Modeling and Infering a Spatio-temporal Dynamic
For
Apple Scab in Orchards

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motivation

Goal:

- To describe and statistically infer epidemiologic parameters of apple scab
- To answer the question: How much mixture plantation affect scab dynamics?

Experimental essay

- 9 contiguous apple orchards of 2 types
  - Pure : only susceptible cultivars (melrouge variety) : 3 orchards
  - Mixture of susceptible and resistant cultivars (pitchounette) : 6 orchards

- Period: season 2006 [may 30 - july 24]
- Pest: apple scab caused by ascomycete fungus: *Venturia inaequalis*
- *Importance of climatic conditions:*
  - *continuous measurements of Humidity and Temperature*

experimental design (2006)

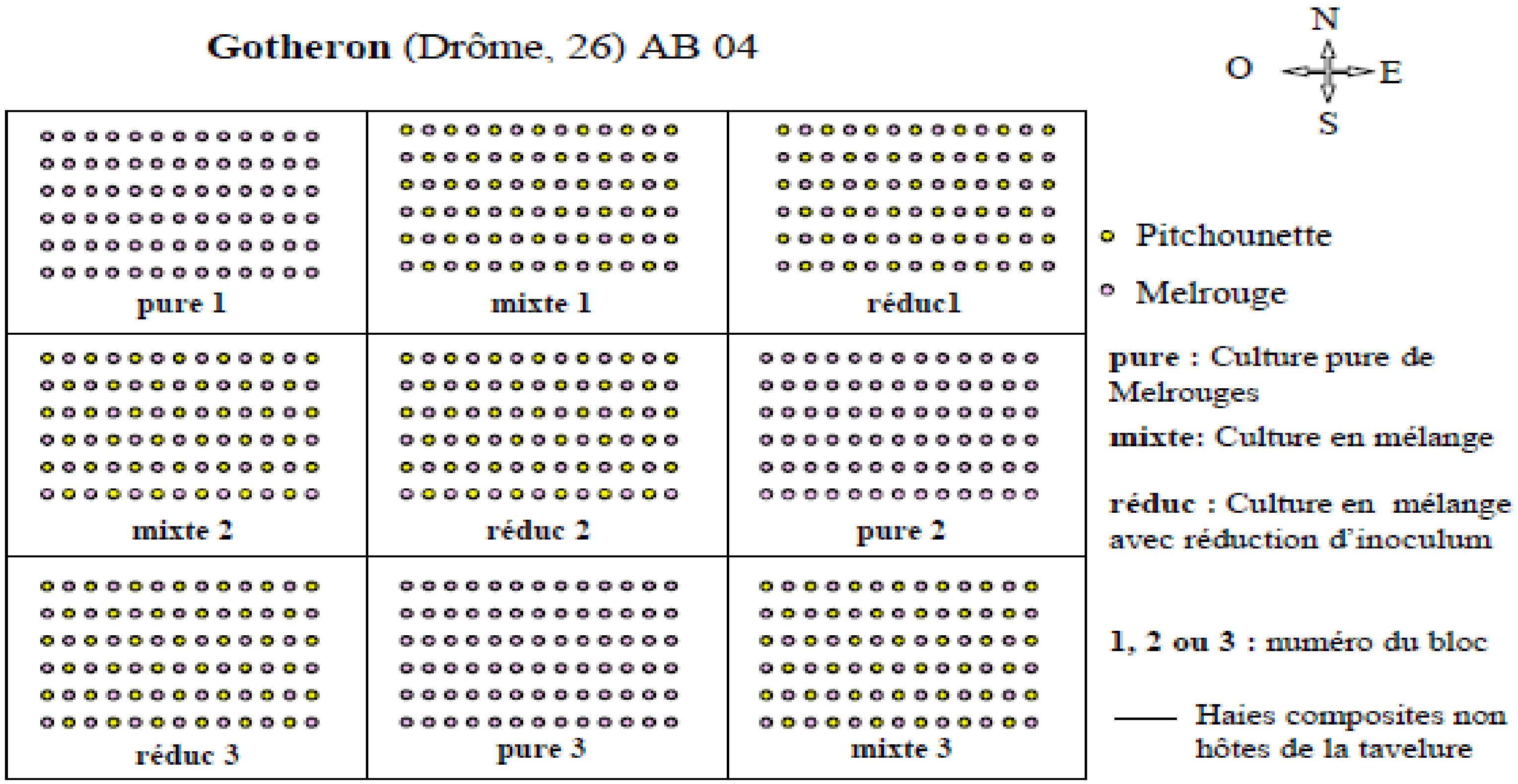
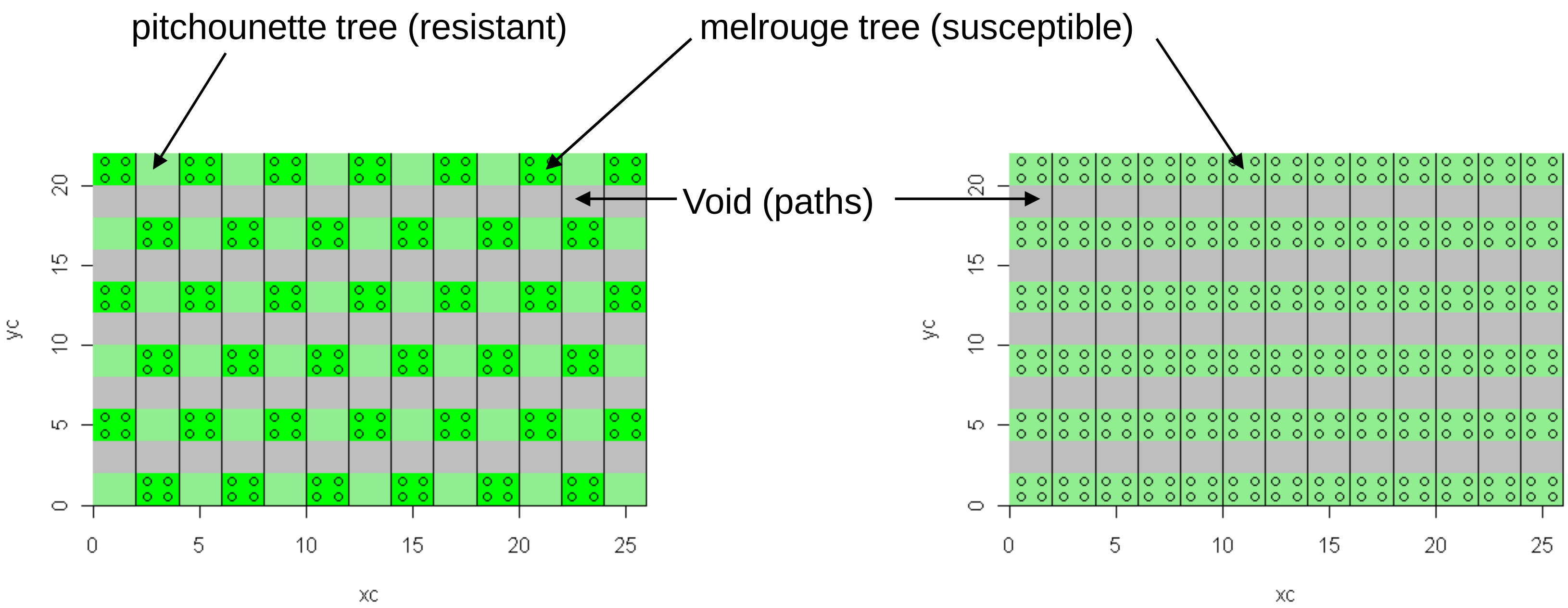


Figure 8 : Plan schématique de la parcelle expérimentale AB04

2 types of orchards



Mixed orchard

pure orchard

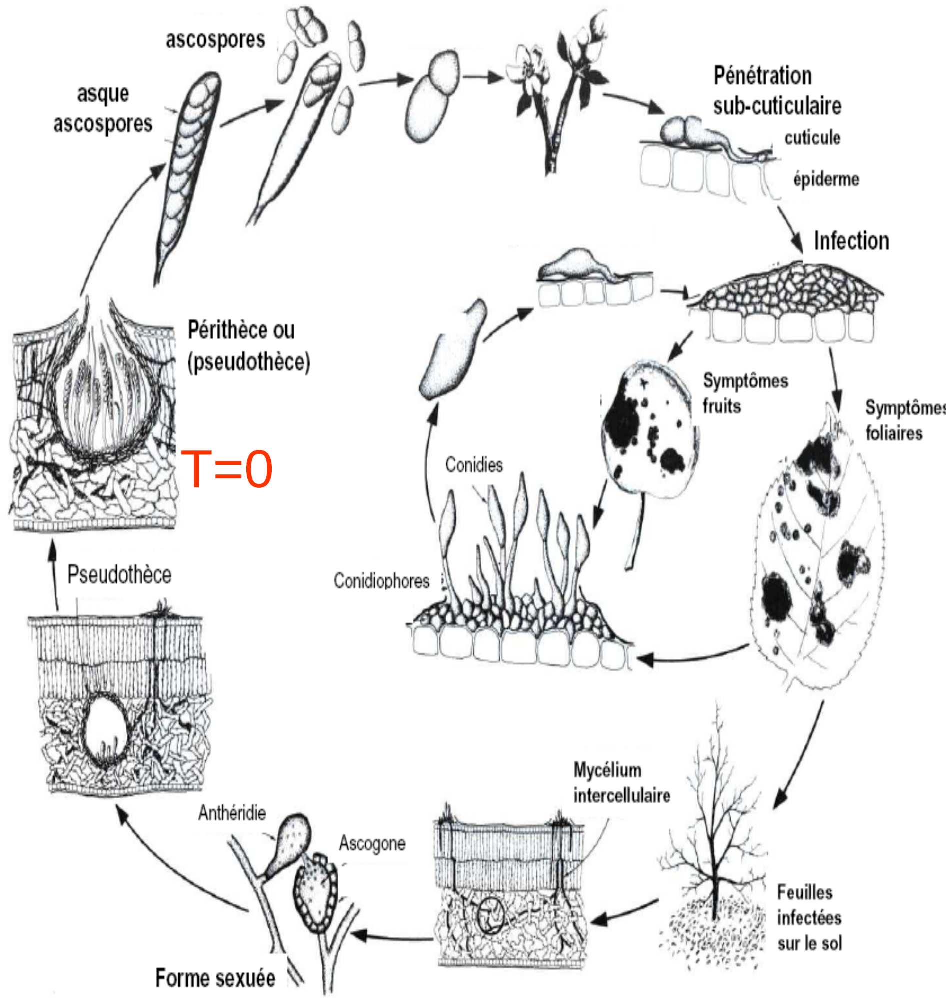
ascomycete fungus: *Venturia inaequalis*

artificial innoculation


Figure 9 : Une pousse inoculée ensachée (Photo D.SIMON)

scab symptoms

Venturia inaequalis Cycle



Tiré de Plant Pathology, G.N. Agrios, 1988

A data *driven* model and assumptions

1. Orchards were distant enough and separated by hedges

   Statistical independence of orchards

   but share the same dispersal mechanism and the same set of parameters

2. Space heterogeneity: void (paths), sensible and resistant cultivars affect spore diffusion:

   Introduction of a local displacement resistivity to dispersal

   ie "epidemiological distance" between locations

3. The location measurements only indicate the cardinal corner of the tree (~ 1 m^{2}):

   Discretisation of space

4. Fungus dispersal took place only during favorable climatic conditions

   Usual time (in days) was inessential

   time is weighted by an infection severity index (sporulation conditions)

   Definition of a proper scab epidemiological time

5. Observation times: random and depend on climatic conditions and technician availability and should be considered as Markovian times (stopping times)

exemple of collected data (for a mixed orchard)

date	day	row	col	loc	leaves	spot_nb1	croxal1	spot_nb2	croxal2	spot_nb3	croxal3
13-juin	74	2	5	SO	1	2	1	0	0	0	0
13-juin	74	4	7	NE	1	1	1	0	0	0	0
20-juin	81	3	12	NE	2	1	1	3	1	0	0
20-juin	81	3	12	NE	1	1	1	0	0	0	0
04-juil	95	3	2	NO	1	1	1	0	0	0	0
04-juil	95	3	12	NE	2	1	1	3	1	0	0
04-juil	95	6	3	SE	1	2	2	0	0	0	0
04-juil	95	3	12	SE	2	6	4	1	1	0	0
24-juil	105	1	4	NE	1	1	1	0	0	0	0
24-juil	105	2	3	SE	1	13	2	0	0	0	0
24-juil	105	3	8	SO	1	20	2	0	0	0	0
24-juil	105	3	12	SO	3	2	1	2	1	2	1
24-juil	105	4	9	NE	1	8	2	0	0	0	0
24-juil	105	4	7	NE	1	14	1	0	0	0	0
24-juil	105	4	7	NE	3	28	3	9	1	20	2
24-juil	105	4	7	NE	1	1	1	0	0	0	0
24-juil	105	6	3	SO	1	2	1	0	0	0	0

Sequence of observations

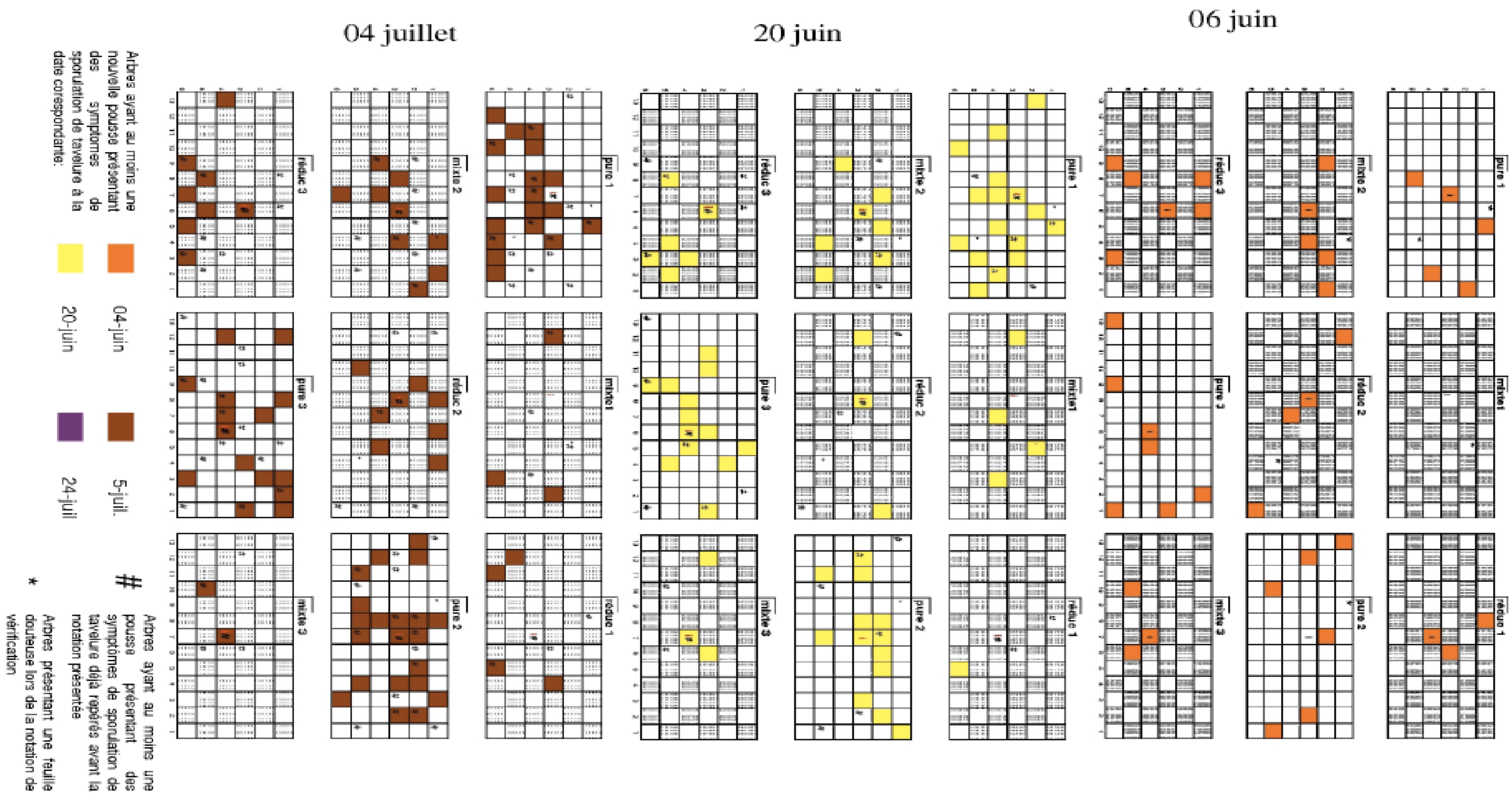
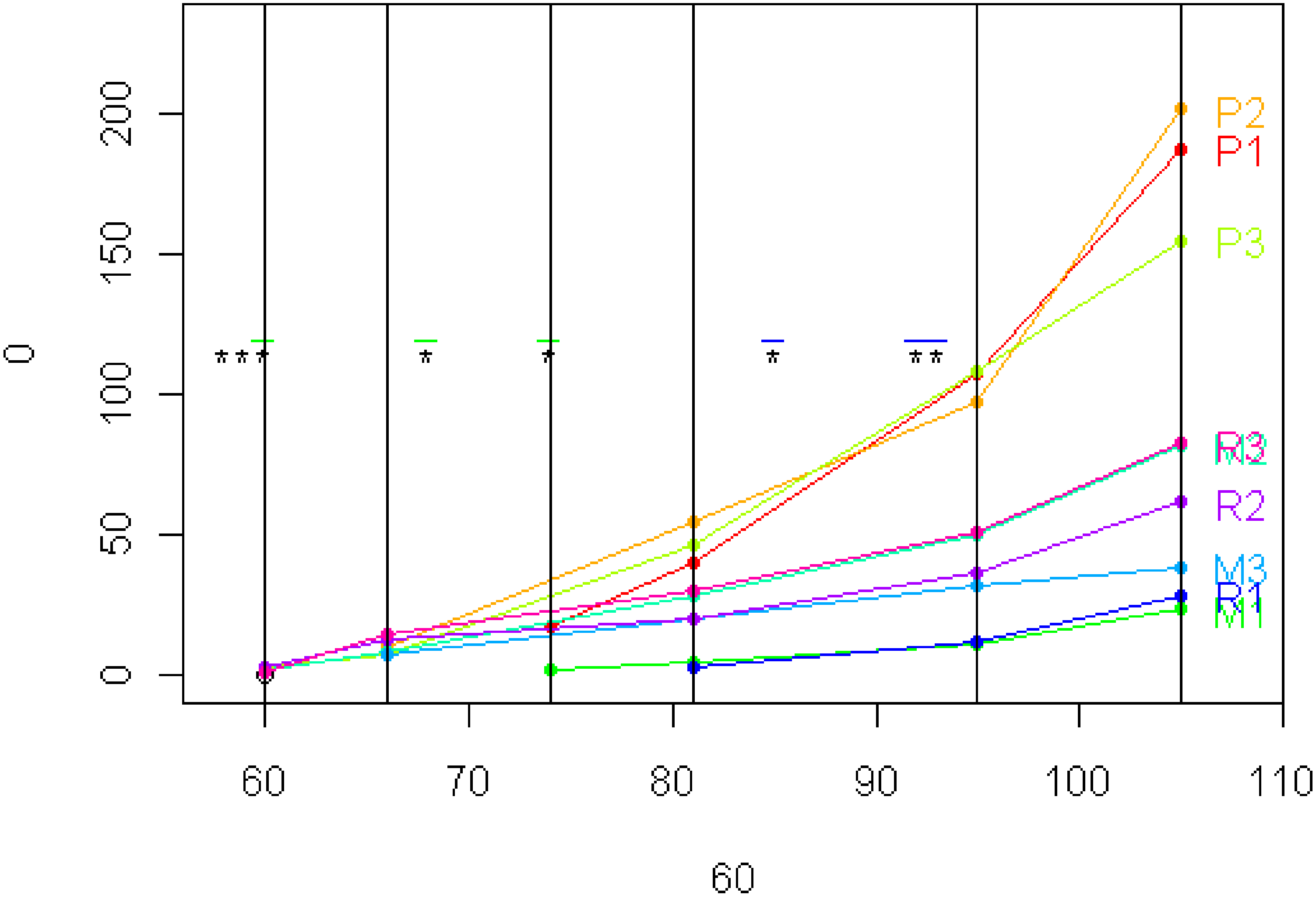
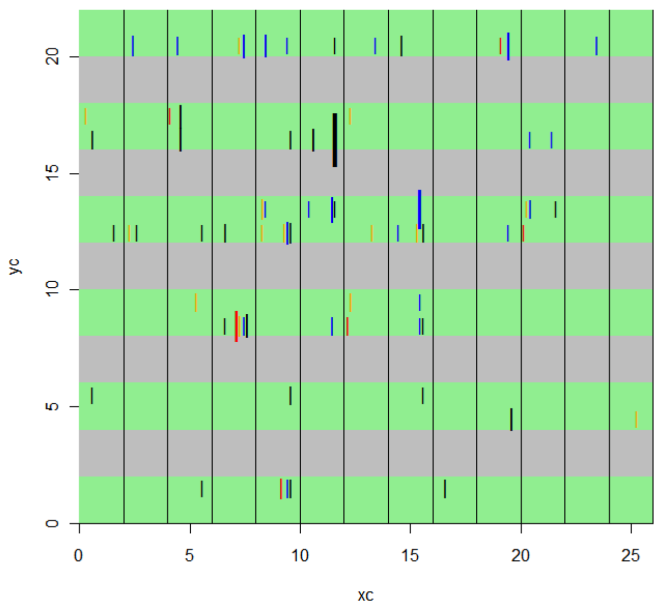


Figure 18 : Schéma d'évolution spatiale des arbres touchés par l'épidémie de tavelure.

Cumulative counts of infected leaves for the 9 orchards

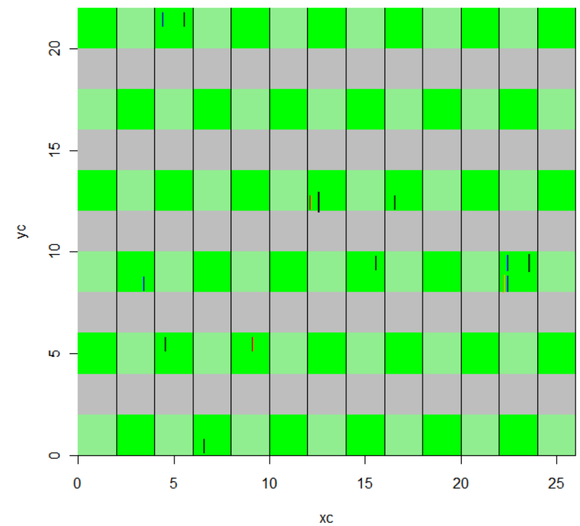


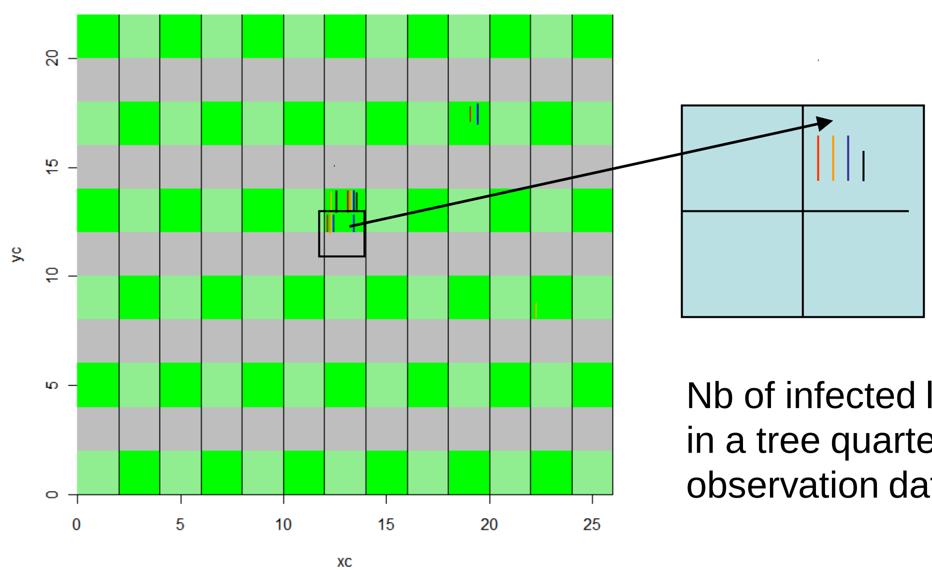
Local space-time dynamics (nb of infected leaves)



Pure orchard 1

Mixed orchards
(3, 5)





Nb of infected leaves
in a tree quarter at 4
observation dates

Climatic conditions/epidemiological time

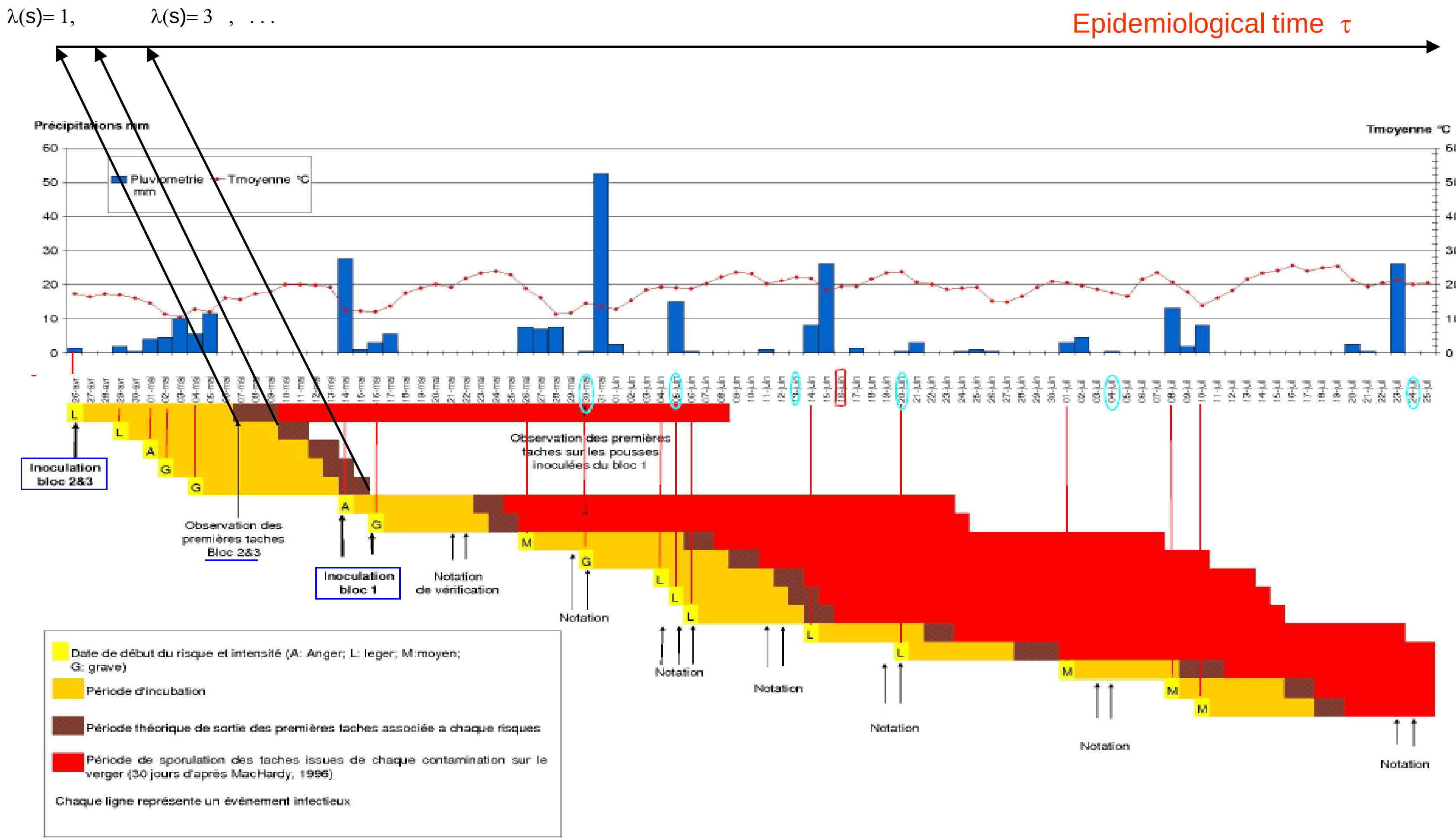


Figure 17 : Schéma de mise en relation des périodes à risques de contamination avec les conditions météorologiques

epidemiological space-time « coordinates » or space-time transformation

1. Space: divided into cells with displacement resistivity ρ :

   ρ(void=reference)=1 , ρ(susceptible) = α_{Mel} and ρ(resistant) = α_{Pich}

   Pseudo distance between locations X and Y:

$$D(X,Y) = \|Y - X\| \int_0^1 \rho(X + t(Y - X))dt \approx \sum_{\text{cells } C_j : C_j \cap [X,Y] \neq \varnothing} \rho(C_j) \|C_j \cap [X,Y]\|$$

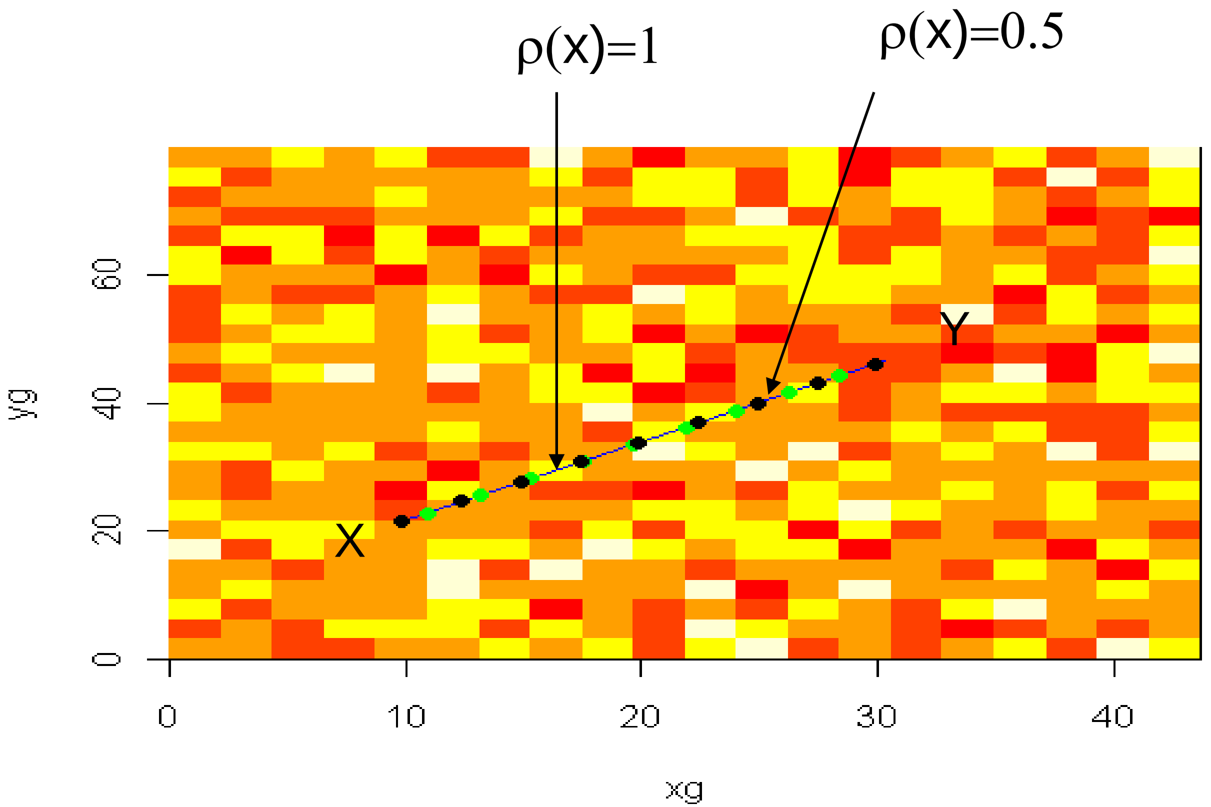
2. Time: only at risk periods weighted by a severity coefficient (ecophysiology behavior of *Venturia inaequalis*) were counted ;

$$\tau(s,t) = \int_s^t \lambda(u)du \approx \sum_{s \prec j \leq t} \lambda(j)$$

Displacement resistivity and epidemiological contiguity

Example:

Euclidean distance $D_{euc}(X,Y)=32.73483$ Epidemiological « distance » $D_{epi}(X,Y)=73.61998$



Climatic conditions/epidemiological time

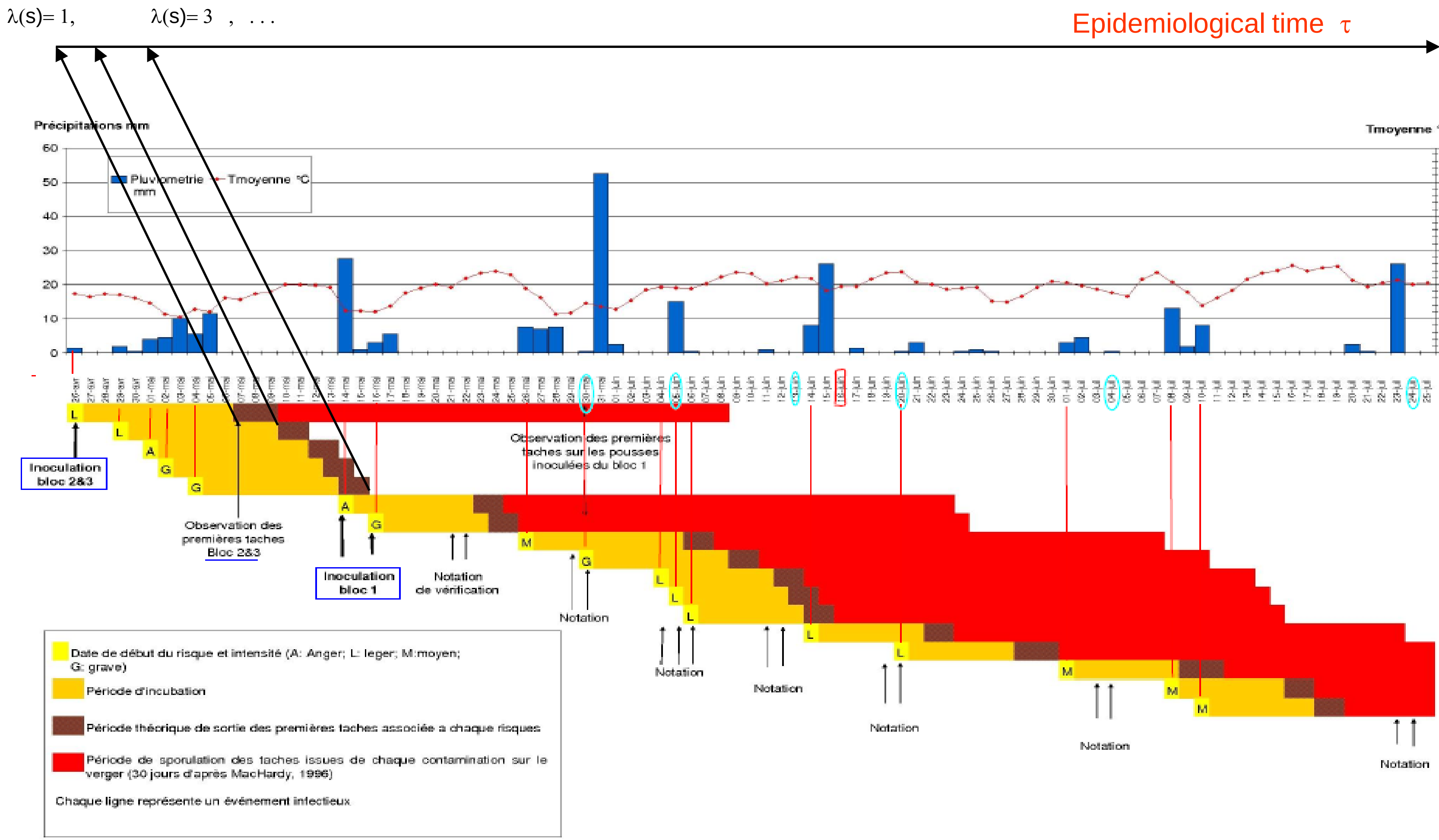


Figure 17 : Schéma de mise en relation des périodes à risques de contamination avec les conditions météorologiques

Natural modeling approach

- Multitype branching process

If $N(\tau_j)=(N(\tau_j, C_k); k=1,\ldots,M)$: counts of infected leaves in all cells C_k (quarters of susceptible trees) observed at time τ_j

- Model the infinitesimal generator of this Markovian process to take account of distances, climate, (easy task)
- Use Kolmogorov Equations and branching properties to set the system of diff. Eq for the set of conditional generating functions (or equivalently a system of linear PDE in this case)
- Solve the system … (this is almost possible by approximation)
- Use inversion formula (or approximation) to recover the corresponding probability functions
- Use maximum likelihood techniques (intractable iteration procedure)

Not to do

A more sensible statistical model

Assumptions on dispersal and dynamics

- Additive and independent effect of infected leaves
- Markovian temporal behavior
- Multiplicative effect of proper time
- Exponential decrease of spore dispersal wrt epidemiological “metric”

Let $N(\tau_j)=(N(\tau_j, C_k); k=1,\ldots,M)$ denote the counts of infected leaves in all cells C_k(quarters of susceptible trees) observed at time τ_j

Likelihood (for one orchard)

$$\prod_{\text{time } \tau_j} \prod_{\text{susceptible cells } C_k} \exp^{-\lambda(\tau_j, C_k, N(t_{j-1}))} \quad \lambda^{N(\tau_j, C_k)}(\tau_j, C_k, N(\tau_{j-1})) / N(\tau_j, C_k)!$$

$$\lambda(\tau_j, C_k, N(\tau_{j-1}) \,|\, \theta) = \exp^{\alpha_{base}} + \sum_{p\,:\,N(\tau_{j-1}, C_p)\neq 0} \exp^{\alpha_{Leaf} + \alpha_{Dist} D(C_k, C_p | \theta) + \alpha_{Time}(\tau_j - \tau_{j-1})}$$

where $\theta = (\alpha_{base}, \alpha_{Leaf}, \alpha_{Dist}, \alpha_{Time}, \alpha_{Mel}, \alpha_{Pich})$

and $D(C_k, C_p \,|\, \theta) = D_{vo\,d}(C_k, C_p) + \alpha_{Mel} D_{Mel}(C_k, C_p) + \alpha_{Pich} D_{Pich}(C_k, C_p)$

Results - Interpretation

Coefficient	Estimate	Std. Error	Interpretation
α_{base}	-2.8366e+00	8.4807e-02	base intensity
α_{Leaf}	-1.4640e+00	8.8841e-02	spot intensity
α_{Dist}	-9.4564e+00	2.5710e-04	epidemiological spatial range
α_{Time}	1.7271e-01	1.4074e-02	climate coefficient
α_{Mel}	4.2663e-02	1.6141e-02	melrouge resistivity
α_{Pich}	1.0000e+00	6.3916e-17	pitchounette resistivity

Effect quantification

Completely random (base) contribution

$\exp(\alpha_{base})$ = 0.0586 infected leaf/cell

Multiplicative climat effect : for a day at risk with severity of grade 2

$\exp(\alpha_{Time} * 2)$ = 1.412583

Results -interpretation

Contribution of a single infected leaf

Local contribution to its propre site (ie Distance =0)

$\exp(\alpha_{Leaf})$ = 0.2313092 : relative important contribution

Contribution of a single infected leaf to a site distant by 1-epidemiological distance during a day with severity 3

$\exp(\alpha_{Leaf} + \alpha_{Dist} *Dist+ \alpha_{Time} *3)$= 3.036348e-05 : negligeable contribution

Note however that « distances » within susceptible regions are also very low

1m(Euclidean or void)= 1m (resistant zone)= 0.0426m(susceptible zone)

Agronomic interest for mixed orchards