cumulative number of farm units that were destroyed per day over the duration of the outbreak.


**Figure 5. Graph of Destruction of Units for a single iteration**

## CONCLUSION

ADMS is a flexible and powerful tool to simulate complex disease outbreak events. As shown in this example, the application can easily import and run scenarios from NAADSM, with reasonable run times, dynamic output visualization, and complex disease control options to explore. Users have access to a large, rich dataset of outputs for further analysis and comparison, allowing for the development and examination of many “what if” scenarios. In addition, new approaches that allow users to develop and reuse parameter blocks increase efficiency and allows for easier sharing of parameters between projects. The format of the user interface of ADSM makes it a good choice for beginning users, while the complexity of disease spread and control options makes it relevant for animal health professionals who need disease spread modeling support for decision-making.

Work on ADSM continues USDA–APHIS–CEAH’s commitment to the NAADSM collaboration with the aim of taking it into the future with improved and more accessible animal disease spread modeling applications.

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