A spatially explicit modelling framework for assessing ecotoxicological risks at the landscape scale

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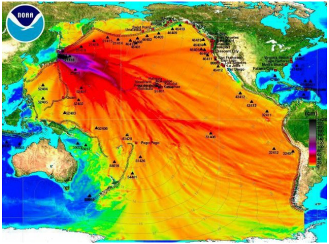
INRA SCIENCE & IMPACT

Context

- **Risk assessment** is the determination of quantitative or qualitative estimate of risk related to a concrete situation and a recognized hazard
- We consider the consequences of pollution or contaminant spread on the environment and exposed populations
- Modelling approaches are needed for quantifying risk and testing management strategies
- Considering large spatial scales is often crucial for Environmental and ecological risk assessment



'Before I say "Yes" I'd like to carry out a risk assessment'

The impact of GM crops on non-target organisms

- Bt crops are GM plants producing insecticidal proteins
- Bt toxins are also expressed in pollen that spread outside fields and can reach habitats of non-target organisms (NTOs)
- GM crops can have ecological impacts on populations within agroecosystems
- Need of **spatial models** at the **landscape scale** for risk assessment and for building management strategies
- In the study we consider the impacts of Bt maize MON810 on the peacock butterfly (which lay eggs on nettle plants)

How to structure simplified agricultural landscapes ?

- Ingredients:

→ Convexe fields

→ GM and non-GM fields

→ Field margins with host-plants

- Control:

→ The number of fields I

→ The mean thickness of host-margins u

→ The proportion of GM fields p

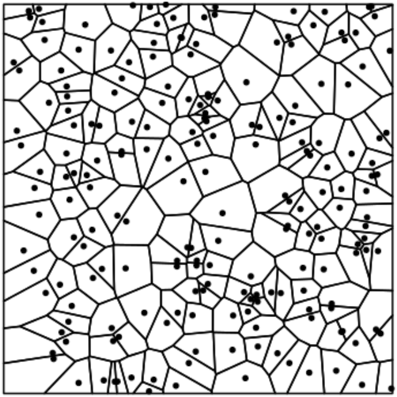
→ Spatial aggregation of GM fields

→ Location of host-margins with respect to GM fields

Structuration of the landscape

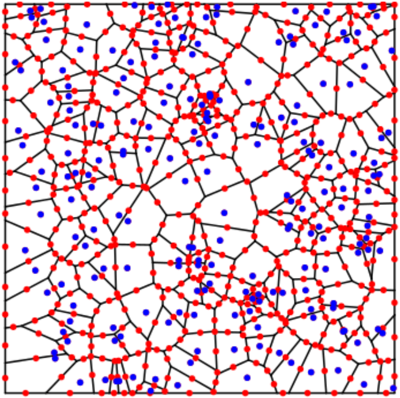
- The landscape is structured by:

  1. Simulating a binomial point process $\mathcal{X} = \{x_1, \ldots, x_I\}$ of I points in $\Omega = 5000 \times 5000m^2$
  2. Drawing a Vornoi tessellation Θ in order to partition Ω from $\mathcal{X}$ as seed points



Marked segment and polygonal processes

- Let E_Θ be the set of segments obtained from the tessellation
- Consider $\alpha(\Theta)$ to be the set of midpoints
- Consider $\mathcal{A} = \alpha(\Theta) \bigcup \mathcal{X}$



Marked segment and polygonal processes

- Consider a Gaussian stationary spatial process Λ with a Matérn autocovariance function

$$\sigma^2 \frac{1}{\Gamma(\nu)2^{\nu-1}} \left(\sqrt{2\nu}\frac{\|x_j - x_k\|}{\rho}\right)^{\nu} K_\nu \left(\sqrt{2\nu}\frac{\|x_j - x_k\|}{\rho}\right)$$

- Then for each $x \in \mathcal{A}$, we draw $\{\Lambda(x_1), \ldots, \Lambda(x_N)\} \sim \mathcal{N}\{(\mu, \ldots, \mu), \Sigma\}$
- We fix $\sigma = 1$, $\nu = 5$, and, $\mu = 0$
- We keep the range parameter ρ

Attaching marks by thresholding the GP

- Field-polygons

$$\mathcal{X}_m = \{\mathcal{X} = \{x_1, \dots, x_I\}; m_{\mathcal{X}} = \{e\ (emitting); o\ (other)\}\}$$

↪ Let $n_c = \lfloor p_c I \rfloor$ be the number of GM fields

↪ Consider the threshold $s_{\mathcal{X}} = \Lambda_{n_c}(x_k)$ that is the n_c*iest* drawn value

$$\begin{cases} m_{\mathcal{X}}(x_i) = e & \text{if} \quad \Lambda(x_i) \leq s_{\mathcal{X}} \\ m_{\mathcal{X}}(x_i) = o & \text{if} \quad \Lambda(x_i) > s_{\mathcal{X}} \end{cases}$$

- Margin-segments

$$\alpha(\Theta)_m = \{\alpha(\Theta) = \{x_1, \dots, x_N\}; m_{\alpha(\Theta)} = \{n\ (neutral); h\ (host)\}\}$$

↪ As we want to control the locations of margins with respect to GM fields $\alpha(\Theta)_m$ is built from $\mathcal{X}_m$

$$\begin{cases} m_{\alpha(\Theta)}(x_k) = h \quad \text{if} \quad (s_{\mathcal{X}} + \tau - \delta) < \Lambda(x_k) < (s_{\mathcal{X}} + \tau + \delta) \\ else \quad m_{\alpha(\Theta)}(x_k) = n \end{cases}$$

- τ is kept as a parameter and we fix $\delta = 0.1$

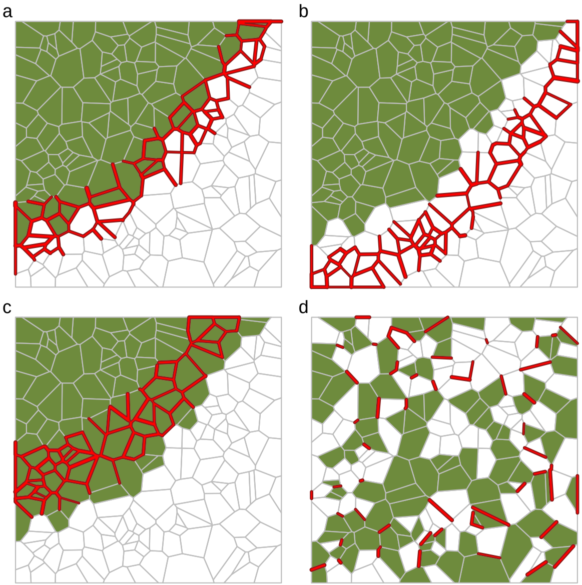
Adding thickness to host segments

- Let $E_{\ominus m}(h) = \{e_1, \ldots, e_{N_h}\}$ be the set of host-margin segments. A thickness $\epsilon_n \geq 0$ is associated to each host segment e_n $(n = 1, \ldots, N_h)$. The thicknesses are identically and independently drawn from a Gamma distribution $(mean = u, variance = 4)$

- Then, for each $n \in \{1, \ldots, N_1\}$, the dilated segments $e_{d,n}$ are obtained by $e_n \mapsto e_n \bigoplus \check{B}_n$ where B is a sphere with diameter $\epsilon_n/2$

$$M = \bigcup_{n=1}^{N_h} e_n \bigoplus \check{B}_n$$

Illustration



Simulation of pollen spread and drop-off

- The amount of pollen grains located at position (x, y) is obtained by calculating the convolution product between the emission $E(x, y)$ and a dispersal kernel K

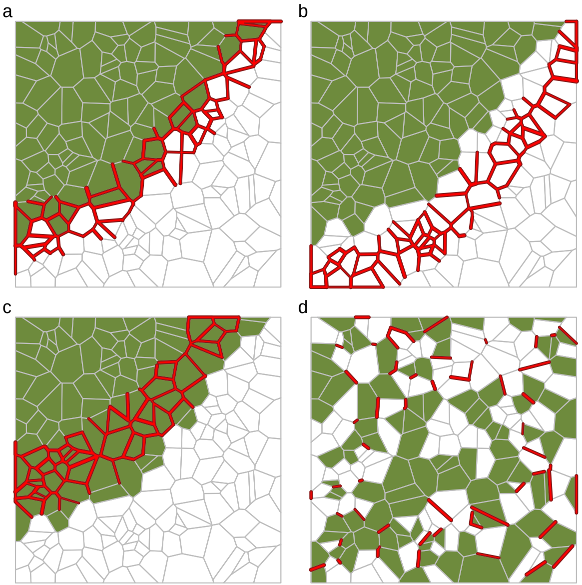
$$R_a(x,y) = \int\int E(x',y')K(x-x',y-y')dx'dy' = E \otimes K(x,y)$$

,

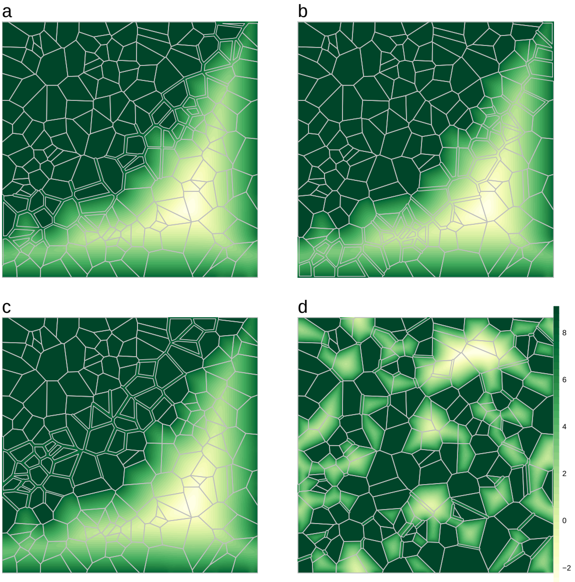
$$R(x,y) = R_a(x,t) * adherence * (1 - loss) = R_a(x,y)\ \omega\ (1-\psi)$$

- Four dispersal kernels are used (isotropic and anistotropic Normal Inverse Gaussian, Geometric and bivariate Student kernels)
- The convolution product was calculated by using Fast Fourier Transforms (FFT) and periodic boundary conditions

Illustration



Illustration



Assessing individual risk within the landscape

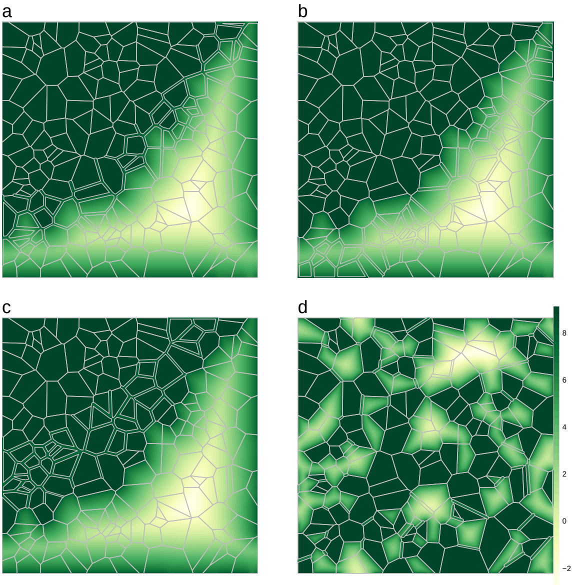
- A risk map is obtained by using the following empirical dose-mortality relationship

→

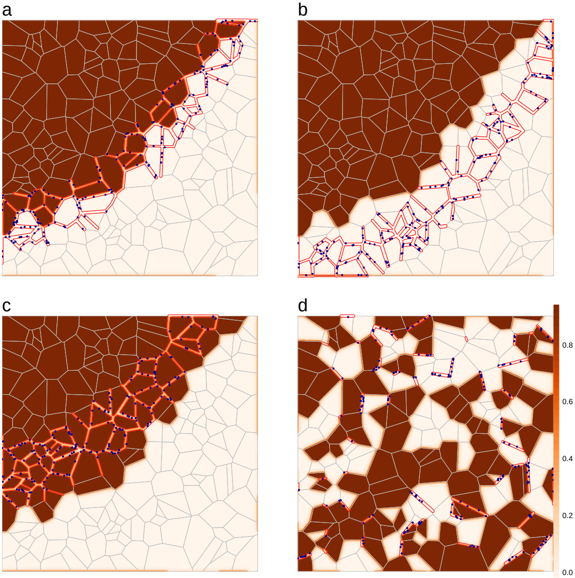
$$P_{death} = \frac{e^{-9.304+2.473\log_{10}(D)}}{1+e^{-9.304+2.473\log_{10}(D)}}$$

- The locations of non-target individuals are simulated by drawing a homogeneous binomial point process on host-margins
- By assessing the risk for each individual we get a distribution of the individual risk for the landscape
- We extract the mean Y_m and the standard deviation Y_{sd} of the distribution

Illustration



Illustration



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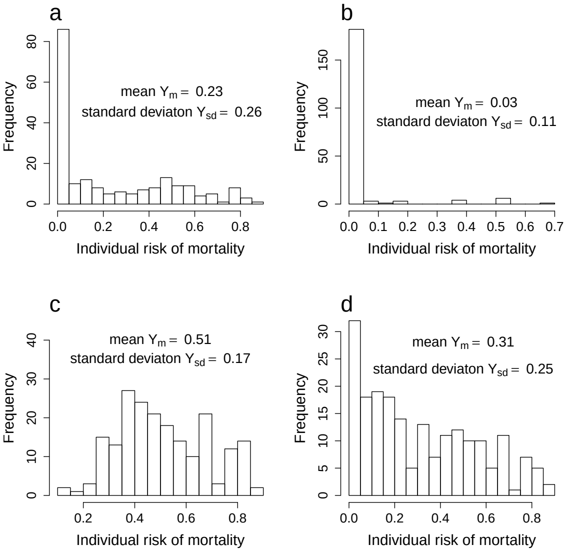
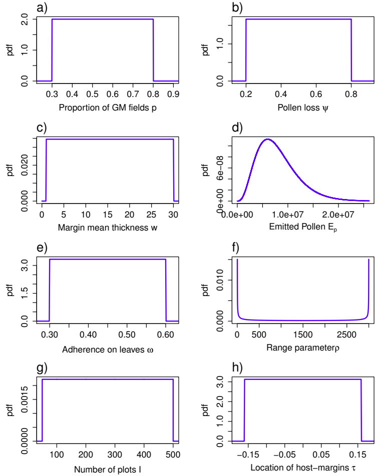
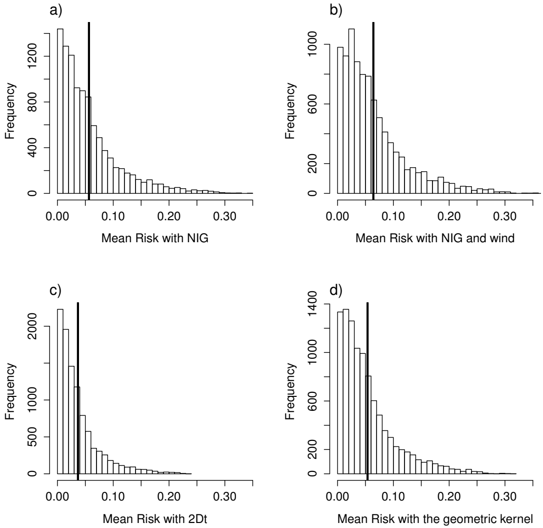


Sensitivity Analysis: assessing the influence of parameters onf the risk

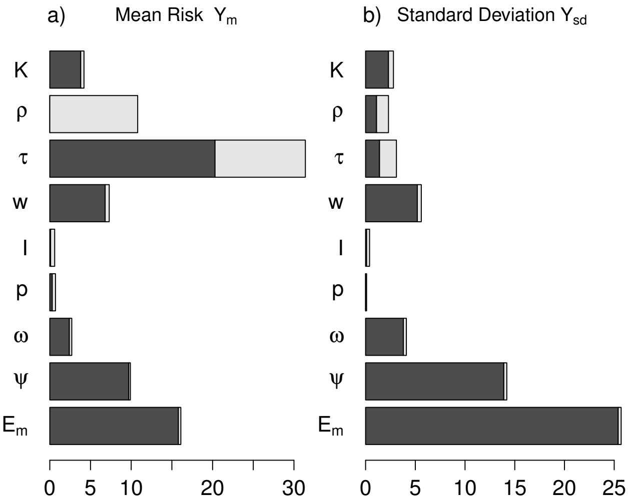
- Optimized Latin Hypercube Sampling (1000 points) with 10 replicates for each point (stochastic model)
- Sensibility indices are obtained by using a metamodel (GLM) for Y_m and Y_{sd}



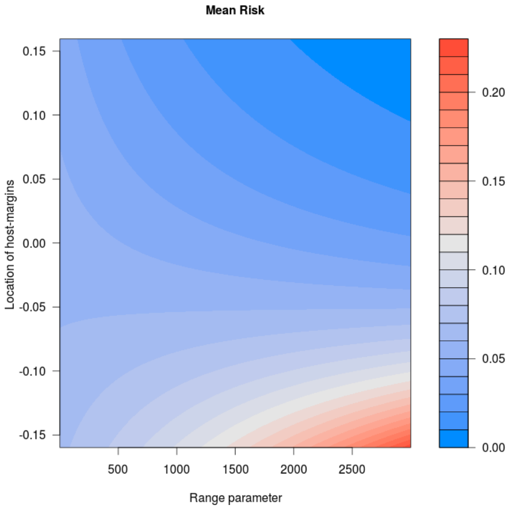
Results


a)
Frequency
0
400
800
1200
0.00
0.10
0.20
0.30
Mean Risk with NIG
b)
Frequency
0
200
600
1000
0.00
0.10
0.20
0.30
Mean Risk with NIG and wind
c)
Frequency
0
500
1000
2000
0.00
0.10
0.20
0.30
Mean Risk with 2Dt
d)
Frequency
0
200
600
1000
1400
0.00
0.10
0.20
0.30
Mean Risk with the geometric kernel

Results


a) Mean Risk Y_m
b) Standard Deviation Y_sd
K
ρ
τ
w
l
p
ω
ψ
E_m
0 5 10 20 30
0 5 10 15 20 25

Results


Mean Risk
Location of host-margins
0.15
0.10
0.05
0.00
-0.05
-0.10
-0.15
500
1000
1500
2000
2500
Range parameter
0.20
0.15
0.10
0.05
0.00

Results

→ Substantial influence of pollen emission, spread and drop-off (difficult to manage)

→ Significant influence of the spatial configuration of the landscape

→ Landscape management may help in reducing the risk of GM crops towards NTOs

From spatial to spatio-temporal risk assessment

- Emitting fields do not necessarily emit pollen at the same time

→ Emitted fields share the same discrete-time emission function $E(t)$

$$R_a(x, y, t) = \int\int E(x', y', t) K(x - x', y - y') dx' dy' = E \otimes K(x, y, t)$$

→ The intensity of available contaminants R at site (x, y) and time t is defined by

$$R(x, y, t) = \{1 - \psi(Z(t))\} R(x, y, t - 1) + \omega R_a(x, y, t)$$

Z is a time-varying positive covariate that linearly influences the loss function ψ (e.g. rain simulated by a stochastic weather generator)

Toxicokinetic-toxicodynamic

- The emipirial dose-mortality relationship does not represent well enough the toxicokinetic-toxicodynamic for exposed individual

→ We suppose that the individuals are affected by the contaminants with a constant *uptake rate* $k_{in} > 0$ and that they can eliminate contaminants from their body at a constant *elimination rate* $k_{out} > 0$

→ The internal concentration of contaminants within individual m,say ρ_m, is given by

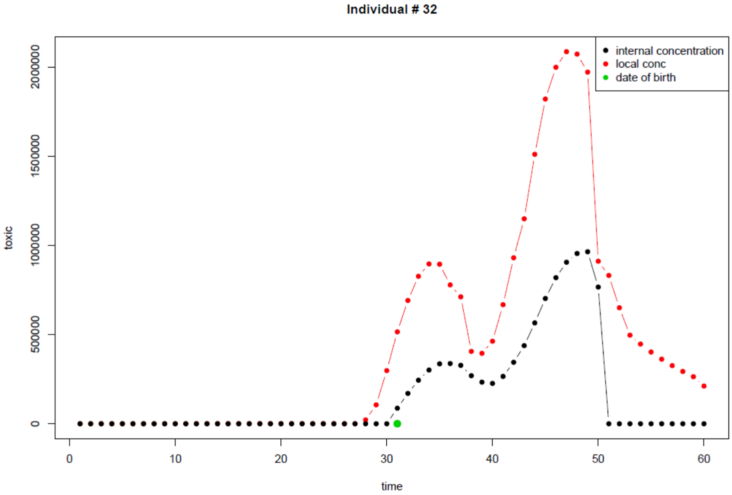
$$\frac{d\rho_m(t)}{dt} = k_{in}R(z_m, \lfloor t \rfloor) - k_{out}\rho_m(t)$$

→ A lethal dose is fixed: when the internal concentration (ρ) of an individual reaches this threshold, the individual is considered dead

- Larvae do not emerge at the same time

→ Individuals are represented by a marked point process with marks describing the time of emergence

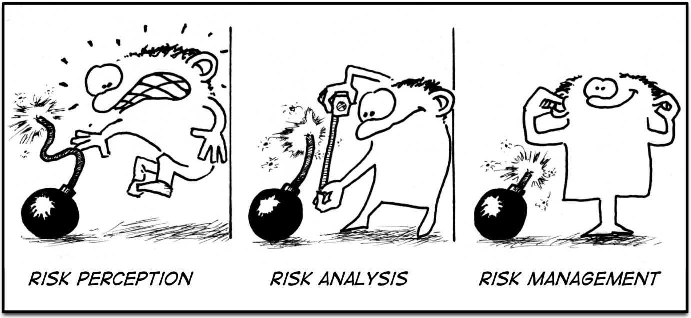
Example


Individual # 32
internal concentration
local conc
date of birth
toxic
0
500000
1000000
1500000
2000000
time
0
10
20
30
40
50
60

Conclusion

- A generic and flexible modelling framework for assessing risks at large spatial scales
- Implemented into the SEHmodel (Spatial Exposure-Hazard model) R package
- A toolbox for risk managers (European Food and Safety Authority) that can easily be expanded for various risk assessments and testing management strategies
- Stochastic geometry and spatial statistics provide interesting tools for simulating simplified heterogeneous and fragmented environments (e.g. agricultural landscapes) and assessing their interactions with the spatio-temporal dynamics of populations
- Studies that combined stochastic geometry-based environment simulators (e.g. landscape simulator) and population dynamics models often allowed ecologists and epidemiologists to point out new management perspectives $\rightarrow$ to be continued...

Thank you for your attention



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