

## **ARGUS INVASIVE SPECIES SPREAD MODEL CONSTRUCTED USING AGENT-BASED MODELING APPROACH AND CELLULAR AUTOMATA**

S. Clifton Parks

Actuarial Division  
707 Texas Avenue Suite 201  
AgriLogic, Inc.  
College Station, TX 77840 U.S.A.

Maxim Garifullin

21, Politechnicheskaya Str.  
XJ Technologies  
St Petersburg, RUSSIA

Rainer Dronzek

3333 Warrenville Road, Suite 200  
Automation Associates, Inc.  
Lisle, IL 60532 U.S.A.

### **ABSTRACT**

The stochastic Argus Invasive Species Spread Model (AISSM) is constructed using an Agent-Based Modeling (ABM) approach with cellular automata (CA) to account for spatial relationships and changes in those relationships over time. The model was constructed to support a wide range of geographical locations; however, this paper focuses on its application in the state of California. A time-series of daily historical weather observations on a 6-kilometer grid was obtained for six weather variables important to insect and disease development. Weather conditions were then simulated using the K- nearest neighbor (K-nn) regional weather generator. The weather simulations were summarized into a monthly time-step and coupled with satellite land cover imagery to identify a habitat quality for each simulated month. This information was combined with the introduction of invasive species in the AnyLogic™ modeling environment. The spread of invasive species is driven by the habitat quality layer, which regulates its dispersal rate.

### **1 INTRODUCTION**

The ability to model the spread of invasive species is increasingly important given the potential impact the pests could have on industries that are the basis for many economies of both industrialized and developing nations throughout the world. The information obtained from a simulation model capable of effectively modeling these threats enables policy makers and industry leaders to better understand, mitigate, manage, and recuperate from the associated risks.

The amplification of the threat is primarily attributed to three factors: the increasing ease of transportation, reduction in trade barriers, and terrorism. These obviously include both accidental and intentional introduction of invasive species as a result of the movement of humans,

animals, or goods. All of these factors must be considered during model development.

As a result of these concerns, research has been conducted by several university and government agencies in an attempt to quantify and mitigate these concerns. Some of the invasive species modeled by researchers have included foot-and-mouth disease and Bovine Spongiform Encephalopathy (BSE) (Schoenbaum and Disney 2002, Disney and Peters 2003, Green 2003). However, the continued development of more robust and adaptive modeling techniques is required to address the broad range of invasive species threatening different segments of the national economy.

The Agent-Based Modeling (ABM) approach has been used in numerous applications including modeling the interactions of both animal and insect agents, including coyotes, stream fish, and mosquitoes (Carnahan et al. 1997; Pitt, Knowlton, and Box 2001; Railsback et al. 1999). The ABM approach can also be applied in a spatial environment using cellular automata (CA) as demonstrated in the glassy-winged sharpshooter model developed by a consortium of university and government researchers (White et al. 2000). The basic principles used in the glassy-winged sharpshooter model were used as a basis during the development of the Argus Invasive Species Spread Model (AISSM).

### **2 DATA**

There are three primary components driving AISSM: the time-series of invasive species introductions, invasive species specific model parameters, and the invasive species specific habitat quality time-series. The first is the simulated time-series of invasive species introductions, which is stochastically selected from a spatial specific time-series of historical invasive species detections by either federal, state, and industry regulating agencies. The time-series is exogenously generated and introduced into AISSM assum-

ing at introduction 1% of the grid point (i.e. a specific geographic location) is contaminated with the invasive species.

The second component is the invasive species specific model parameters that define the pest's behavior. The parameters detail the rate of dispersal at 100% habitat quality, limitations on the dispersal, the minimum detectable infestation, and the distributions of the times required to detect, respond, eradicate, and quarantine the species. A parameter is also included to randomly introduce invasive species into grid points where detections have not historically occurred. The parameters used in AISSM are depicted in Table 1.

Table 1: AISSM Parameters

Parameter	Unit
spreadCriticalValue	% Infestation
maxDistancePerMonth	Km / Month
gridResolution	Km
minDetectablePopulation	% Infestation
detectionMinMonths	
detectionMode	Months
detectionMax	Months
eradicationMin	Months
eradicationMode	Months
eradicationMax	Months
quarantineMin	Months
quarantineMode	Months
quarantineMax	Months
depopulationCriticalValue	% Infestation
eradicatedPerMonth	% Reduction
minHQWithoutPopRed	% Habitat Quality
randomInfestationIntro	% Grid Points / Month

The third component is the invasive species specific habitat quality time-series for each grid point. The habitat quality time-series is identified as a combination of three primary variables: simulated weather conditions, satellite land cover imagery, and the invasive species specific parameters. Weather conditions are simulated using the K-nearest neighbor (K-*nn*) regional weather generator. The generator enables a wide range of weather variables to be simulated while maintaining correlation between a large number of geographic locations (Yates et al. 2003). The simulated daily weather conditions are summarized into a monthly value. The weather quality (WQ) in a specific simulated month for a particular invasive species is identified by weighting the 6 weather variables, which identifies the importance each weather variable has to a particular invasive species' development. The invasive species specific WQ is converted into a habitat quality (HQ) by multiplying it to the percent of land cover in the grid point considered a host for the invasive species of interest. The HQ time-series regulates the invasive species' dispersal in the model.

### 3 MODELING ENVIRONMENT

AISSM was developed in the AnyLogic™ modeling environment. The software is flexible and allows the modeler to define agent behavior using state charts and other graphical constructs, as well as using equations and algorithmic functions. In AISSM, agents are characterized by a number of parameters which can be easily interchanged to model different invasive species. Most spatially specific invasive species models have previously been constructed in the Swarm modeling environment. However, the AnyLogic™ platform is preferred for this application due to its user friendly characteristics and model animation component.

### 4 MODEL FRAMEWORK

AISSM was constructed on a 6 kilometer (km) grid resulting in 14,240 grid points for the state of California. The ABM approach in AISSM is to define each grid point as an agent with numerous properties. The primary property is the percent of the grid point infested by the invasive species while other properties such as eradication timeouts and quarantine restrictions are maintained as an agent's internal variables. Each cell changes its state at the end of month, with the state change dependent on neighboring cells' states, random invasive species introductions, and the cell's habitat quality.

The invasive species are introduced into AISSM in two manners. The first is through actual historic detections that are stochastically selected. The detections are grid point specific and ensure that the underlying distributions are reproduced on a monthly and annual basis. The second manner an invasive species may be introduced is randomly in any grid point. The percent probability is specified in the randomInfestationIntro model parameter.

Once the invasive species is introduced into the model, its rate of dispersal is defined by the species specific maxDistancePerMonth (MD) model parameter. The MD parameter is augmented by the species and grid point specific HQ times-series. The MD assumption is the maximum distance an invasive species can travel per month at 100% HQ. It is assumed that the invasive species will spread within a grid point each month as long as the percent HQ exceeds a minimum threshold as defined by the minHQWithoutPopRed (mHQ) parameter. The percent infestation increase for grid point 1 in month  $t$  ( $IPI_{t,GP1}$ ) is calculated by multiplying the MD variable to the percent habitat quality for month  $t$ ,

$$IPI_{t,GP1} = HQ_{t,GP1} * MD.$$

The total percent infestation for month  $t$  is calculated by adding the increase in the percent infestation in month  $t$  to the percent infestation for the grid point in month  $t-1$ ,

$$PI_{t,GP1} = IPI_{t,GP1} + PI_{t-1,GP1}.$$

The infestation spreads until it is detected by either an industry member or a regulating agency. The time before the invasive species is detected ( $DT_{t,GP1}$ ) is determined using a triangle distribution. The distribution is characterized on a monthly time step and is defined by the detectionMin ( $DT_{Min}$ ), detectionMode ( $DT_{Mode}$ ), and detectionMax ( $DT_{Max}$ ) model parameters,

$$DT_{t,GP1} = \text{TRIANGLE}(DT_{Min}, DT_{Mode}, DT_{Max}).$$

Once the invasive species is detected, the eradication distribution is triggered. The eradication distribution details the time period required for the industry or regulating agency to respond to the detection. Often a lag of up to 10 days occurs in order to better define the species' dispersal and concentration so treatment measures may be used in the most effective manner. A triangle distribution defined by the eradicationMin ( $ET_{Min}$ ), eradicationMode ( $ET_{Mode}$ ), and eradicationMax ( $ET_{Max}$ ) model parameters is used to stochastically generate the time before eradication is initiated ( $ET_{t,GP1}$ ),

$$ET_{t,GP1} = \text{TRIANGLE}(ET_{Min}, ET_{Mode}, ET_{Max}).$$

The eradication program ( $E_{t,GP1}$ ) is initiated once the duration that the infestation has been detectable in the grid point, as defined by minDetectablePopulation parameter, is equivalent or exceeds the summation of the detection and eradication periods,

$$E_{t,GP1} = \text{IF}(IT_{GP1} \geq (DT_{t,GP1} + ET_{t,GP1}), 1, 0).$$

The infestation is reduced on a monthly basis by the eradicatedPerMonth (PE) model parameter once the eradication program has been triggered. The parameter is the percent of the infestation that is assumed to be eradicated on a monthly basis. The remaining percent infestation in month  $t$  after eradication ( $EPI_{t,GP1}$ ) is the product of the percent infestation in month  $t-1$  ( $PI_{t-1,GP1}$ ) and the difference of 1 minus the portion eradicated (PE),

$$EPI_{t,GP1} = \text{IF}(E_{t,GP1} = 0, PI_{t,GP1}, [PI_{t-1,GP1} * (1 - PE)]).$$

Once an eradication program is initiated, the grid points immediately surrounding the point triggering the program are also eradicated. The eradication program continues until the infestation for the grid point is less than the depopulationCriticalValue (DV). Once the value is encountered, the species is assumed to be eradicated and the percent infestation is forced to 0% for the next time step.

If the HQ is less than the mHQ, then the infestation is reduced proportionally and the final percent infestation ( $FPI_{t,GP1}$ ) is identified for the simulated month,

$$FPI_{t,GP1} = \text{IF}(HQ_{t,GP1} > HQm, EPI_{t,GP1}, EPI_{t-1,GP1} * (1 - (HQm - HQ_{t,GP1}) / HQm).$$

The infestation spreads to surrounding grid points after it exceeds the spreadCriticalValue parameter. The infestation's rate of dispersal into surrounding grid points is dictated by the HQ time-series for each grid point.

Quarantine programs are triggered in the same manner as eradication programs. The model parameters defining the quarantine duration are defined by the quarantineMin, quarantineMode, and quarantineMax model parameters. Once quarantines are initiated, the rate at which the invasive species can spread is drastically reduced to account for the restricted movement of host material.

AISSM dynamically adjusts eradication and quarantine durations in the model to meet criteria specified by the regulating agency for the specific invasive species being modeled. Eradication and quarantine programs are ceased when the infestation in the grid point and grid points immediately surrounding are eradicated and the buffer time period has lapsed, which is invasive species specific. Therefore, depending on the invasive species being modeled, the eradication and quarantine actives will continue beyond the elimination of the infestation as detailed by the quarantine regulations.

## 5 MODEL RESULTS

AISSM produces a time-series of the invasive species percent infestations, duration of eradication, and quarantine activities for each grid point in the region. The output is currently written to a text file, but it can also be exported in a variety of other file formats and may be directly exported to a relational SQL database.

AISSM may also be monitored during a model run using the AnyLogic™ modeling environment. Two different views of AISSM's animation are displayed in Figure 1 and Figure 2.

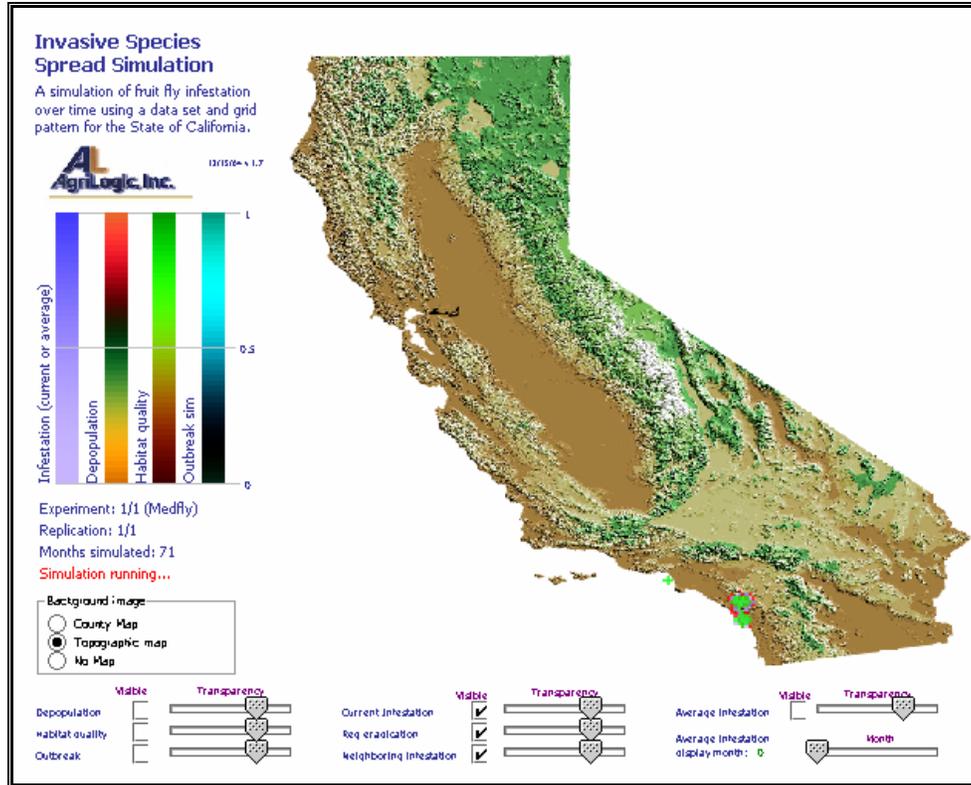


Figure 1: Invasive Species Spread Model in AnyLogic™ Modeling Environment (Topographic Map)

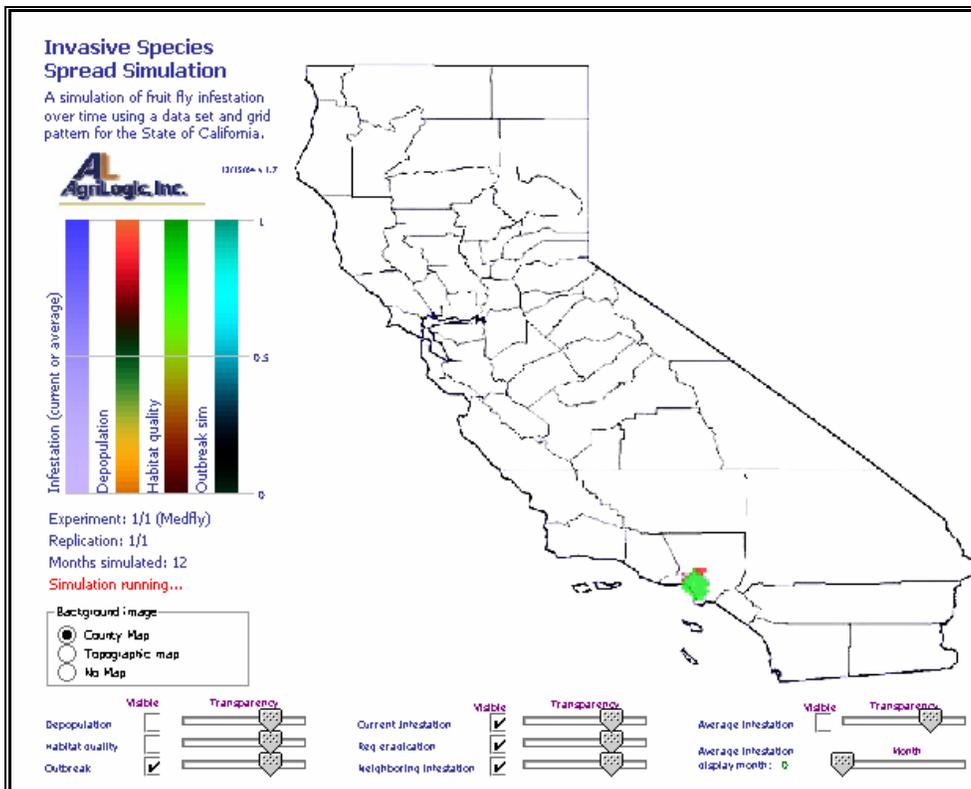


Figure 2: Invasive Species Spread Model in AnyLogic™ Modeling Environment (County Map)

The actively spreading Mediterranean fruit fly invasive species infestations are represented by the bright green areas depicted in the figures. AISSM is currently parameterized for numerous invasive species including both insects and diseases. Some of the species included in the model are Caribbean fruit fly, Mediterranean fruit fly, Mexican fruit fly, Melon fruit fly, Oriental fruit fly, Asiatic citrus canker, and Karnal bunt. Through the use of on-screen controls, the animation and agent properties can be modified as the model is running.

## 6 CONCLUSION

The ABM modeling approach coupled with the principles of cellular automata, as demonstrated in AISSM, offers a considerable advancement in the modeling of invasive species. Provided the increasing threat invasive species pose to nations' economies worldwide, the ability to effectively model these pests will become ever increasingly important. Principles used in AISSM will enable policy makers and industry leaders to better mitigate, manage, and recuperate from the associated risks posed by invasive species worldwide.

## REFERENCES

- Carnahan, J., L. Song-gang, C. Costantini, Y. Touré, and C. Taylor. 1997. Computer simulation of dispersal by *Anopheles Gambiae s.l.* in West Africa. *Artificial Life V: Proceedings of the Fifth International Workshop on the Synthesis and Simulation of Living, Complex Adaptive Systems*. MIT Press, Cambridge, MA, 387-394.
- Disney, W. Terry and Mark A. Peters. 2003. Simulation modeling to derive the value-of-information for risky animal disease-import decisions. USDA, Food Safety Inspection Service (Disney) and USDA, Agricultural Marketing Service (Peters). *Preventive Veterinary Medicine* 61: 171-184. Published by Elsevier Science B.V.
- Green, J. Personal Communication, Nov. 2003. Animal and Plant Health Protection Services, United States Department of Agriculture.
- Pitt, W., F. Knowlton, and P. Box. 2001. A new approach to understanding canid populations using an individual-based computer model: preliminary results. *Endangered Species UPDATE* 18: 103-116.
- Railsback, S., R. Lamberson, B. Harvey, and W. Duffy. 1999. Movement rules for individual-based models of stream fish. *Ecological Modelling*. Published by Elsevier Science B.V.
- Schoenbaum, Mark A. and W. Terry Disney. 2002. Modeling alternative mitigation strategies for a hypothetical outbreak of foot-and-mouth disease in the United States. USDA, APHIS, Veterinary Services, Center of Epidemiology and Animal Health. *Preventive Veterinary Medicine* 58: 25-52. Published by Elsevier Science B.V.
- White, M., P. Box., M. Luck, S. McKirdy, I. Fung, C. Bonfils, R. Redak, R. Mizell, G. Jones, and N. McCoy. 2000. Glassy-winged sharpshooter model proposal. Submitted to the *National Science Foundation*.
- Yates, D., S. Gangopadhyay, B. Rajagopalan, and K. Strzepek. 2003. A technique for generating regional climate scenarios using a nearest-neighbor algorithm. *Water Resources Research* 39: 7.

## AUTHOR BIOGRAPHIES

**S. CLIFTON PARKS** is Director of the Actuarial Division for AgriLogic, Inc.. His work has encompassed a broad range of modeling activities including invasive species, discrete event, agent-based, actuarial, and econometric modeling. His e-mail address is <[cparks@agrilogic.com](mailto:cparks@agrilogic.com)>.

**MAXIM GARIFULLIN** is a software programmer and modeler for XJ Technologies. He has been involved in the development of numerous systems dynamics, discrete event, and agent-based modeling projects. His e-mail address is <[maxim@xjtek.com](mailto:maxim@xjtek.com)>.

**RAINER DRONZEK** is Vice President of Automation Associates, Inc.. He has developed numerous simulation models for the healthcare, manufacturing, material handling, distribution, and service industries. His e-mail address is <[rainer@simulation-modeling.com](mailto:rainer@simulation-modeling.com)>.