ZoonosisMAGS : Une plateforme générique pour la géo-simulation de la propagation de zoonoses

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A generic platform for population-based geo-simulation of zoonose spread

Overview

- ur Population-Based Geosimulation Projects
- owards a Generic Approach for the Geo-Simulation of Zoonose Spread
- hallenges and Main Ideas
- he ZoonosisMAGS Project and Platform
- formed Virtual Geographic Environment
- he Spatial Dimension and Compartment Models
- nhancing Compartment Models with Spatial Characteristics
- verview of our Software Suite
- ur Matlab Simulator: A Tool to Assess Complex Compartment Models
- xperiments with the Matlab Simulator
- he ZoonosisMAGS Platform (C++ Simulator)
- onclusion

ur Population-Based Geosimulation Projects

- VNV-MAGS Project to simulate the propagation of West Nile Virus (2004-2008) financed by INSPQ and part of the Geoide-supported MUSCAMAGS Project
- The LymeMAGS Project (2009-13 - Financed by INSPQ and Ministère de la santé et des services sociaux du Québec), part of the Geoide-supported CODIGEOSIM Project
- Simulation of the propagation of Lyme disease (ticks – rodents - birds – deer interactions) for decision support in Public Health
- The ZoonosisMAGS Platform: a generic platform to create population-based geo-simulation of zoonoses
- The SénartMAGS Project (agent-based geosimulation) of the risk of Lyme Disease in peri-urban parks (Collaboration with Godard's team of Paris 8 University)

Towards a Generic Approach for the Geo-Simulation of Zoonose Spread

oonoses (infectious diseases transmitted by insects to animal nd to humans) such as the West Nile virus and Lyme disease are concern for public health authorities, especially in a context of limate change (temperatures, rain and snow falls)

Monitoring systems developed by public health organizations rovide data, on which hypotheses can be tested and spatial and tatistical analyses can be carried out, ***but they do not easily take nto account spatial-temporal and behavioral (mobility) aspects***

here is a ***need for flexible tools to understand the 'dynamics' of isease propagation*** resulting from the combination of various actors (i.e. *temperature, land-cover, mobility, seasonality*)

imulation is a candidate approach to tackle such complexity and rovide friendly tools to explore scenarios (climate, intervention)

ifferent approaches have been proposed to model and simulate

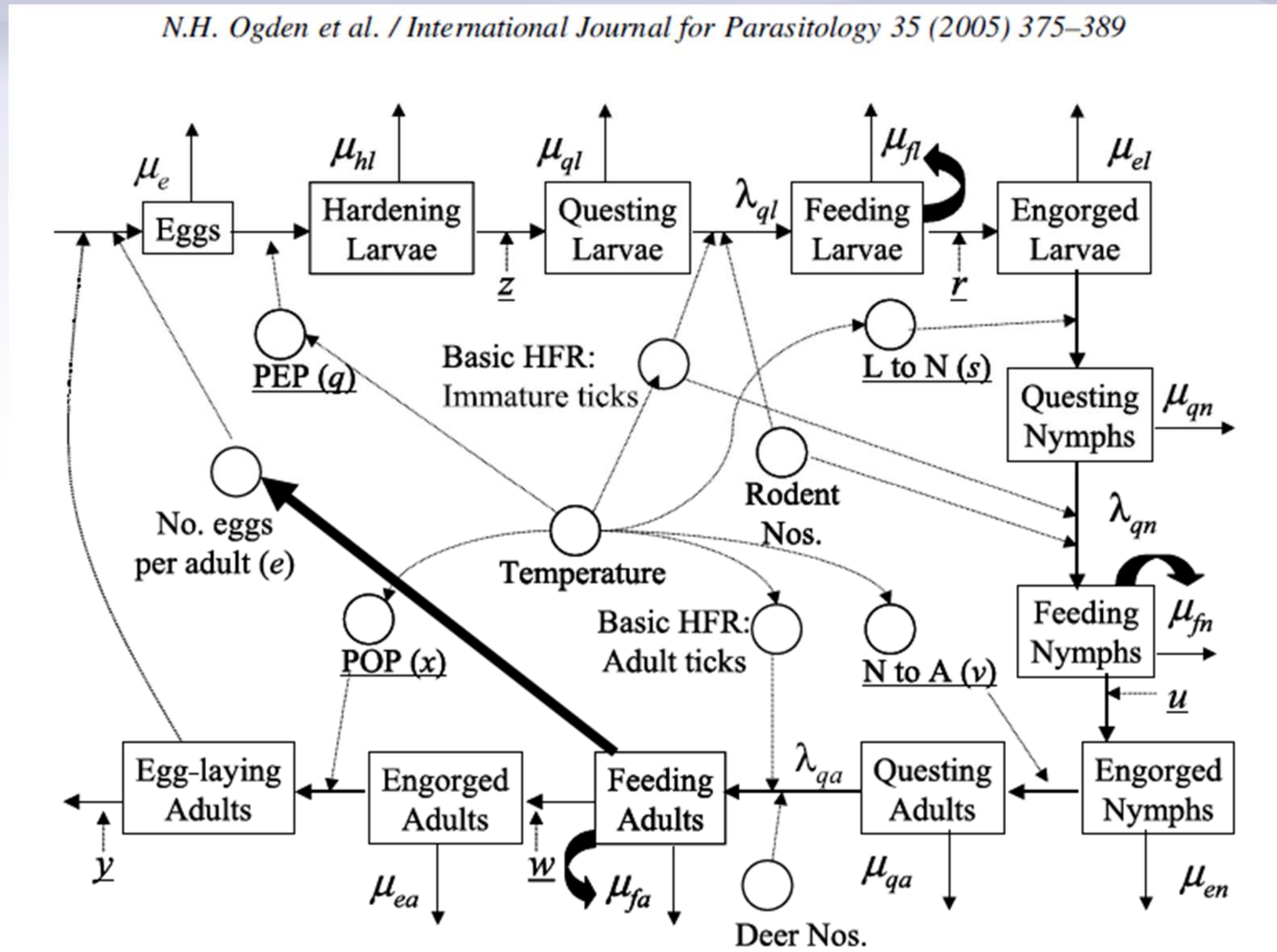
Shortcomings with respect to 'space'

Approaches	Shortcomings
Mathematical modeling (i.e. compartment models, population-based models)	Does not take into account specificities of the geographical space (implicit homogeneity assumption)
Cellular automata	Represent diffusion processes, cannot represent individuals/groups mobility
Multi-agent systems (individual-based models)	May take advantage of data provided by Geographic Information Systems (GIS), but simulate at the individual level

oreover, Zoonoses involve huge populations of individuals

/e propose a ***population-based geosimulation approach*** using ***IS data*** and taking into account the ***influence of land-cover on*** ***e evolution of species and their interactions/displacements***

System Dynamics Model for Ticks (Ogden 2005)



Note: This model does not take into account:

Challenges

- How to model huge populations and their interactions taking into account geographic characteristics (i.e. land-cover in relation to habitat suitability)?
- How to efficiently simulate these interactions as well as species evolution (especially for insects such as mosquitoes and ticks), and animals' displacements?
- How to calibrate these models (data availability)?
- How to develop friendly tools to help decision makers understand the phenomena (visualization) and to assess different scenarios (climate, interventions)
- How to couple spatial and statistical analysis tools to support these assessments?

Main Ideas

eate a virtual geographic environment (VGE) whose cells corres-
nd to habitat patches influencing species' biology (suitability)

ssociate with each cell the populations of the involved species at
fferent stages (i.e. evolution, infection)

odel the evolution and interactions of these populations using an
hanced compartment model taking into account environmental
rameters (i.e. temperature, geographic characteristics)

nhance the VGE with information related to species' mobility
haviors (migration, emigration, dispersal) → Informed VGE

nhance the compartment model with 'transfer compartments' and
obility transitions

plement this model as efficient state-transition mechanisms in
e geo-simulator exploiting the IVGE

evelop a prototyping tool (Matlab) for model exploration and

Informed Virtual Geographic Environment

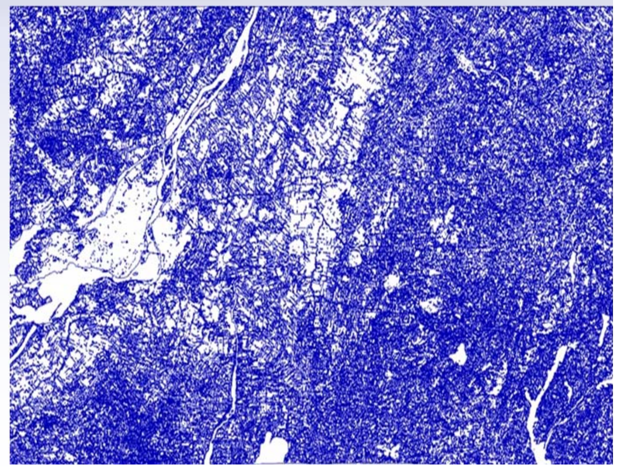
- Ve propose to introduce a spatial model in simulations in the form f an Informed Virtual Geographic Environment (IVGE) which rasps some of the biological characteristics of the involved pecies and of the landscape (i.e. land cover)
- he IVGE is divided into a set of cells (polygons) in which the ifferent stages of the involved populations can be simulated
- he cells are associated with attributes (qualitative and/or uantitative) reflecting biological characteristics of the species .e. suitability of the habitat)
- ur 'biologically informed' VGE provides the foundation for the mulation of a variety of spatial-temporal phenomena such as the igration of birds importing infected insects (i.e. juvenile ticks in e case of Lyme disease) or deer carrying ticks (mainly adults) nd the survival of tick colonies in suitable areas

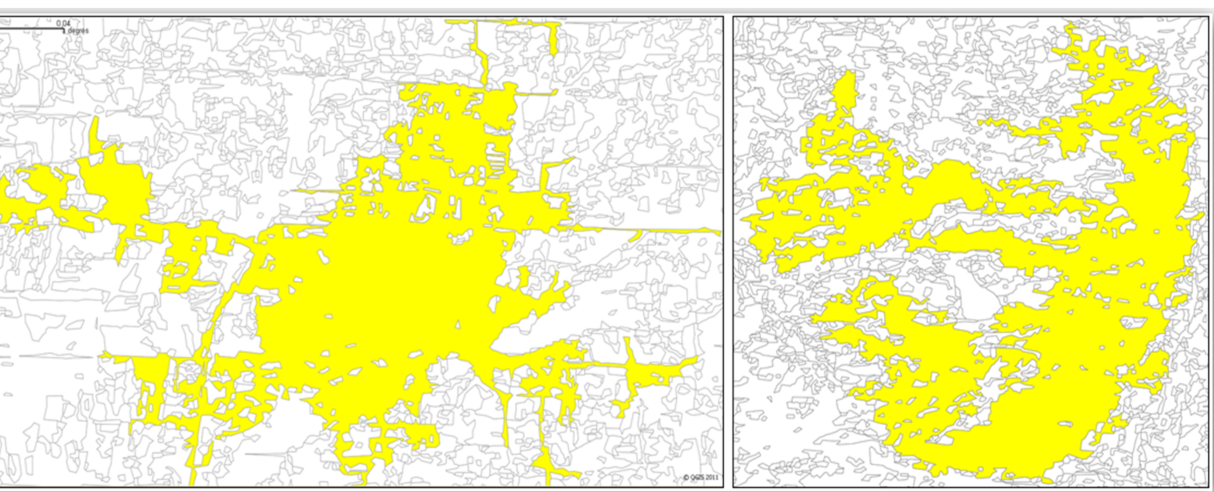
ptimizing the VGE for Geo-Simulation Purposes

ch region can contain more than 120 000 polygons.

ch a huge number of polygons cannot be used in a osis geosimulation in which we have to compute the tions of the different biological stages of the ved species populations, as well as their interactions

me polygons may have complex shapes and holes

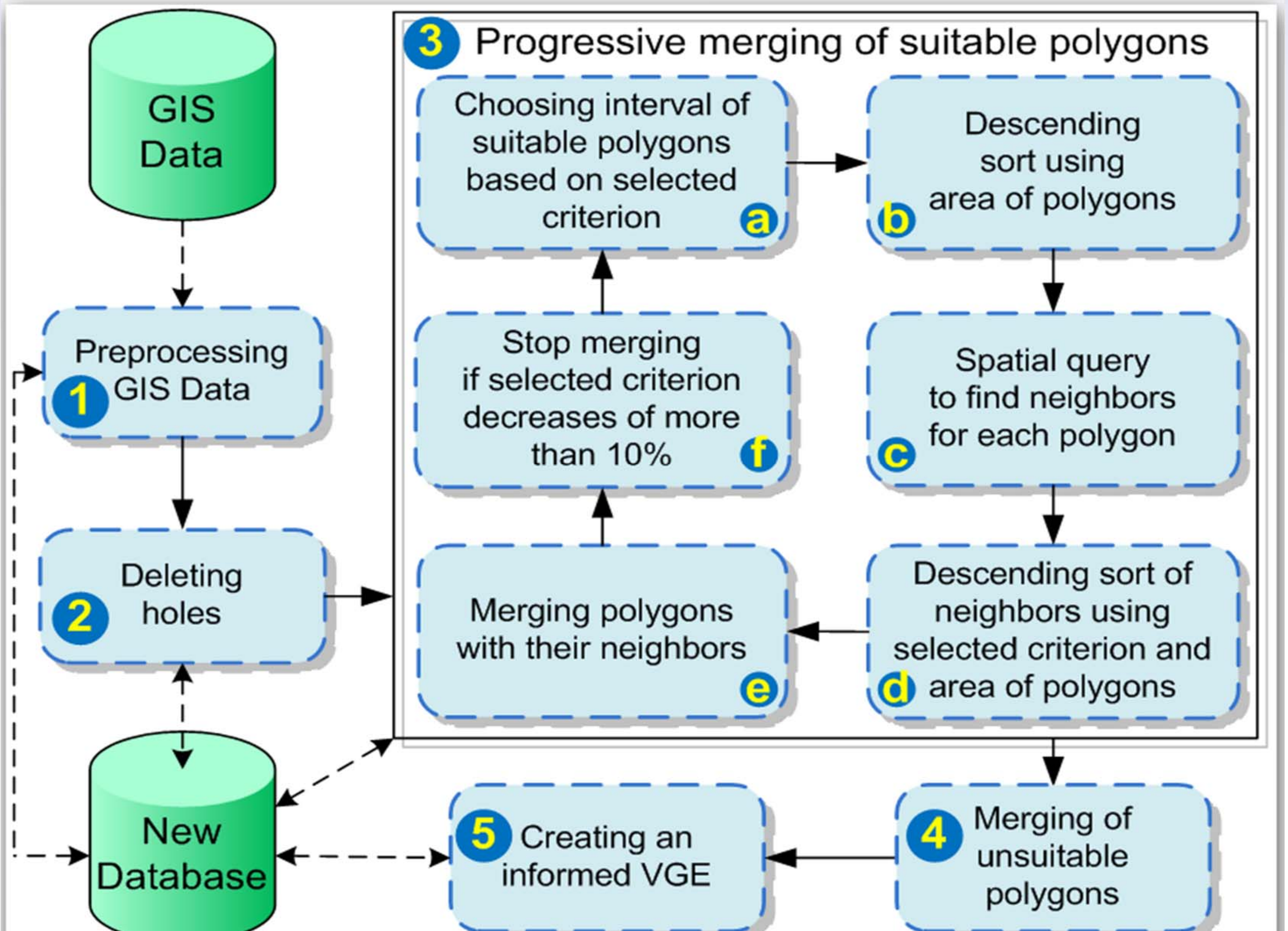




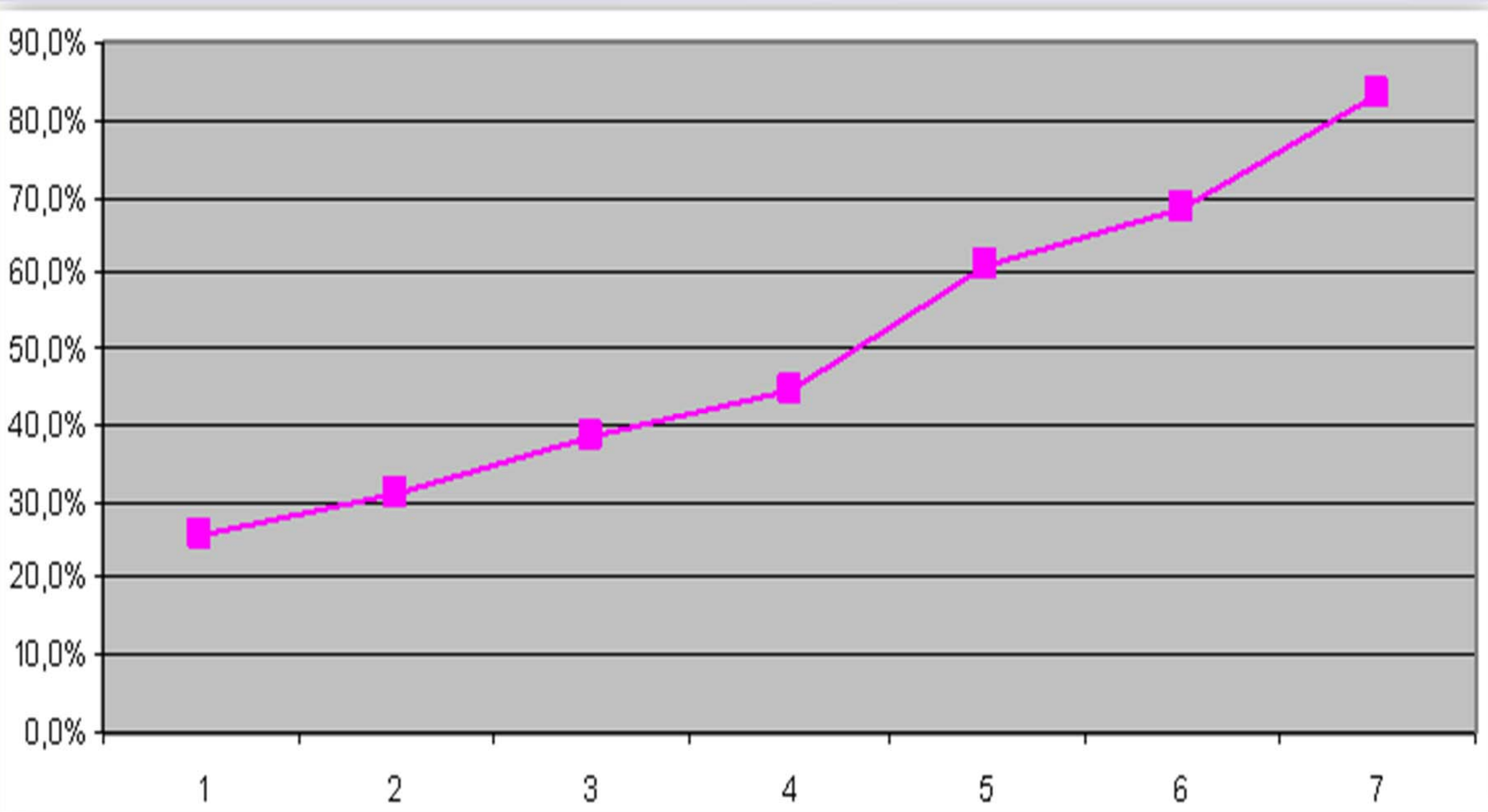
Example: Geobase Region 31H contains 133 780 distinct polygons and its dimension is nearly 156 x 110 km

blem: *How to significantly reduce the huge number of land-cover*

Our Approach for the Progressive Merging of Suitable Polygons



esults of the Progressive Merging of Cells



roportions of cells removed after the successive merging iterations:
ne first process is the deletion of holes and the last process is the

ne Spatial Dimension and Compartment Models

ditional compartment models implicitly assume that species nteract in an *homogeneous space* (OK at a global level) and do not nodel interactions (use only parameters in differential equations)

a (meso) level ***we need to take into account the geographic haracteristics of space.*** Can we still use compartment models ?

need *a compartment model efficiently processed by a eosimulation engine* (applied to thousands of spatial cells at each eration)

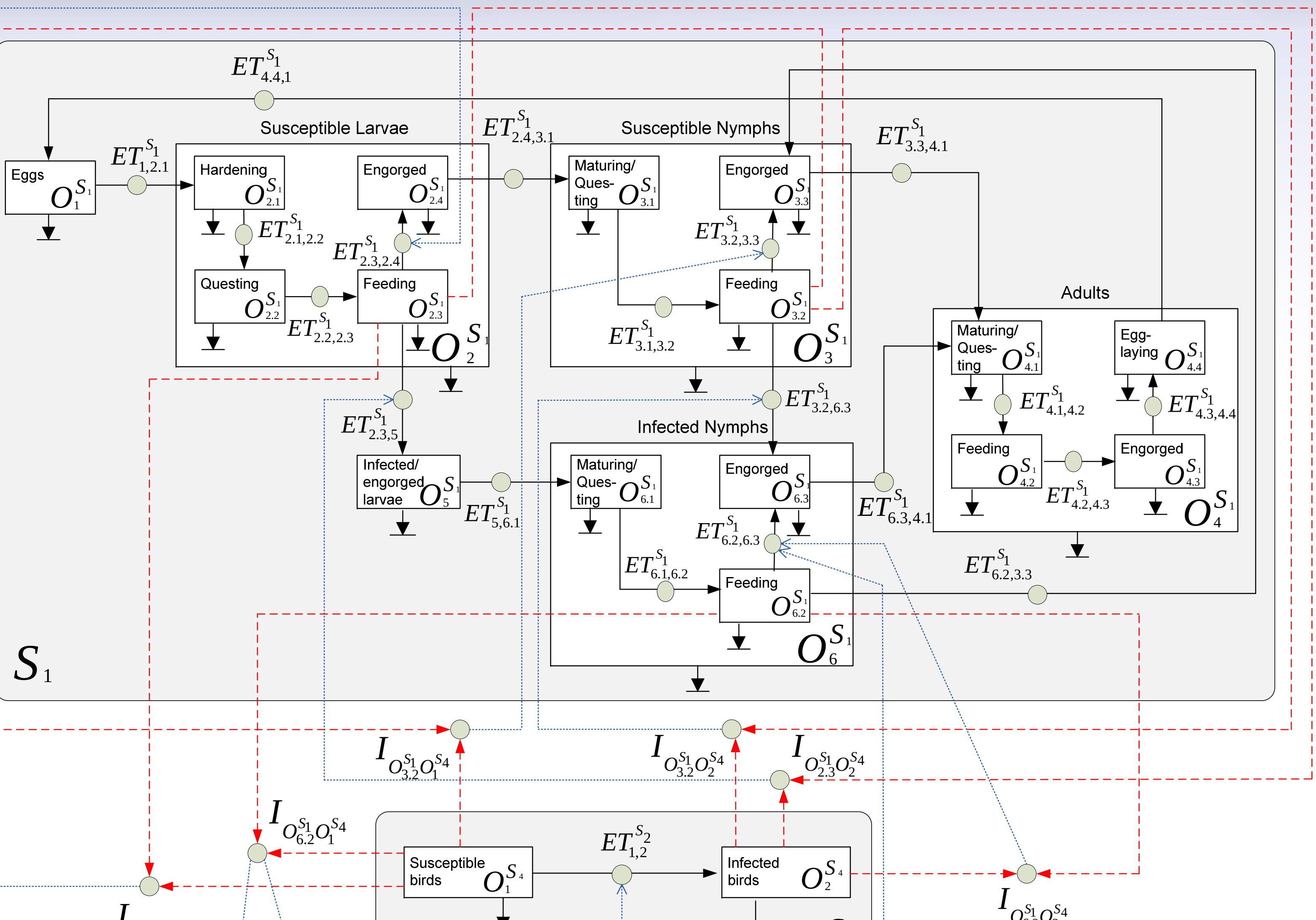
r approach is based on *transitions* between *states* that represent the ifferent stages of the evolution of a species (compartments)

distinguish different types of transitions:

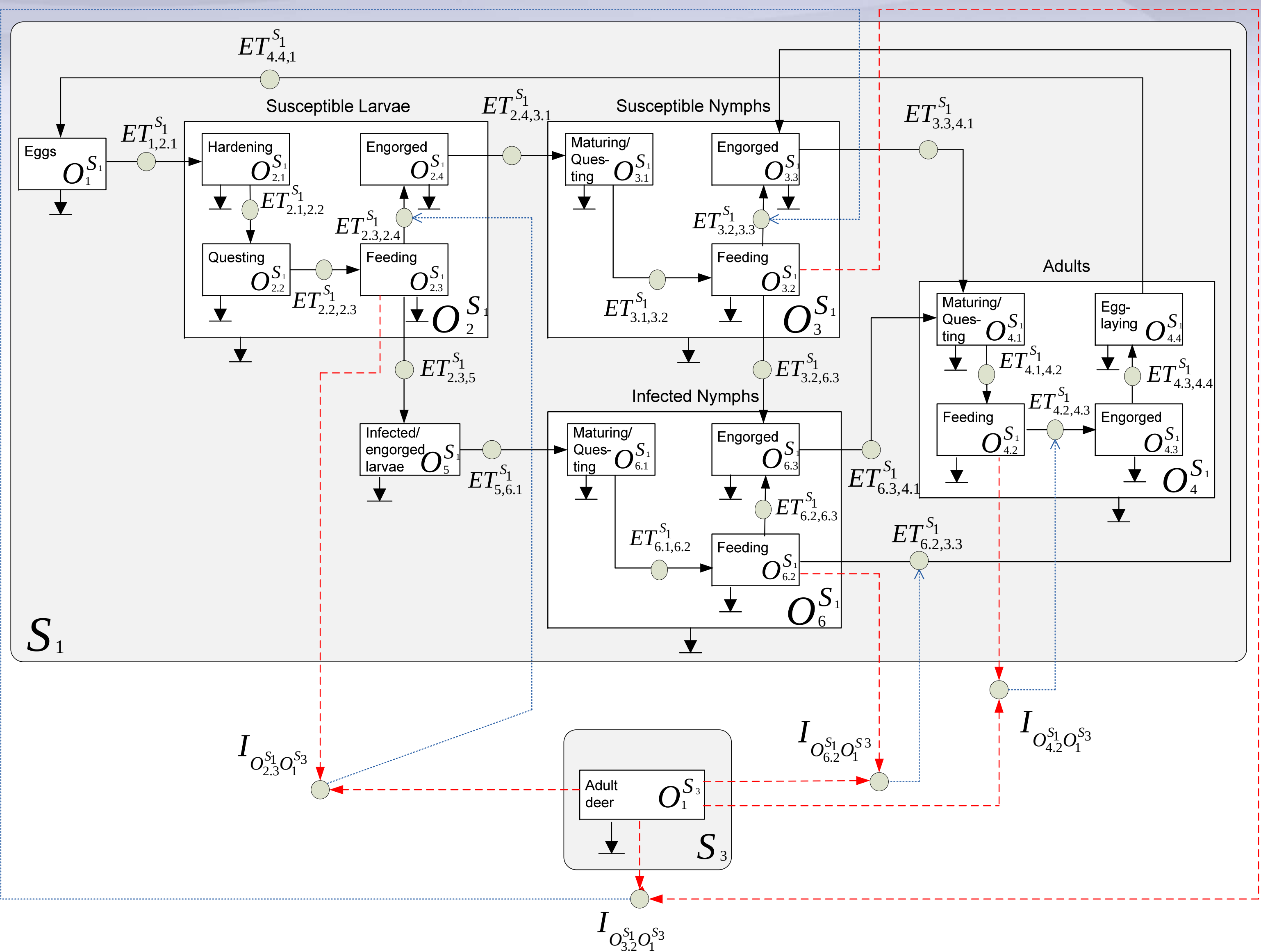
Evolutionary transitions (ET), *Interaction transitions* (I)

eraction transitions show the coupling between 2 compartments of ifferent species and trigger one or several *Evolutionary Transitions*

ur Model: Interactions between Ticks and Birds (taking into account the infection)



nteractions Between Ticks and Deer



A New Approach Enhancing Compartment Models with Spatial Characteristics (2012)

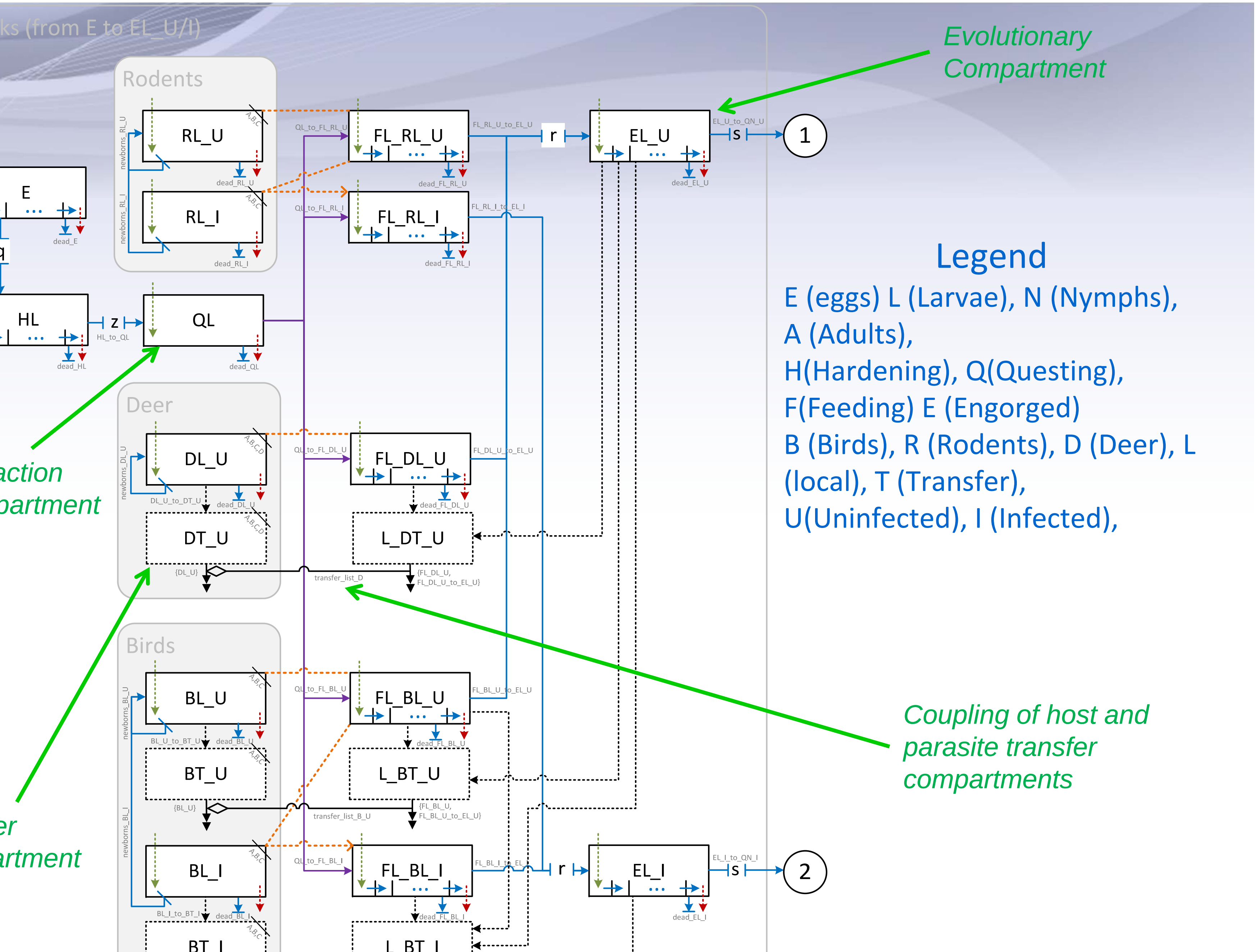
In some compartments we need to manage the maturation of ticks over time (we introduce the notion of cohort)

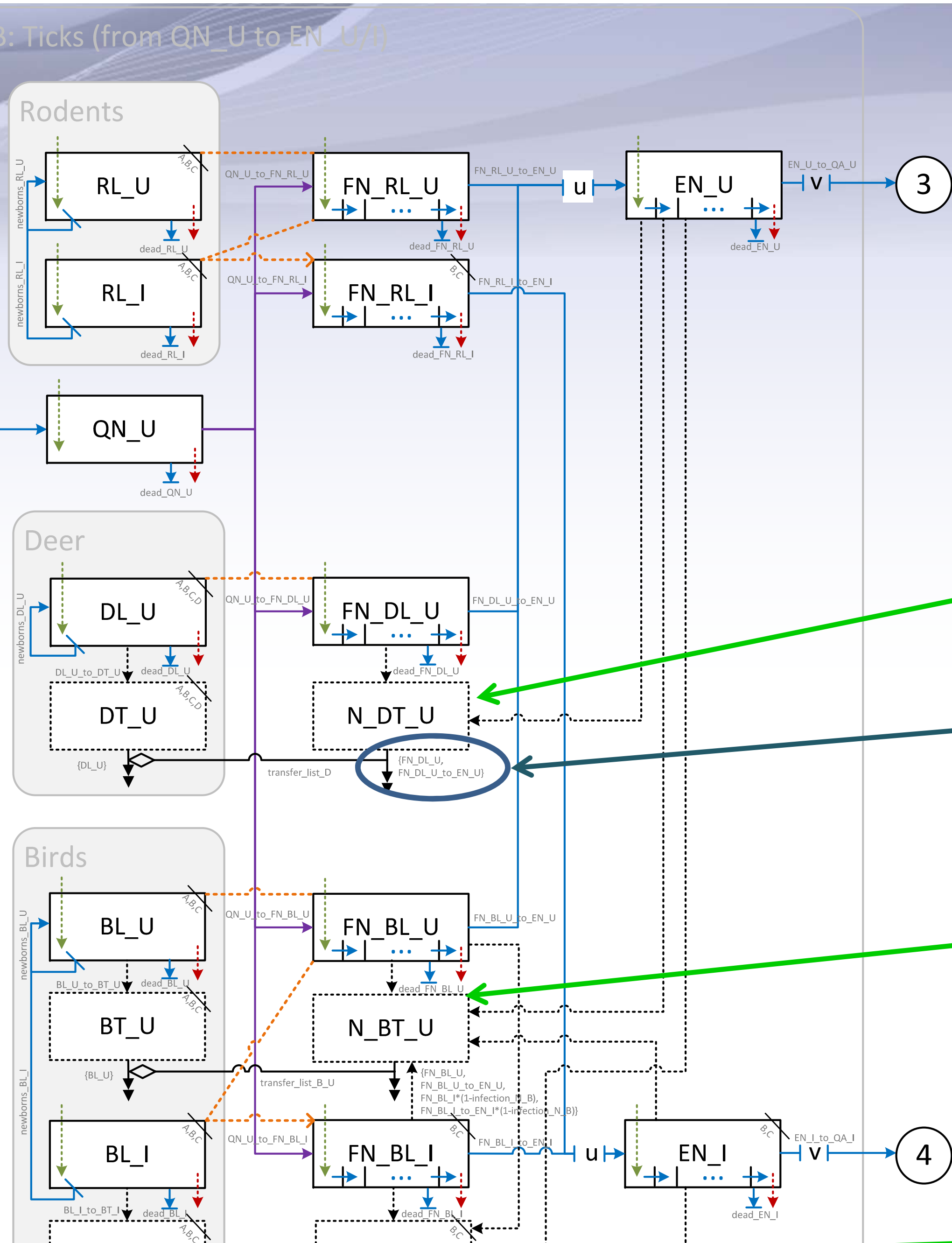
We introduce compartments for groups of individuals that stay in the cell as well as **compartments for groups that transfer from one cell to another** (to take into account displacements). We also need to consider infected and non infected groups

In the following slides we present an extended compartment model to specify the interactions of ticks, rodents, birds and deer, *taking into account infection and* ***spatial displacements of birds and deer (during migration period)***

There are three different kinds of compartments

- Evolutionary Compartments (with cohort management and maturation)
- Interaction Compartment


ks (from E to EL_U/I)
Rodents
RL_U
RL_I
FL_RL_U
FL_RL_I
EL_U
r
s
1
E
HL
z
QL
Evolutionary Compartment
Deer
DL_U
DT_U
FL_DL_U
L_DT_U
action
partment
transfer_list_D
Birds
BL_U
BT_U
FL_BL_U
L_BT_U
BL_I
BT_I
FL_BL_I
L_BT_I
EL_I
2
transfer_list_B_U
er
artment
Coupling of host and parasite transfer compartments
Legend
E (eggs) L (Larvae), N (Nymphs), A (Adults),
H(Hardening), Q(Questing),
F(Feeding) E (Engorged)
B (Birds), R (Rodents), D (Deer), L (local), T (Transfer),
U(Uninfected), I (Infected),



Legend

E (eggs) L (Larvae), N (Nymphs),
A (Adults),
H(Hardening), Q(Questing),
F(Feeding) E (Engorged)
B (Birds), R (Rodents), D (Deer), L (local), T (Transfer),
U(Uninfected), I (Infected),

Nymph Transfer On Deer

(Feeding Nymphs+ Engorged Nymphs)

Nymph Transfer On Uninfected Birds

Nymph Transfer On

The ZoonosisMAGS Project and Platform

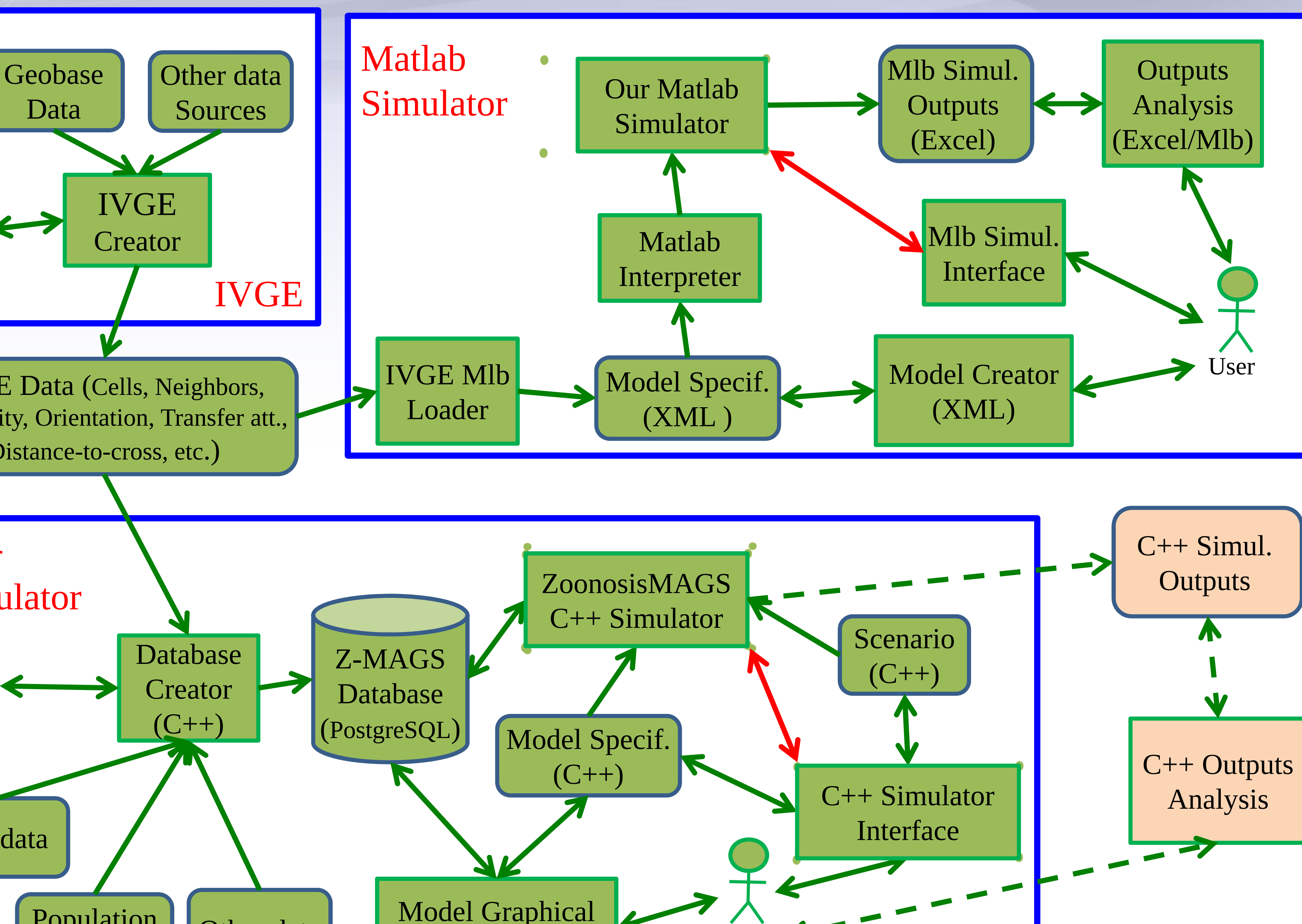
We developed a generic geosimulation platform to simulate the propagation of zoonoses such as the WNV and Lyme disease (Current application), and taking into account the characteristics of the geographic environment and its influence on the evolution/interactions of the involved species;

The objective is to enable Public Health Officers to: 1) *analyze the spatial-temporal characteristics* of the spread of a zoonose 2) *to specify different climate and/or intervention scenarios and to compare their outcomes*

The platform design takes into account:

- a hierarchical organization of the virtual geographic space,
- data imported from a variety of sources,
- a new conceptual approach of compartment models that integrates the spatial dimension (new formalism)

Overview of our Software Suite



Tool to Assess Complex Compartment Models

ectives:

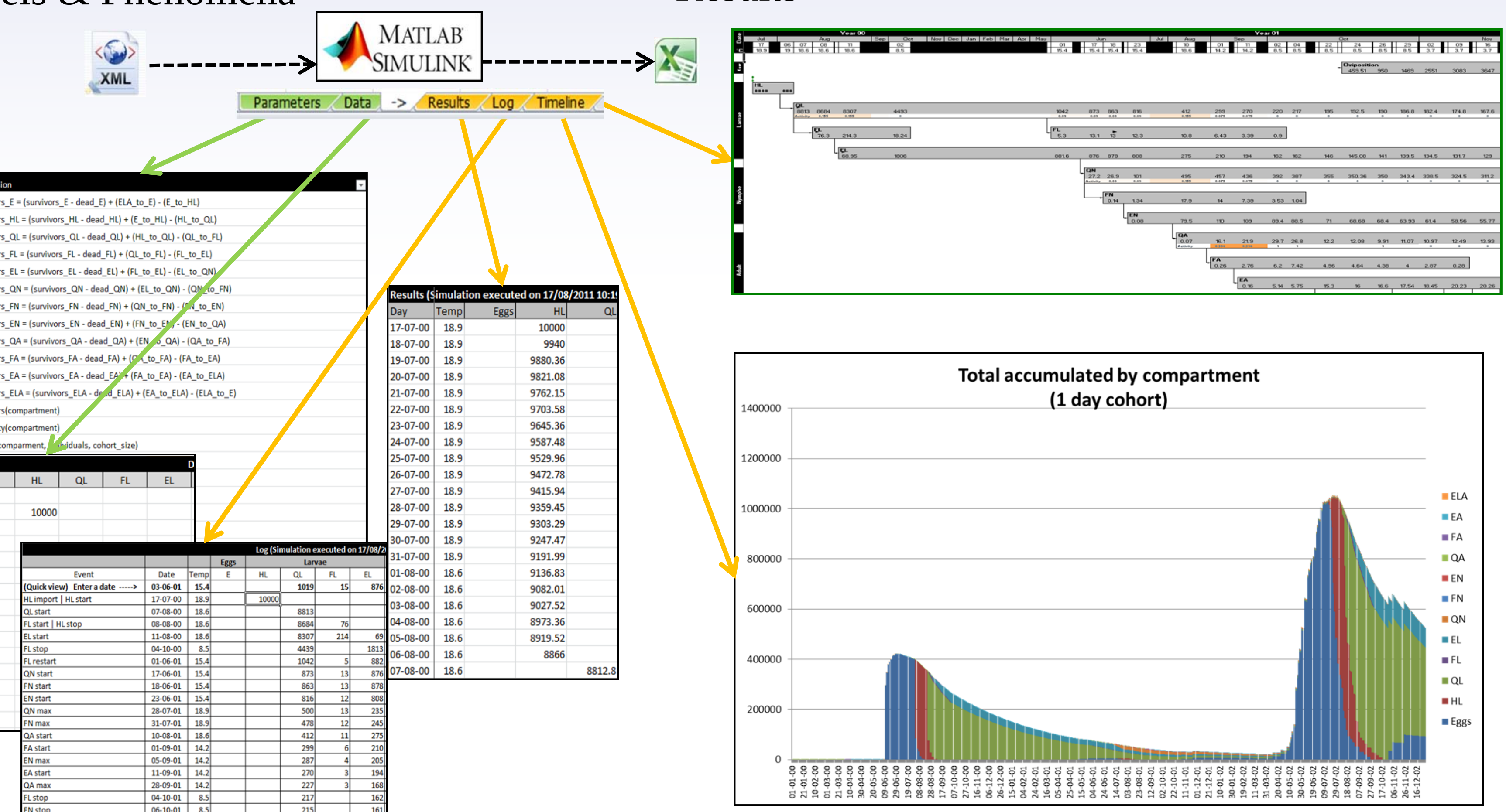
- o study complex compartment models' dynamics
- o analyse the joint behaviour of multiple variables (significant s. less significant) (Sensitivity analysis)
- o develop a rapid prototyping software to experiment with ifferent versions of compartment models and the influence of arious biological, meteorological, temporal and spatial arameters (and compare with models available in the literature)
- o analyse the influence of cohort related parameters
- o compare with existing implemented models (i.e. Ogden's tella simulator)
- o offer tools to specify various scenarios and compare the utcomes of the corresponding simulations

Our Matlab Simulator

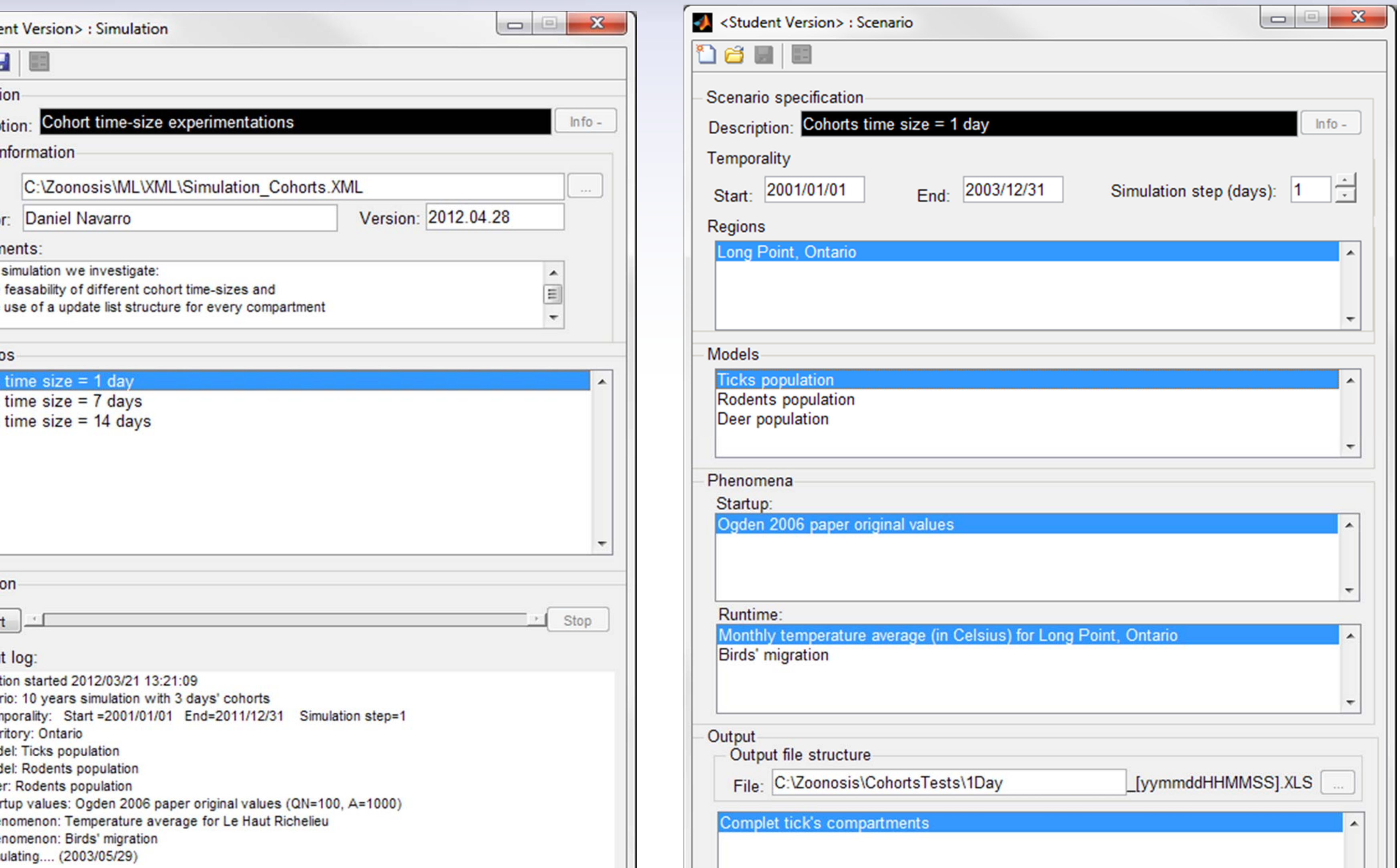
arios data source → Data output, Log & Timeline

els & Phenomena

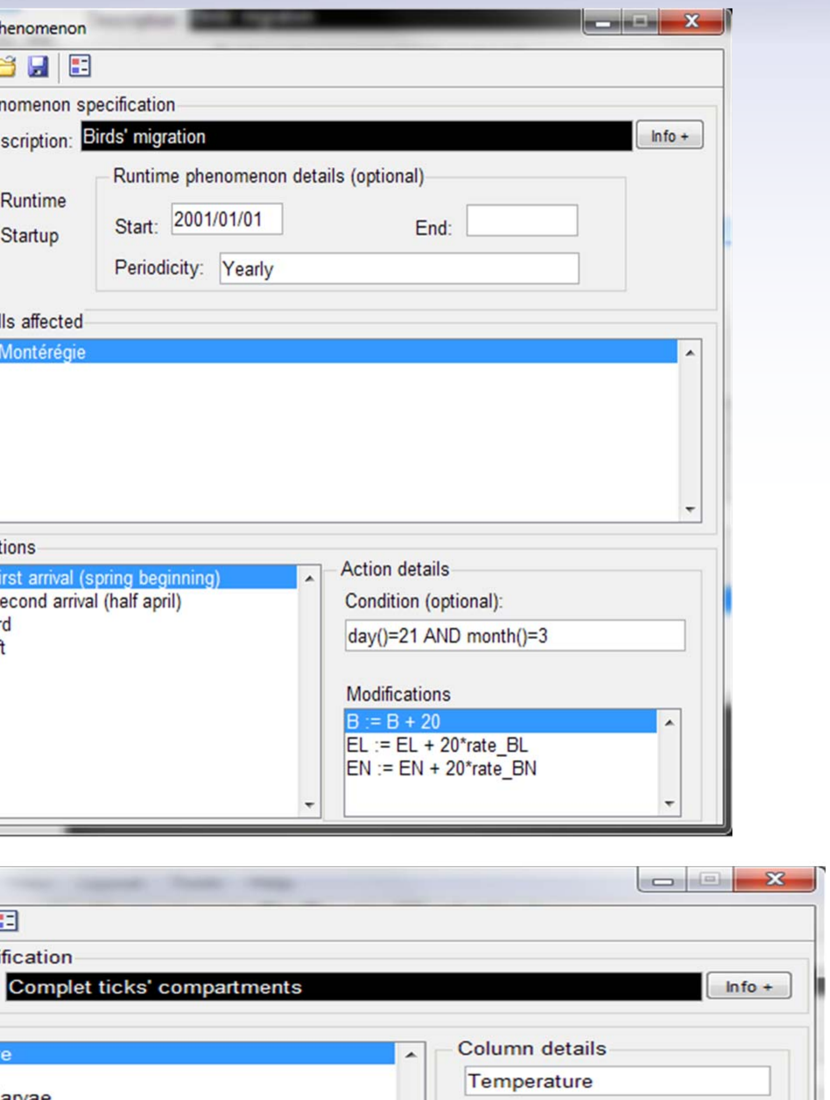
Results

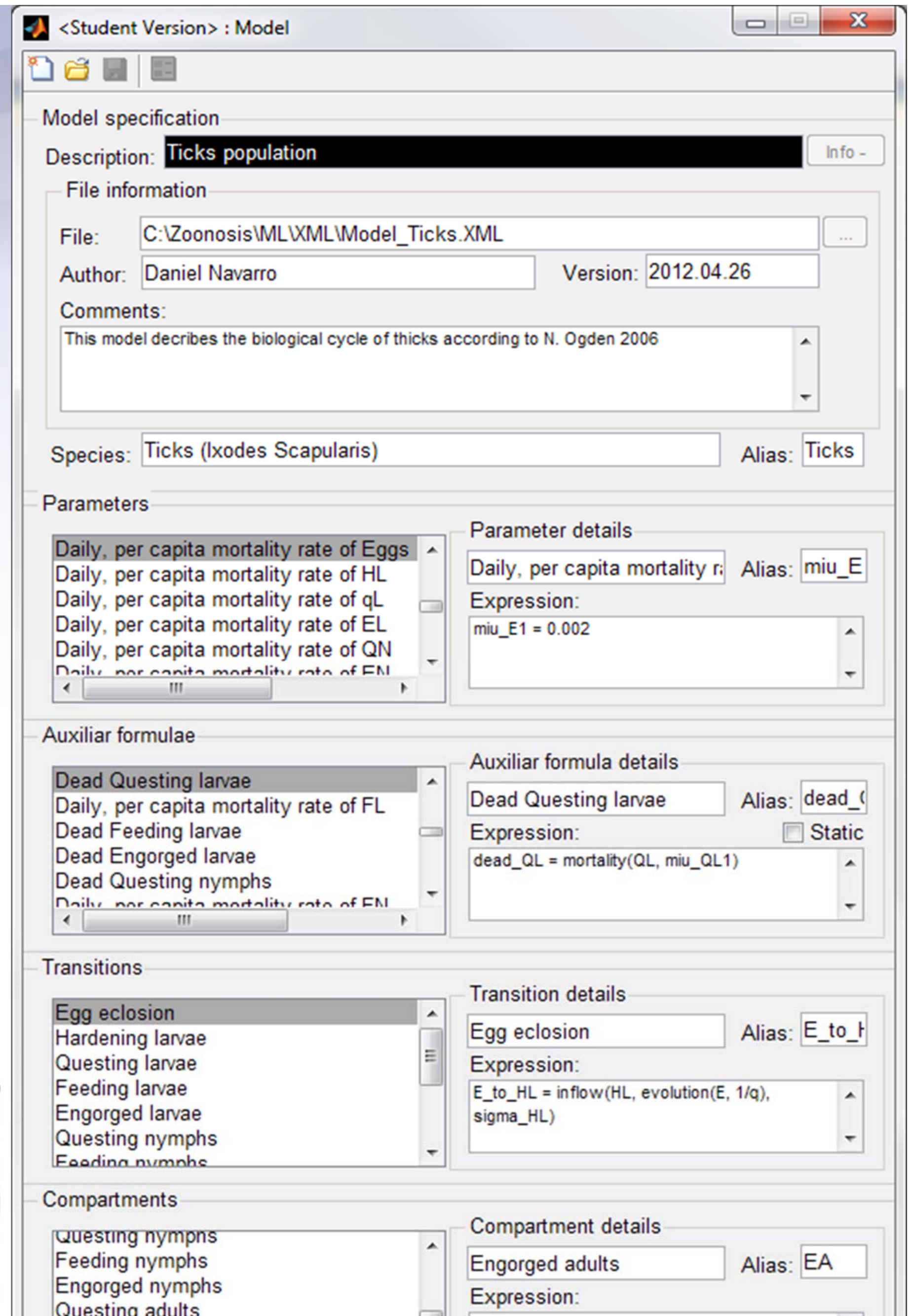


Scenario Specification Interface (1/2)



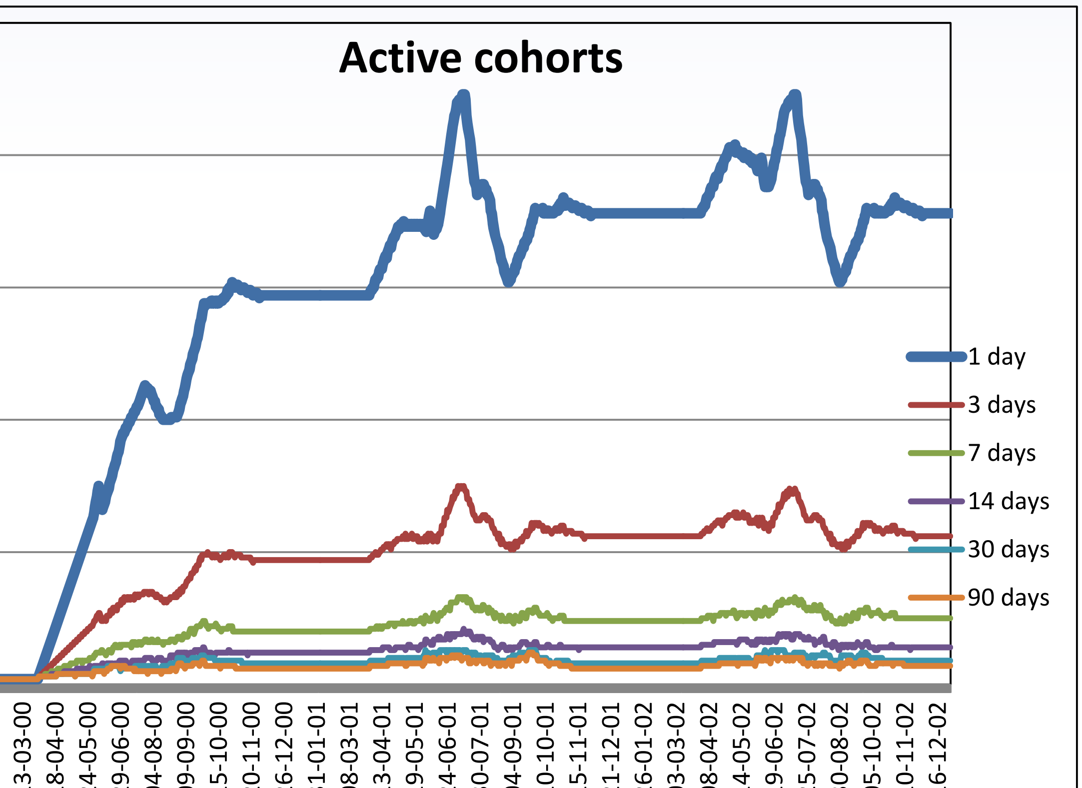
cenario Specification Interface (2/2)

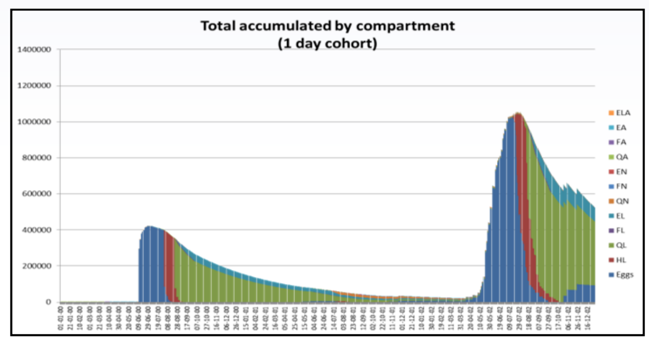


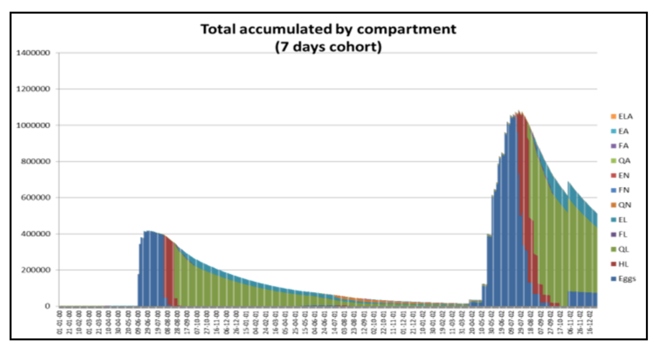


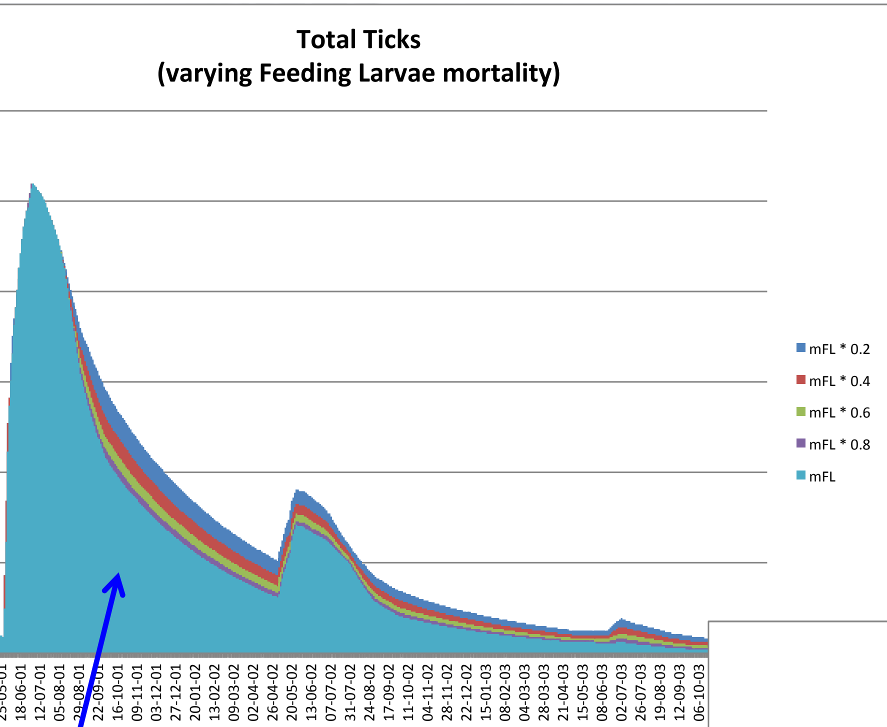
Experiments with the Matlab Simulator

We carried out several experiments to compare different time lapses to create cohorts in Evolutionary Compartments. We aim at reducing the number of the required simulation time steps while still representing faithfully the maturation phenomenon (with minimum loss of fidelity)







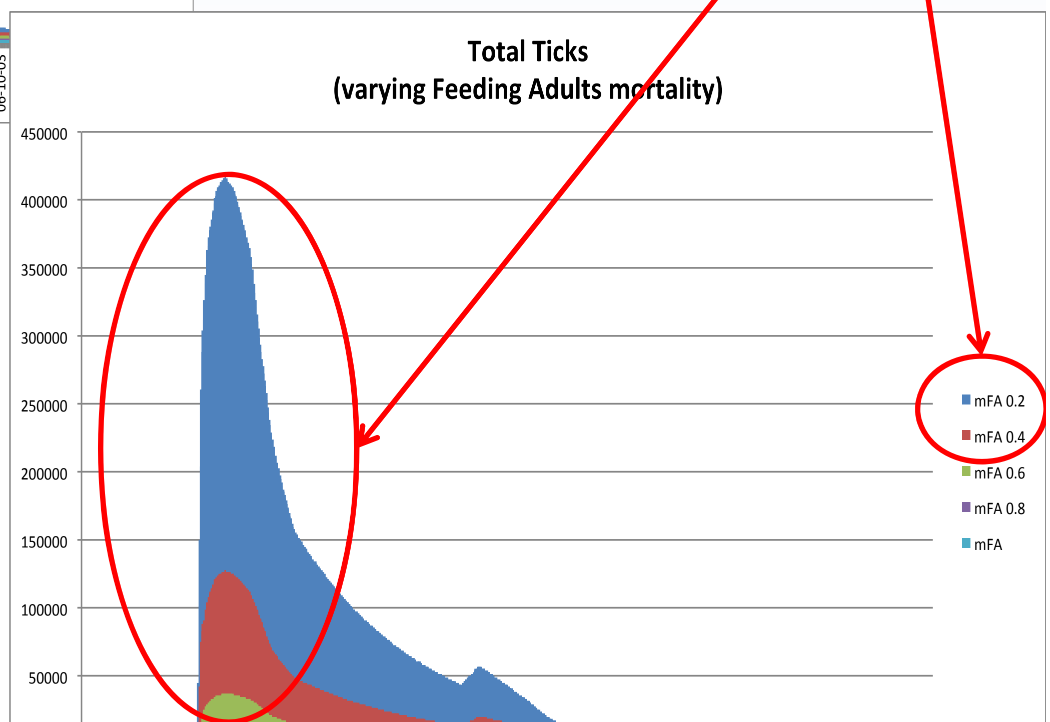


Sensitivity Analysis

Influence of Tick Mortality Rates (Larvae, Nymphae)

Important Sensitivity

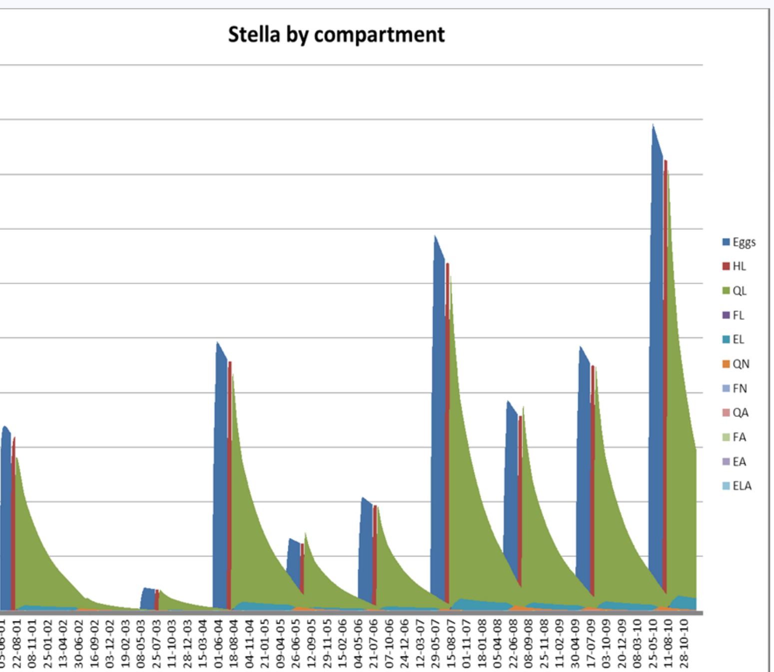
lumber of (ref Ogden's data)

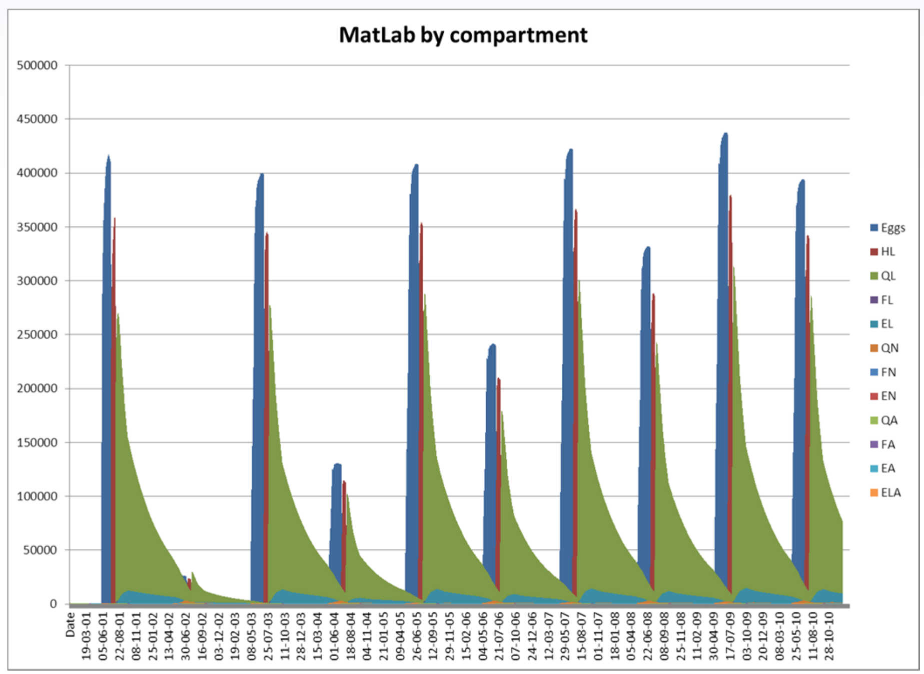


Sensitivity Analysis - Tick Mortality Rates

mparison with Ogden's Stella Model (on 10 yrs)

or calibration purposes we compared our results with the imulation of the tick dynamics carried out by Ogden's team sing Stella (ISEE's System Dynamics Simulator)





number of questions arose during this comparison especially

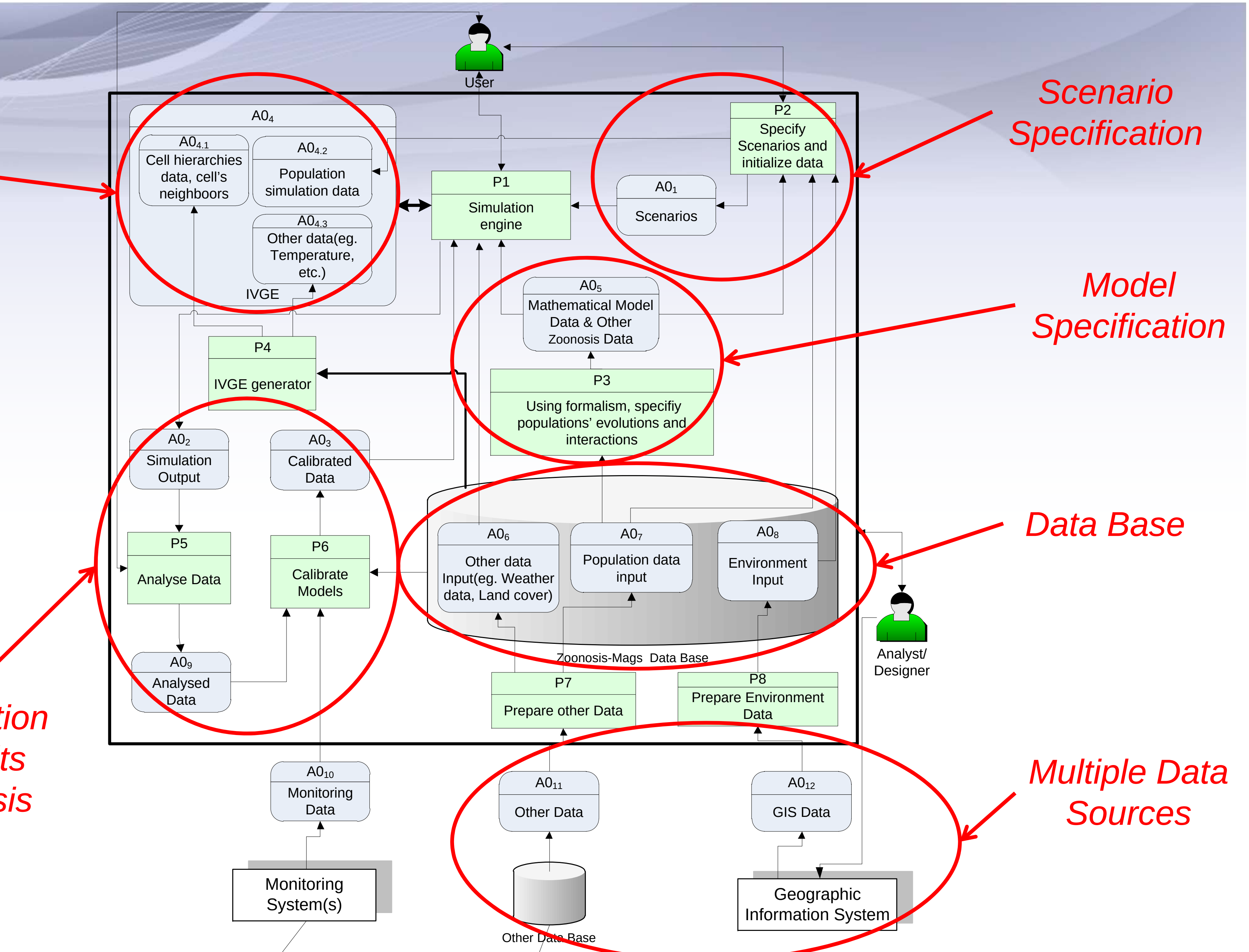
Conclusion about our Matlab Simulator

- Our Matlab Simulator is quite efficient and practical to assess compartment models (including our extended model enhanced with spatial information provided by the IVGE)
- It is extensively used to generate data to test the C++ Simulator and help us ensure that the coding and behaviour of ZoonosisMAGS is correct
- Several new analyses are now possible thanks to our Matlab Simulator
- However, the *C++ Simulator* is needed to be able to carry out *simulations on large territories* represented by tens of thousands of cells
- The C++ System is much more complex than the Matlab simulator (which benefits from the Matlab programming environment and the Matlab math expression parser)

e ZoonosisMAGS Platform (C++ Simulator)

e ZoonosisMAGS Platform aims at offering an integrated set tools and user-friendly interfaces to specify:

- the ***virtual geographic environment*** (VGE) of the studied area in the form of a hierarchy of spatial plans composed of irregular cells that reflect the ‘biology of the phenomena’ (land-cover characteristics, suitability of areas to the survival of involved species) as well as administrative divisions useful to the user
- ***models that describe the biological evolution*** of the different species involved in the zoonose (equivalent to mathematical compartment models) as well as models of these species’ interactions (stage evolution, infection propagation)
- ***models of the movements and spatial interactions of sub-populations*** of the species across the landscape (represented by the VGE cells)
- ***scenarios*** (climatic, human interventions)


User
A0$_4$
A0$_{4.1}$
Cell hierarchies data, cell's neighboors
A0$_{4.2}$
Population simulation data
A0$_{4.3}$
Other data(eg. Temperature, etc.)
IVGE
P1
Simulation engine
A0$_1$
Scenarios
P2
Specify Scenarios and initialize data
Scenario Specification
A0$_5$
Mathematical Model Data & Other Zoonosis Data
Model Specification
P4
IVGE generator
P3
Using formalism, specifiy populations' evolutions and interactions
A0$_2$
Simulation Output
A0$_3$
Calibrated Data
P5
Analyse Data
P6
Calibrate Models
A0$_6$
Other data Input(eg. Weather data, Land cover)
A0$_7$
Population data input
A0$_8$
Environment Input
Data Base
Zoonosis-Mags Data Base
Analyst/ Designer
A0$_9$
Analysed Data
P7
Prepare other Data
P8
Prepare Environment Data
A0$_{10}$
Monitoring Data
A0$_{11}$
Other Data
A0$_{12}$
GIS Data
Multiple Data Sources
Monitoring System(s)
Other Data Base
Geographic Information System

Matlab Simulator

id Prototyping on limited areas
(One or few tens of cells)

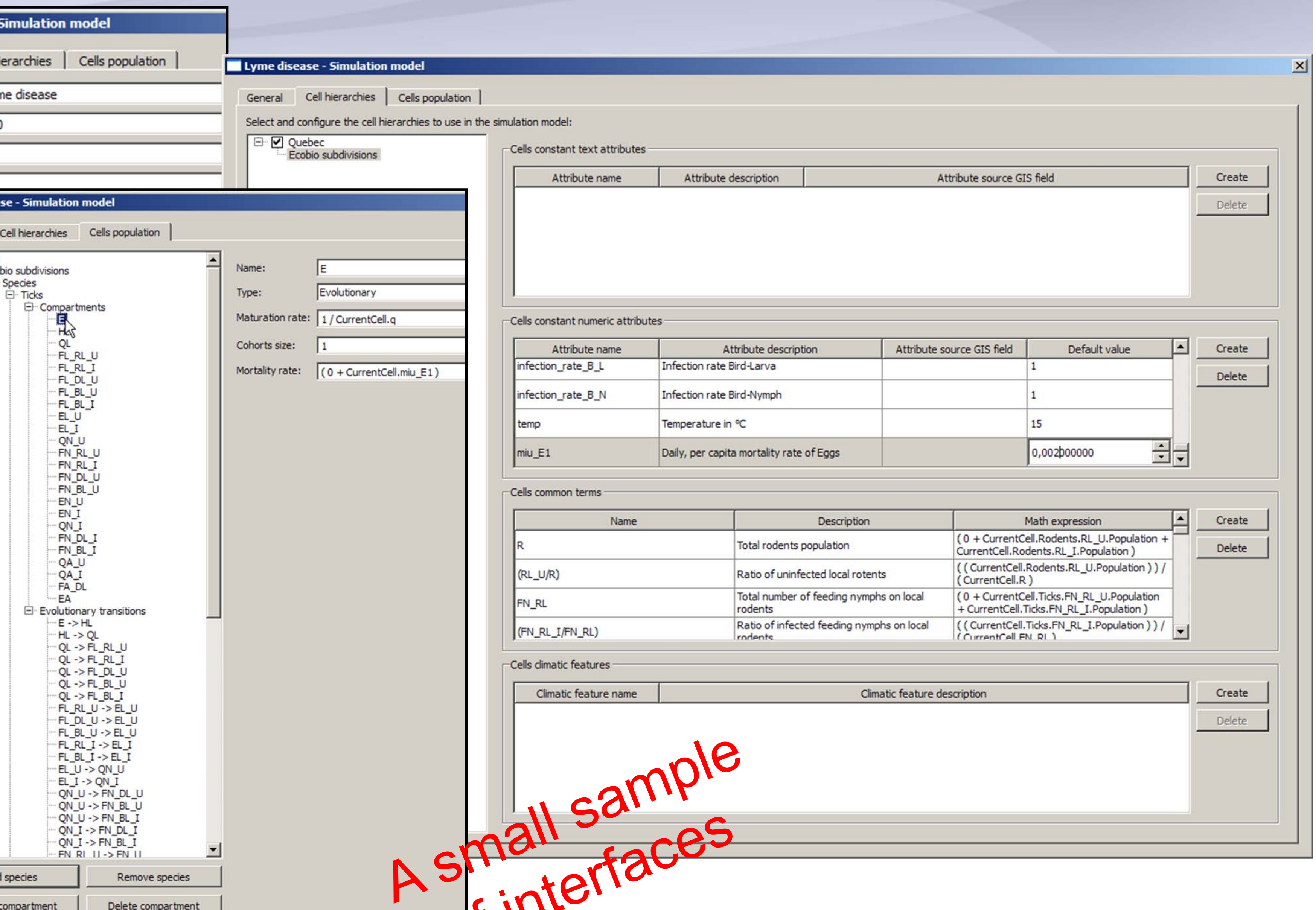
- Objective 1: Assess/Compare models and simul. output, Analyse the effects of changing model parameters, of using different scenarios
- Objective 2: Test sets of equations and functions (Models) before implemen-ting them in C++; Develop/Implement and test simulation mechanisms that can subsequently be reengineered & implemented in the C++ simulator
- Objective 3: Generate data sets (input & output) to test the validity of the C++ simulation in selected 'test areas'

C++ Simulator

Simulation carried out on large areas
(Thousands of cells)

- Objective 1: Carry-out full-scale simulations on large territories with complete data about the landscape, species data (resident and migrating)
- Objective 2: Assess/Compare the results of these simulations using different scenarios
- Objective 3: Carry out spatial analyses on the simulation results on large territories (taking advantage of a hierarchical organization of space) and data collected in the field

ating a Compartment Model in ZoonosisMAGS



Matlab Simulator

nput:
- XML files for the models, functions, mathematical expressions
- Daily temperatures are set using an external file; Cells' attributes are obtained from a file generated by the IVGE Creator
- User Interfaces to set parameters of scenarios, provide data entries, etc.
- All data are loaded in the Main Memory

Specific Feature: Mathematical expressions are parsed on-the-fly by Matlab interpreter

Time step: one day

Simulation Output: Temporal evolution of all compartments recorded in an Excel Sheet

Output Analyses: Results can be analysed either in Excel or Matlab. Very convenient to assess the evolution of various variables

C++ Simulator

- Input:
  - A variety of data source is used (GIS data, population data, temperature data, etc.) plus the IVGE are input in a PostgreSQL data base
  - A variety of user interfaces to set the various parameters during the different operations of the system
  - Input of Compartment Models either using Interfaces or using a Visio graphical interface (partial implementation)
  - User Interfaces to set parameters of scenarios : (Not implemented yet)
- Specific Feature: Capacity for managing hierarchical set of cells to enable the spatial analysis at different levels of detail
- Time step: one day
- Simulation Output: (Currently) in the same tabular Excel format to simplify the comparison with the Matlab Simulator
- Output Display and Analyses: (Not implemented yet)

Summary

r approach and software suite offer tools to:

- Assess/Compare Spatially Explicit Epidemiological Models
- Study the influence of landscape and population ecology (Landscape Epidemiology)
- Integrate different models (Model Integration/Fusion)
- Integrate data from multiple sources
- Simulate various scenarios (w.r.t. climate, human intervention)

r approach can be extended to:

- Integrate various spatial and statistical analysis tools
- Integrate other data sources (Remote sensing, etc.)
- Evolve toward a Public Health Decision Support System
- Use enhanced simulation techniques (parallelism, stochasticity individual + population based, etc.)

Acknowledgements

- Geoide, the Canadian Network of Centers of Excellence in Geomatics
- INSPQ (Institut National de Santé Publique du Québec)
- Ministère de la santé et des services sociaux du Québec
- Public Health Canada
- Ministère des ressources naturelles et de la faune du Québec
- Defence Research and Development Canada

Acknowledgements

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MAISONS DES SCIENCES DE L'HOMME RÉSEAU

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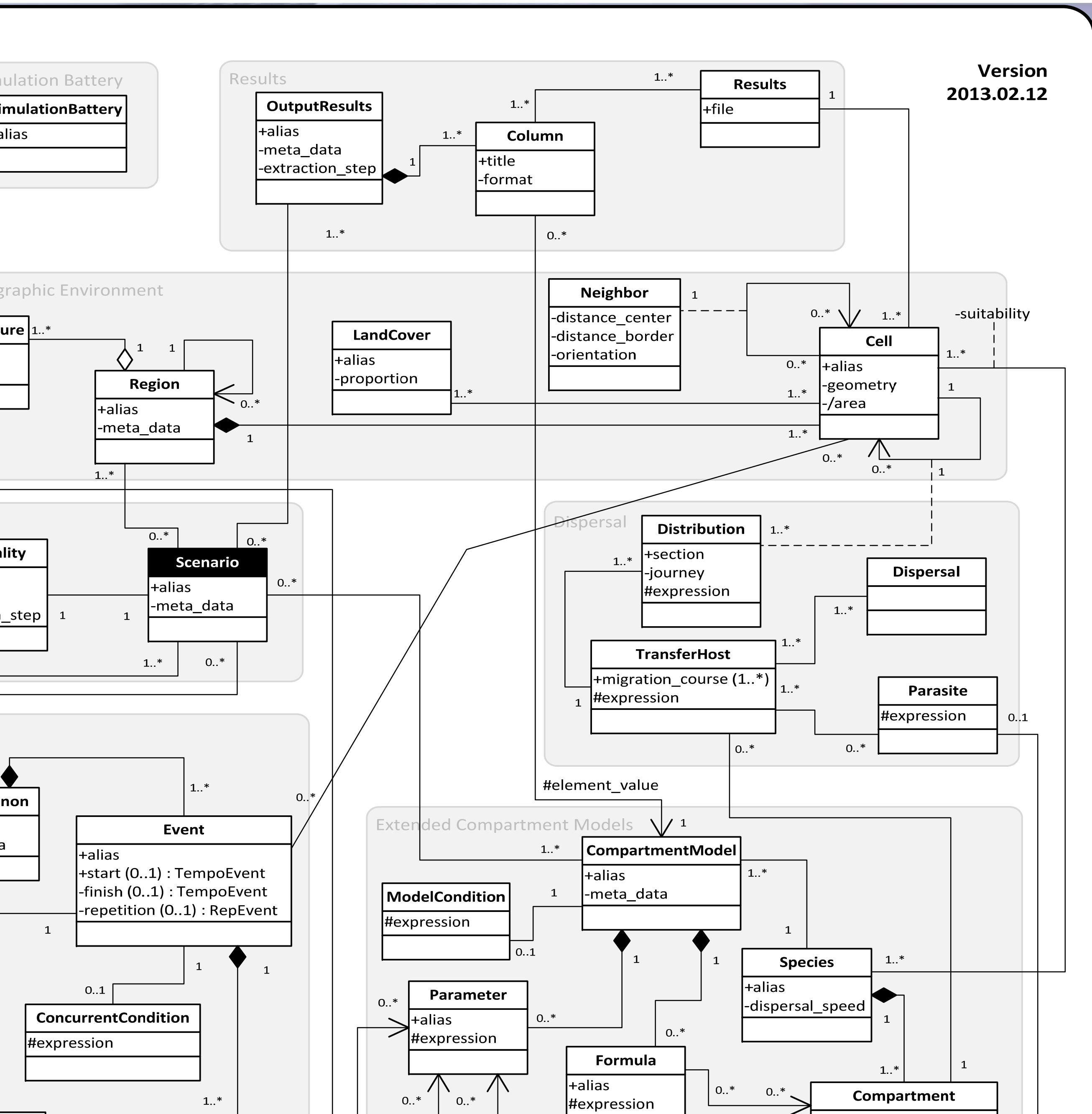
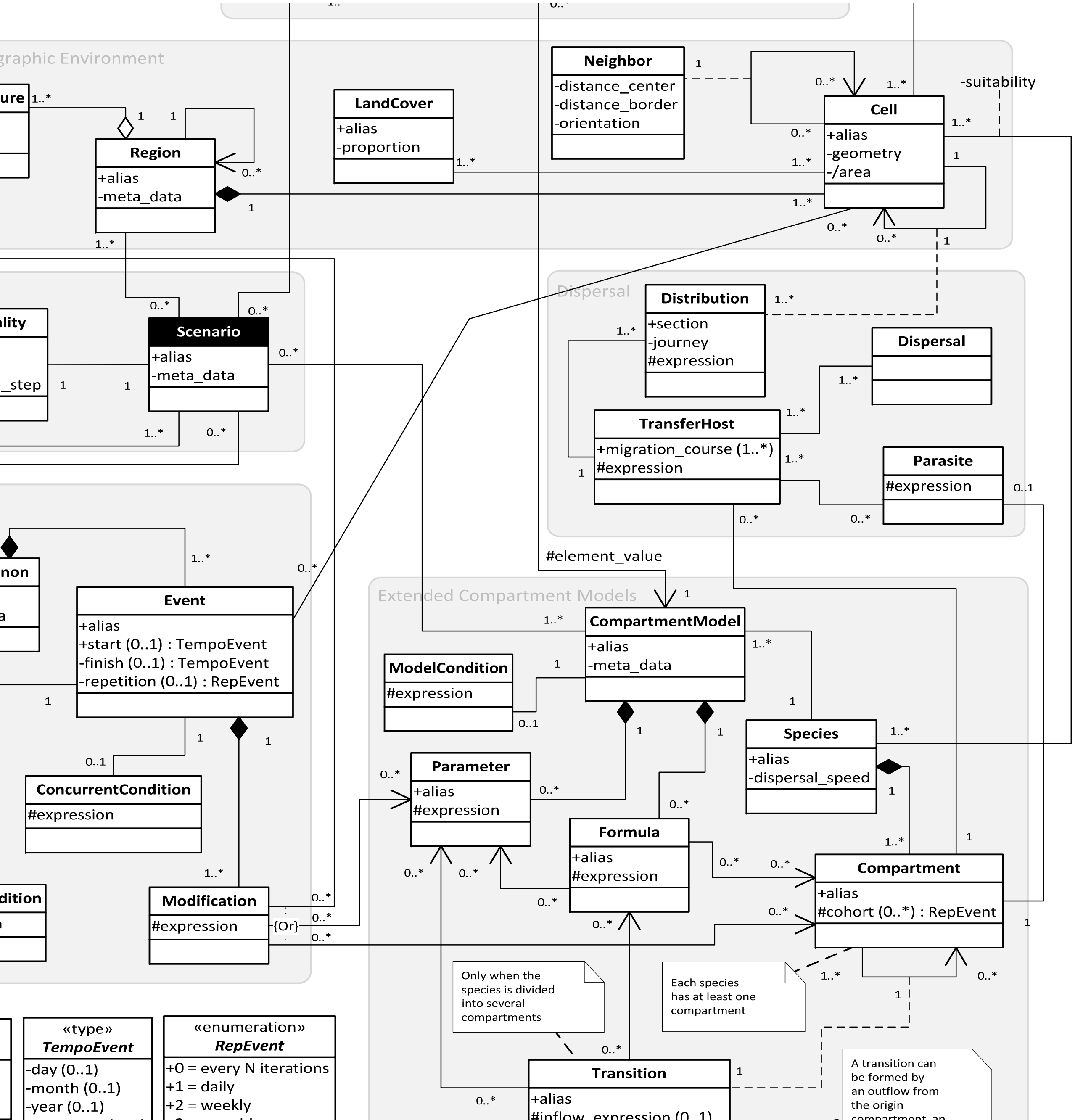
Appendices

Conceptual model of a multi-scenario simulation




graphic Environment
ure
Region
+alias
-meta_data
LandCover
+alias
-proportion
Neighbor
-distance_center
-distance_border
-orientation
Cell
+alias
-geometry
-/area
-suitability
ality
_step
Scenario
+alias
-meta_data
Dispersal
Distribution
+section
-journey
#expression
Dispersal
TransferHost
+migration_course (1..*)
#expression
Parasite
#expression
#element_value
Extended Compartment Models
CompartmentModel
+alias
-meta_data
ModelCondition
#expression
Species
+alias
-dispersal_speed
Parameter
+alias
#expression
Formula
+alias
#expression
Compartment
+alias
#cohort (0..*) : RepEvent
non
a
Event
+alias
+start (0..1) : TempoEvent
-finish (0..1) : TempoEvent
-repetition (0..1) : RepEvent
ConcurrentCondition
#expression
dition
n
Modification
#expression
{Or}
Only when the species is divided into several compartments
Each species has at least one compartment
A transition can be formed by an outflow from the origin compartment, an
Transition
+alias
#inflow_expression (0..1)
«type»
TempoEvent
-day (0..1)
-month (0..1)
-year (0..1)
«enumeration»
RepEvent
+0 = every N iterations
+1 = daily
+2 = weekly

Result of the Progressive Merging of Cells

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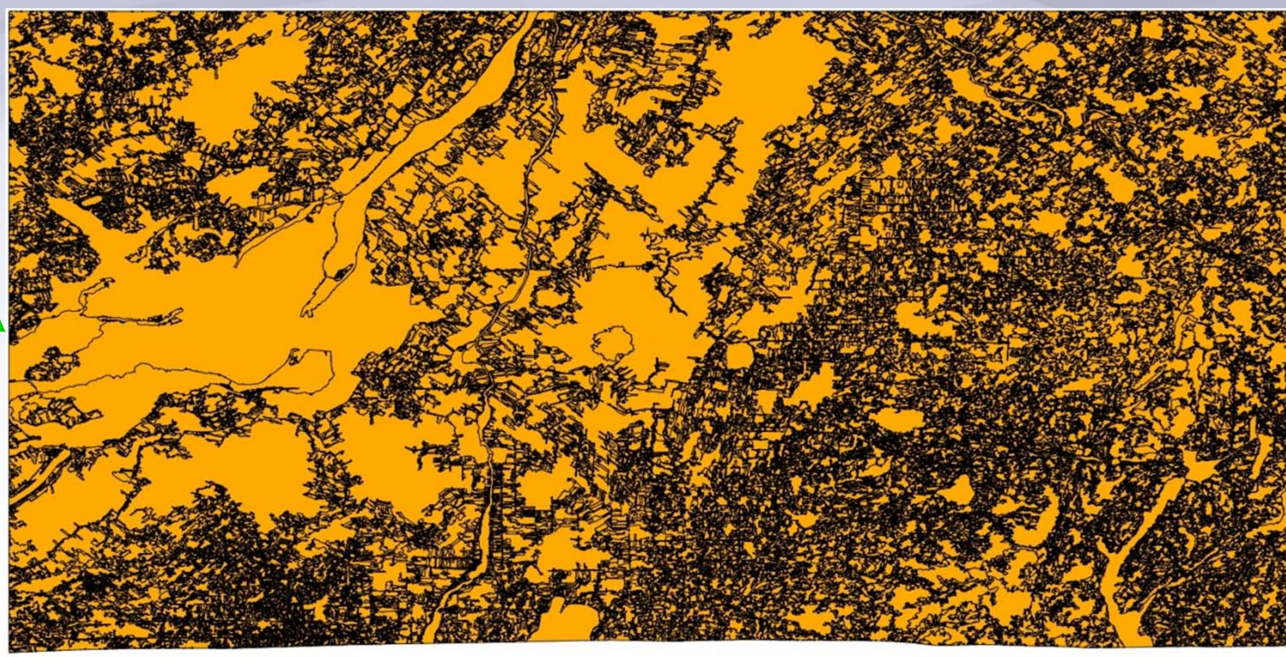

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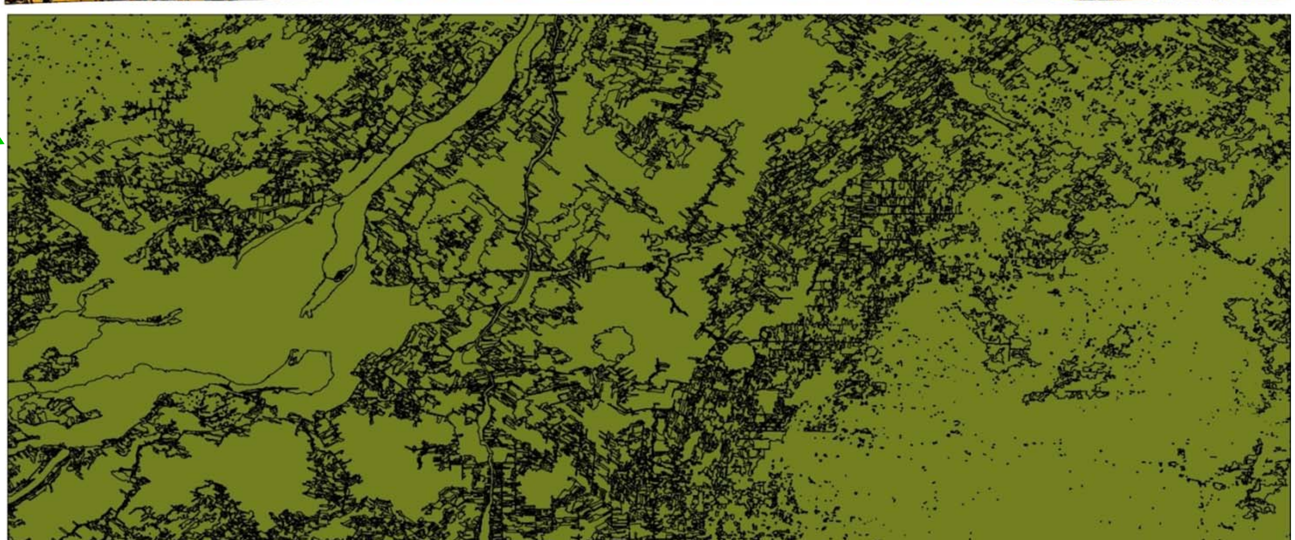

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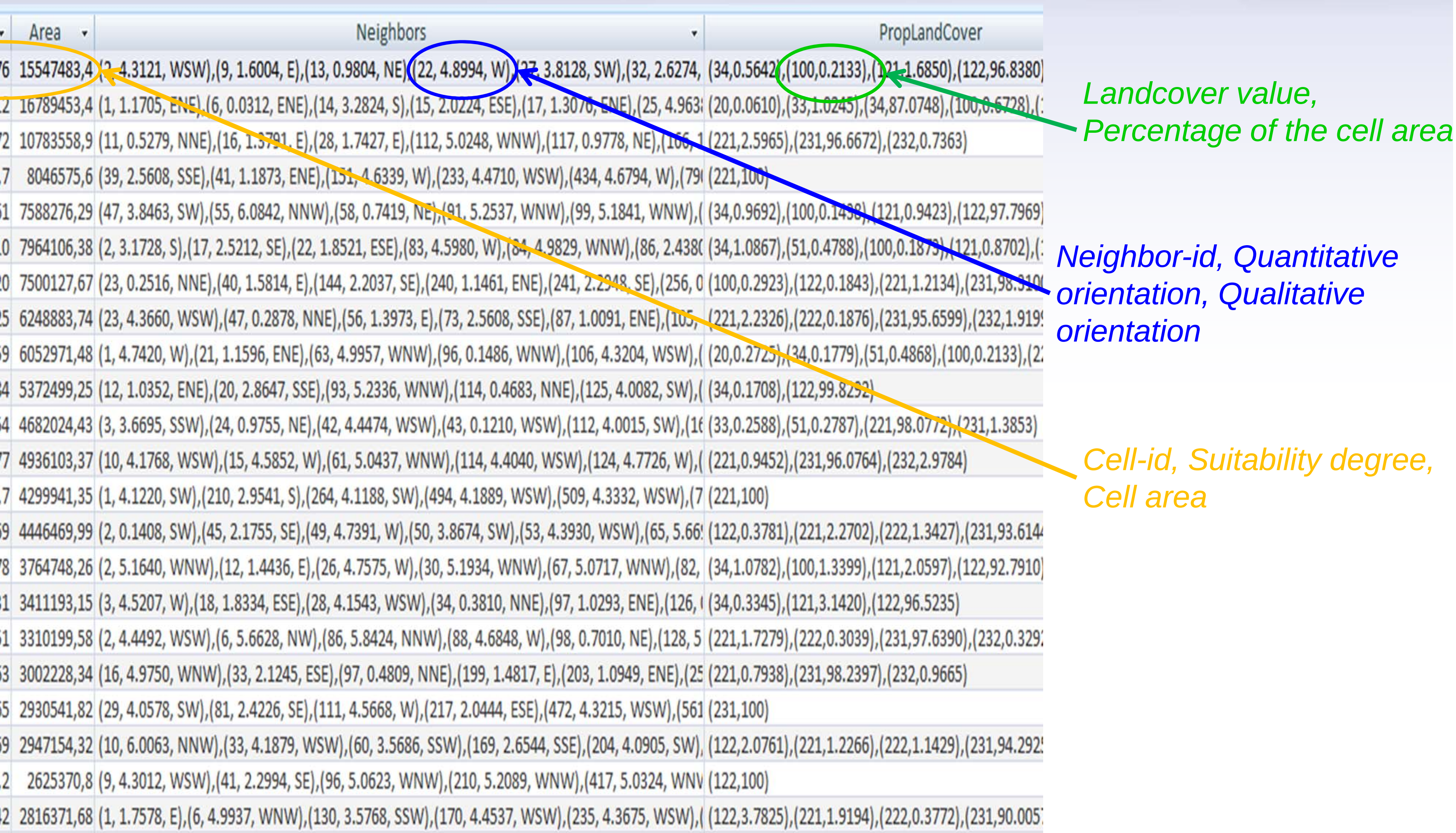


	Area	Neighbors	PropLandCover
76	15547483,4	(2, 4.3121, WSW),(9, 1.6004, E),(13, 0.9804, NE),(22, 4.8994, W),(27, 3.8128, SW),(32, 2.6274,	(34,0.5642),(100,0.2133),(121,1.6850),(122,96.8380)
12	16789453,4	(1, 1.1705, ENE),(6, 0.0312, ENE),(14, 3.2824, S),(15, 2.0224, ESE),(17, 1.3076, ENE),(25, 4.963	(20,0.0610),(33,1.0245),(34,87.0748),(100,0.6728),(
72	10783558,9	(11, 0.5279, NNE),(16, 1.3791, E),(28, 1.7427, E),(112, 5.0248, WNW),(117, 0.9778, NE),(166, 1	(221,2.5965),(231,96.6672),(232,0.7363)
17	8046575,6	(39, 2.5608, SSE),(41, 1.1873, ENE),(151, 4.6339, W),(233, 4.4710, WSW),(434, 4.6794, W),(79	(221,100)
51	7588276,29	(47, 3.8463, SW),(55, 6.0842, NNW),(58, 0.7419, NE),(91, 5.2537, WNW),(99, 5.1841, WNW),(	(34,0.9692),(100,0.1498),(121,0.9423),(122,97.7969)
10	7964106,38	(2, 3.1728, S),(17, 2.5212, SE),(22, 1.8521, ESE),(83, 4.5980, W),(84, 4.9829, WNW),(86, 2.438	(34,1.0867),(51,0.4788),(100,0.1873),(121,0.8702),(
20	7500127,67	(23, 0.2516, NNE),(40, 1.5814, E),(144, 2.2037, SE),(240, 1.1461, ENE),(241, 2.2948, SE),(256, 0	(100,0.2923),(122,0.1843),(221,1.2134),(231,98.310
25	6248883,74	(23, 4.3660, WSW),(47, 0.2878, NNE),(56, 1.3973, E),(73, 2.5608, SSE),(87, 1.0091, ENE),(105,	(221,2.2326),(222,0.1876),(231,95.6599),(232,1.919
59	6052971,48	(1, 4.7420, W),(21, 1.1596, ENE),(63, 4.9957, WNW),(96, 0.1486, WNW),(106, 4.3204, WSW),(	(20,0.2725),(34,0.1779),(51,0.4868),(100,0.2133),(2
34	5372499,25	(12, 1.0352, ENE),(20, 2.8647, SSE),(93, 5.2336, WNW),(114, 0.4683, NNE),(125, 4.0082, SW),(	(34,0.1708),(122,99.8292)
54	4682024,43	(3, 3.6695, SSW),(24, 0.9755, NE),(42, 4.4474, WSW),(43, 0.1210, WSW),(112, 4.0015, SW),(16	(33,0.2588),(51,0.2787),(221,98.0772),(231,1.3853)
77	4936103,37	(10, 4.1768, WSW),(15, 4.5852, W),(61, 5.0437, WNW),(114, 4.4040, WSW),(124, 4.7726, W),(	(221,0.9452),(231,96.0764),(232,2.9784)
17	4299941,35	(1, 4.1220, SW),(210, 2.9541, S),(264, 4.1188, SW),(494, 4.1889, WSW),(509, 4.3332, WSW),(7	(221,100)
59	4446469,99	(2, 0.1408, SW),(45, 2.1755, SE),(49, 4.7391, W),(50, 3.8674, SW),(53, 4.3930, WSW),(65, 5.66	(122,0.3781),(221,2.2702),(222,1.3427),(231,93.614
78	3764748,26	(2, 5.1640, WNW),(12, 1.4436, E),(26, 4.7575, W),(30, 5.1934, WNW),(67, 5.0717, WNW),(82,	(34,1.0782),(100,1.3399),(121,2.0597),(122,92.7910)
31	3411193,15	(3, 4.5207, W),(18, 1.8334, ESE),(28, 4.1543, WSW),(34, 0.3810, NNE),(97, 1.0293, ENE),(126,	(34,0.3345),(121,3.1420),(122,96.5235)
61	3310199,58	(2, 4.4492, WSW),(6, 5.6628, NW),(86, 5.8424, NNW),(88, 4.6848, W),(98, 0.7010, NE),(128, 5	(221,1.7279),(222,0.3039),(231,97.6390),(232,0.329
53	3002228,34	(16, 4.9750, WNW),(33, 2.1245, ESE),(97, 0.4809, NNE),(199, 1.4817, E),(203, 1.0949, ENE),(25	(221,0.7938),(231,98.2397),(232,0.9665)
55	2930541,82	(29, 4.0578, SW),(81, 2.4226, SE),(111, 4.5668, W),(217, 2.0444, ESE),(472, 4.3215, WSW),(561	(231,100)
59	2947154,32	(10, 6.0063, NNW),(33, 4.1879, WSW),(60, 3.5686, SSW),(169, 2.6544, SSE),(204, 4.0905, SW),	(122,2.0761),(221,1.2266),(222,1.1429),(231,94.292
12	2625370,8	(9, 4.3012, WSW),(41, 2.2994, SE),(96, 5.0623, WNW),(210, 5.2089, WNW),(417, 5.0324, WNV	(122,100)
42	2816371,68	(1, 1.7578, E),(6, 4.9937, WNW),(130, 3.5768, SSW),(170, 4.4537, WSW),(235, 4.3675, WSW),(	(122,3.7825),(221,1.9194),(222,0.3772),(231,90.005

++ Simulator Preliminary Efficiency Tests (Dec 2012)

mber of common terms on the cells: 42

mber of mathematical expressions per cell: 105

mber of compartments for each of the 4 species

Ticks : 25 (20 evolutionary, 5 interactive)

Rodents : 2 (2 interactive)

Deer : 1 (1 interactive)

Birds : 2 (2 interactive)

Total : 30 (25 evolutionary, 5 interactive)

mber of evolutionary transitions:

Ticks : 35 Rodents : 1 Deer : 0 Birds : 1 Total : 37

transfer transition

al number of '1-day' time steps: 365 (equivalent to one year)

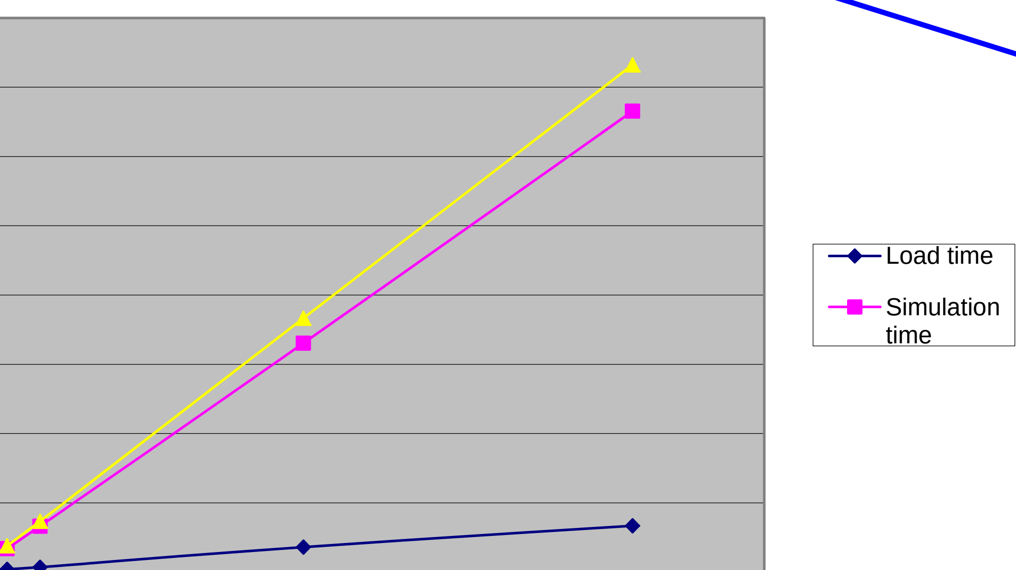
mputer: Intel Core 2 Duo 6400 @ 2.13GHz (dual core)

B RAM Windows XP Professional 32 bits (service pack 3)

Simulator Preliminary Efficiency Tests (Dec 2012)

Load time (ms)	Load time (min)	Simulation time (ms)	Simulation time (min)	Total time (ms)	total time (min)
2234	0,0372	6890	0,1148	9124	0,1521
4140	0,0690	34000	0,5667	38140	0,6357
7157	0,1193	66313	1,1052	73470	1,2245
36204	0,6034	330406	5,5068	366610	6,1102
66953	1,1159	665391	11,0899	732344	12,2057
98547	1,6425	996719	16,6120	1095266	18,2544
129953	2,1659	1328031	22,1339	1457984	24,2997

Math Expr Per Cell: 105
Nb of Compartments: 30
Nb of Transitions: 37
Nb of time steps: 365



Encouraging results *for the Load operation and for the simulation time*

We have not worked on
optimization yet