A Tool for Simulating the Spread of Invasive Mosquitoes
Ute Vogel\textsuperscript{1}, Renke Lühken\textsuperscript{2}, Ellen Kiel\textsuperscript{2}

Abstract
There are many concerns about the spread and establishment of exotic mosquito species in Europe, some of which are highly competent to transmit pathogens. The fast spread of some invasive mosquito species, e.g. the Asian bush mosquito, might be explained by a combination of natural dispersal and human transport. Therefore, the aim of this study was the development of a software tool that is capable to model the local spatial-temporal spread of invasive mosquitoes through natural dispersal and their transportation through human transport via cars. The evaluation of the tool shows that it is capable to simulate the spread but also reveals the need for more biological data about invasive mosquito species.

1. Introduction
Mosquitoes can cause significant nuisance and are important vectors of several pathogens [8]. Therefore, this group of insects was and is subject of research all over the world, but especially in areas with health concerns due to mosquito-borne diseases, e.g. Africa [5]. Nevertheless, in view of the worldwide range expansion of several mosquito species, some of which are highly competent to transmit pathogens, the interest in this research topic is also increasing in other geographical areas [2]. Especially climate change and globalisation are considered to facilitate the spread and establishment of these species [2,27].

There are many concerns about the introduction and establishment of exotic mosquito species in Europe, some of which are highly competent to transmit pathogens [16]. The worldwide most important invasive mosquito species is the Asian tiger mosquito (\textit{Aedes albopictus}). The species is known to be a highly competent vector of several pathogens and is considered to be the vector, which caused the autochthonous transmission of Chikungunya virus [6,19] and Dengue virus [4,14,20] in Southern Europe. Surveillance studies at potential introduction sites in Germany identified motorway service stations as important gateways [1,10,18,26]. Individuals of the Asian tiger mosquito are considered to enter cars or trucks in Southern Europe, where the species is established since several years and transported by transit traffic.

The fast spread of another invasive mosquito species in Germany, the Asian bush mosquito (\textit{Ochlerotatus japonicus}), highlighted the necessity of dispersal analyses and the demand for modelling tools to predict the spread of invasive mosquito species. The species was firstly detected in the year 2008 in Southern Germany at the border to Switzerland. During the following years, the species was found to spread fast in Southern Germany and additional populations were detected in Northern Germany (reviewed by [11]). The fast spread of the Asian bush mosquito might be explained by a combination of natural dispersal and human transport [25]. The distribution and habitat preference of invasive mosquitoes were analysed in several studies in Europe. At least for the Asian tiger mosquito there are several habitat models on the basis of climate data and landscape parameters, which give information on the actual and potential distribution in Europe [3]. However, there are only few studies on the spatial-temporal spread of invasive mosquito species via traffic.

\textsuperscript{1} University of Oldenburg, 26111 Oldenburg, Germany, Ute.Vogel@informatik.uni-oldenburg.de, Department of Computing Science, Environmental Informatics
\textsuperscript{2} University of Oldenburg, 26111 Oldenburg, Germany, Renke.Luehken@uni-oldenburg, Ellen.Kiel@uni-oldenburg.de, Institute of Biology and Environmental Sciences, Research Group Aquatic Ecology and Nature Conservation
[23]. This applies in particular to the small scaled, regional spread through natural dispersal and human transport (e.g. cars). Information on the potential spread of invasive species especially can help to develop an adequate surveillance program and control strategies.

Therefore, the aim of this study was the development of a software tool that is capable to model the local spatial-temporal spread of invasive mosquitoes through natural dispersal and their transportation through human transport via cars.

2. Mosquito Tool
A software tool for predicting a possible exposure of mosquitoes has to take the passive transport by vehicles as well as the active dispersal of mosquitoes into account. These two processes take place on different scales in time and space. Such multi-scale modelling is often used to model physical phenomena [24]. Hoekstra et al. [7] studied the modelling of complex automata by coupling cellular automata with different temporal and spatial scales. A framework for modelling ecological systems as multi-scale models has already been proposed [21,22]. The theoretical background of this framework models complex spatial processes on different scales by so-called hierarchical asymmetric cellular automata, which allow the coupling of cellular automata (layers) with different spatial and time scales as well as restricted interactions between layers. The Mosquito Simulation Tool (MoSiTo) presented here follows this approach. It consists of two automata: the MosquitoCA on a spatial fine-scale layer and the Tool VASim, which models the dissemination of mosquitoes by traffic on a coarse spatial level.

Both components of MoSiTo have been prototypically implemented in Python as a Plugin for the geographic information system QGIS (version 1.8 and 2.x, resp.) and can also be used independently from each other.

2.1. Traffic network Tool VASim
Tourist traffic from regions with established mosquito populations are considered as a potential reason for mosquito dispersal. The traffic network tool VASim ([17]) models this transport.

The transport can be viewed as a generalized (asymmetric) cellular automaton [21] where the cells represent starting points, stops (at resting places, motorway stations), and destinations of vehicles. The neighbourhood relation is determined by a traffic route from the starting point to the destination with stops in between.

The movement of cars on a traffic route and the release of mosquitoes at stops is modelled by the cells’ state: The cell at the starting point of the route is initialized with a vehicle object. Each vehicle object (VO) represents a set of cars, which traverse the same route. It is characterized by parameters to describe its behaviour:

- The minimal distance between stops \( d_{\text{min}} \) and its mileage determine where the vehicle object will stop and possibly release mosquitoes.
- The distribution of the number of mosquitoes inside the VO at the start of the simulation and the probability for mosquitoes leaving the vehicle at every single stop determine how many mosquitoes will be initially in the VO and leave it at a stop.

Beside the information about the VO, the cell stores the distance to the prior cell (attribute length) and the number of mosquitoes, which have been released (attribute mosquitoes). The behaviour is modelled as transfer step and update step:

- The transfer step moves the VO information to the next cell:

\[
\text{cell}[i+1].\text{VO} = \text{cell}[i].\text{VO}
\]
The update step describes the release of mosquitos inside a cell:

```python
cell[i].VO.mileage += cell[i].length
If cell[i].VO.mileage > random_km(cell[i].VO.dmin):
    mosquitos_out = random_Mosquitos(cell[i].VO.inside)
    cell[i].mosquitos += mosquitos_out
    cell[i].VO.inside -= mosquitos_out
    cell[i].VO.mileage = 0
```

The random-functions allow random deviations from the minimal distance between stops of a vehicle and from average number of mosquitos released.

Hence, a traffic route defines a one-dimensional cellular automaton. As it is possible to assign an arbitrary number of routes to one simulation scenario, a more complex neighbourhood relation is possible.

For initialization of VASim at least one traffic route between arbitrary starting points and destinations and a list of possible stops along the route (rest areas, service stations) must be specified as xml-documents. VASim extracts the cell attributes and topology from these inputs. The documents can be generated by the web services OpenRouteService (http://openrouteservice.org) and the Overpass API (http://www.overpass-api.de/), which are based on OSM XML OpenStreetMap data. The vehicle objects at the starting position of each route are initialized according to user-specified probability distributions for the initial number of mosquitos inside and the release of mosquitos.

So far VASim does not model time explicitly. In one simulations step the VO is transferred from one cell to the following - the real time, which corresponds to this transition, depend on the distance between the stops, i.e. length of the cells.

### 2.2. MosquitoCA

The MosquitoCA [13] models the autonomous dispersal and the possibility of establishing a population as a fine-scale 2-dimensional cellular automaton with a regular grid of cells. The dynamic is based on the static data about the area using the Corine landcover information (http://www.cora.europa.eu/) and integrates climatic information about the regional temperature.

Each cell is characterized by its habitat quality factor \((\text{hab} \in [0,1])\), the number of its adult mosquitoes (adults) and mosquito larvae (larvae), which vary during the simulation. The maximum mosquito or larvae capacity of cells depends on the habitat quality. Hence the optimal capacities of adult mosquitoes \((A_{max})\) or larvae \((L_{max})\) are reduced by the habitat quality factor. The size of the cells depends on the flying range of the mosquito species in the given time step.

The dynamics of the number mosquitoes per cell depends on the mortality rate \((m)\), reproduction rate \((r)\), the length of a gonotrophic cycle \((u)\), i.e. the time span of alternate feeding and laying of eggs, and the larvae’s development rate \(d\). \(u\) and \(d\) depend on climatic factors (temperature) and are defined as in [15]. The variable \(P\) describes the length of a time step in the simulation and corresponds to one day.

The default dynamic of the cellular automaton is based on rules for reproduction, mortality, and dispersion based on the MALCAM model published by [15] with some minor improvements concerning the different habitat qualities. The dynamic of adults and larvae inside each cell is determined by

\[
\text{larvae}(t) += P \cdot (\text{adults}(t-1) \cdot \frac{r}{u} - d \cdot \text{larvae}(t-1)) \cdot \text{hab} \cdot \frac{1 - \frac{\text{larvae}(t-1)}{L_{max} \cdot \text{hab}}}{1}
\]
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\[ \text{adults}(t) + = P \cdot (d \text{ larvae}(t-1) - m \text{ adults}(t-1)) \cdot \text{hab} \cdot \left(1 - \frac{\text{adults}(t-1)}{\Lambda_{\text{max}} \cdot \text{hab}}\right) \]

Alternatively to this predefined dynamics inside each cell, user specified rules can be specified and used in MosquitoCA.

For each cell the number of leaving mosquitos is computed as in [15] by

\[ \text{leaving}(t) = \text{adults}(t) \cdot \frac{p}{u}. \]

We simplified the MALCAM model for the entering of cells: the flow of mosquitos from cell\([i]\) to cell\([j]\) is computed by cell\([i]\).leaving\((t)\) weighted by the normalized habitat quality factor of cell\([j]\):

\[ \text{cell}[j].\text{entering}(t) = \text{cell}[i].\text{leaving}(t) \cdot \frac{\text{cell}[j].\text{hab}}{\sum_{k \text{ neighbor of } i} \text{cell}[k].\text{hab}} \]

The simulation of MosquitoCA results in a map, which shows the distribution and abundance of mosquitoes in the cellular automaton.

2.3. Coupling

MosquitoCA and VASim are only loosely coupled: In a first step, VASim computes the initial occurrences of mosquitos at the stops along the routes for a given set of routes and vehicle objects. These stops comply with cells of the MosquitoCA. This allows to check, whether the suspected traffic flows are able to transport mosquitos that far. Starting from these stops as initial places, MosquitoCA computes the dispersal of mosquitos.

In the next version of MoSiTo, we plan to integrate a refined time concept: as the survival rate of transported mosquitos and the behaviour of the mosquitos depend on the time of the day, in future version VASim cells will transfer mosquitos numbers tagged with a time stamp information.

Evaluation scenarios

For ensuring the correct implementation of the underlying models, the MoSiTo layers MosquitoCA and VASim have been successfully tested separately with virtual scenarios. Due to the limited availability of data about the detailed behaviour of neozoa and their spread, we based our real world evaluation on existing publications.

2.4. Scenario 1: Spread of Mosquitos

The fast spread of the invasive Asian bush mosquito (Ochlerotatus japonicus) in Germany highlights the necessity of dispersal analyses and the demand for modelling tools to predict the spread of invasive mosquito species. The species was firstly detected in the year 2008 in Southern Germany at the border to Switzerland. During the following years, the species was found to spread fast in Southern Germany (reviewed by [11]). This spread is probably due to natural dispersal and, therefore, is a good case study to evaluate the MosquitoCA tool.

Huber et al. [9] presented a map where the Asian bush mosquito has been found in 2011. Their study only included punctually data. Therefore, raster grids cells in a resolution of a topographic map (1:25.000, 18km×10km) were defined as colonized, if at least one positive point lay in the respective grid cell. As this scale is much to coarse for a detailed simulation, we initialized the automaton with 135×55 cells of size approx. 0.01×0.01 square degree (1.1km×1.1km) and focused to the infested area in the south of Baden-Württemberg, using a daily rates of 0.1 (mortality \(m\)) and 1.0 (reproduction rate \(r\)), and a constant temperature of 20°C. The habitat qualities of the cells were derived from the Corine landcover data 2006 on a 250m×250m grid. Based on expert knowledge
the landcover types were classified as “not suitable”, “medium suitable” and “very suitable” and each cell was assigned a habitat quality of 0.01, 0.5 or 10, resp. As the cell size of MosquitoCA and the Corine grid differed, the landcover in the centre of the cell determined its habitat quality.

In order to start MosquitoCA with the map of 2011, about 20 cells in the infested area were initialized with 1000 mosquitoes and 5000 larvae and (pre-)simulated for 25 time steps (days). Figure 1 shows the occurrence of mosquitoes and after the pre-simulation phase with 2011 distribution data [9]. The infected areas from 2011 show a medium to high occurrence of mosquitoes. Below the simulated occurrence after about 120 time steps can be seen with a map section of the 2014 distribution.

![Legend](http://www.ecdc.europa.eu/)

Figure 1: Simulated mosquito occurrences after pre-simulation (left, upper) and after 120 timesteps (left, lower). Positive Ochlerotatus japonicus raster grids in 2011 [9] in a resolution of a topographic map (1:25,000, 18km x 10km) are edged dark gray (left, upper). Small sketch in the right show the observation from Ochlerotatus japonicus in this region from 2014.

Our modelling results showed a much faster spread of Ochlerotatus japonicus compared to the observed spread in the real-world. This might be explained by different reasons: 1) the input data do not have a very good quality and are only based on a very broad meshed mosquito survey. Colonized areas with very low Ochlerotatus japonicus might be not detected. Therefore, the currently published distribution maps might not reflect the actual distribution of the species. 2) Furthermore, our model use several assumptions and simplifications, e.g. each cell have the same, relatively high temperature (20°C) and there are no temperature variations in space and time, which significantly accelerate the spread in our model. Therefore, the incorporation of upper and lower development temperature thresholds might give a more realistic picture.

### 2.5. Scenario 2: Transport and Spread

Further Ochlerotatus japonicus foci were detected in Northern Germany (reviewed by [11]), which appeared to be too far away to be explained by natural dispersal, but might be explained by human transport via car traffic [25]. Therefore, this scenario 2 was used to evaluate the VASim tool in the first place. Beyond that, subsequent simulation of the spread with the tool MosquitoCA, starting from service stations might explain findings of the main traffic routes.
In scenario 2, the object of investigation was the possibility of an introduction of mosquitoes from southern Germany by traffic which is passing the motorway junction Weilheim (nearby Heilbronn and the most northern point of *Ochlerotatus japonicus* observation in the federal state Baden-Württemberg [9]) and going north in direction to motorway junction Hilden (nearby Düsseldorf). North bound motorway routes in this area were generated by OpenRouteService and service stations along the routes were determined by the web service Nominatim. The “fastest route” via the motorways A67 and A3 crosses the north eastern region of further *Ochlerotatus japonicus* foci [12].

VASim was initialized with three routes having each 1000 vehicle objects. Each VO was meant to represent a set of cars with an average of 60 mosquitoes per VO, an initial, uniform distributed initial mileage of 50 up to 250 km, and a minimum distance between stops of 200 km. Figure 3 shows the number of VOs (“Cars”) and the final number of exposed mosquitoes per station. The stations have been sorted by their (Euclidean) distance from the start at Weilheim. Figure 3 shows that the number of released mosquitoes correlates linearly to the number of cars. Despite the uniform distribution of the initial mileage, waves of resting cars become obvious.

The *Ochlerotatus japonicus* observations from [12] were located by manually georeferencing the sketch (Figure 2). The resulting map was validated using Open Street Map data locations of cemeteries.

Figure 4 shows the modelling results of scenario 2 produced with the MosquitoCA tool. For the service station Siegburg West at km 299, an exposure of 1460 Mosquitos was computed by VASim and simulated by MosquitoCA in order to prove, if the nearby findings at locations in the north, east and south-west can be attributed to exposures at Siegburg West. Each of these positive sites has a distance of about 5 km. With the parameters of the scenario, Corine landcover data with a resolution of 100m×100m and nearly equally sized cells (0.0015×0.0015 square degrees), we
found, that only the observations in the eastern location can be explained. Figure 4 shows the simulation after 100 and 200 simulation steps.

As stated above, the tools of MoSiTo are only loosely coupled and communicate asynchronously via data files. As a next step, it is planned to allow a tighter and timed coupling between the two layers, which will also allow the integration of seasonal changes in traffic flows as well as in the mosquitoes’ survival conditions into the model.

Conclusion
The research on invasive mosquito species predominantly focus on static information about the recent and future distribution based on environmental data and lacks studies and tools to predict and understand the spatial-temporal spread especially on the regional and local scale. The tool MoSiTo with its layers VASim and MosquitoCA is the first approach, combining the natural dispersal and the transportation through human transport via road traffic. From the vector ecologist’s perspective, the tools can help to understand the historic dispersal of exotic mosquito species. However, the ultimate objective of this project is the establishment of a tool, which allows predicting the future spread and distribution of the exotic mosquito species. This tool offers extensive application possibilities, e.g. an exact geographic definition for the design of mosquito surveillance or control programs. The next steps in this ongoing project are the evaluation of the system by real world scenarios as well as the enhancement of the layers by a refined concept of time.

References
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