On Vector-borne plant diseases[1]

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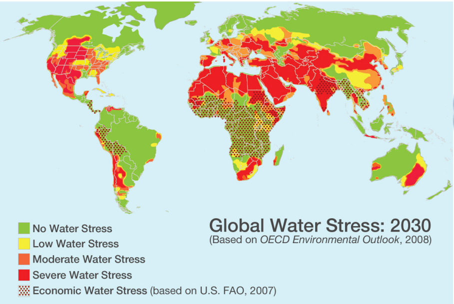
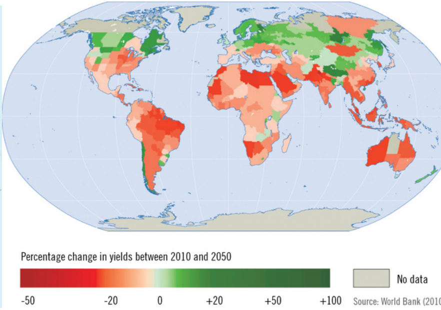
[1] Ongoing Works with Michael Chapwanya (UP, South Africa)

Food Safety is a Major Challenge around the World. In particular in a changing environment!





Studying Plant(Crop)-Pest (Disease) Interactions are important challenges, both from the experimental, modelling and theoretical point of view.

Introduction

Background

- Every Year, a lot of crop losses are due to Pest and Diseases: about 26% of these losses are due to Diseases. This is an important problem in terms of Food Security, in many countries.
- There are many viruses that may affect crops.
- Arthropod vectors (sap-sucking insects) transmit most plant viruses are *aphids* (more than 50%), whiteflies, leafhoppers, thrips, beetles, mealybugs, mirids, and mites.
- For instance *Alfalfa mosaic virus (AMV)*, that is an *alfamovirus*, can impact peas, lentils, potatoes, clovers, etc, can be transmitted by different insects, like aphids.

Plant Epidemiology: several way of transmissions

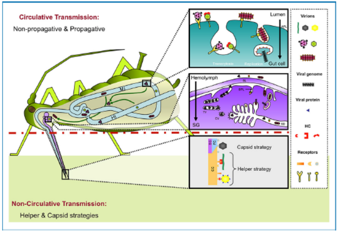
Plant vector-borne diseases have particularities:

Mode of transmission: Circulative vs Noncirculative

- noncirculative viruses: attached to the exterior mouthpieces of the insects
- circulative viruses: live in the vector and are innoculated with the saliva into a new plant host. Two subclasses: propagative and nonpropagative.

Three groups of viruses

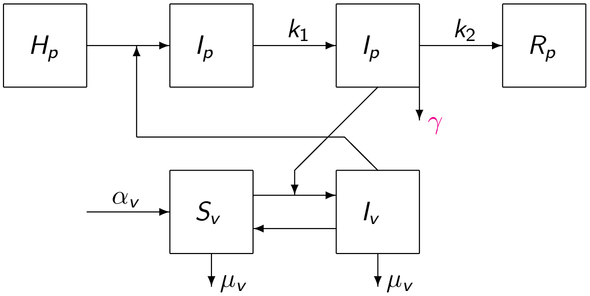
- non persistent
- semi-persistent
- persistent



Generally non-circulative viruses are nonpersistent or semi-persistent, while circulative viruses are semi-persistent or persistent.

An example of a (noncirculative) epidemic model

Non persistent (noncirculative) virus



- H_p: Healthy Plants
- L_p: Latent Plants: infected but not yet infective
- I_p: Infective Plants
- R_p: Recovered/Removed Plants
- S_v: Susceptible Vectors
- I_v: Infective vectors

An example of a (noncirculative) epidemic model

We assume that the plant population is constant, i.e. $H_p + L_p + I_p + R_p = K$ and the vector population, having a smaller lifespan, is such that $V = S_v + I_V$ is governed by a logistic-like equation

$$\frac{dV}{dt} = \alpha_v V - (\mu_1 + \mu_2 V)V.$$

The Force of infection from Plant to Vector is: $\phi a \frac{I_p}{K}$.
The force of infection from Vector to Plant is: $b\frac{\phi I_V}{V}\frac{I_p}{K}$, where

- ϕ the number of plants a vector visits per unit of time
- a the probability of transmission from P to V.
- b the probability of transmission from V to P.

An example of a (noncirculative) epidemic model

Then we consider a disinfecting force on the infective vectors

$$e^{-\phi a I_p/(\delta K)},$$

where $1/\delta$ is the average time of existence of the virus on the vector.

It means that a long as we have Infective Plants, $I_p > 0$, the vector will stay infective.

If $\phi a I_p/(\delta K)$ goes to zero then $e^{-\phi a I_p/(\delta K)} \to 1$ meaning that Infective vectors become susceptible again, at rate δ.

An example of a (noncirculative) epidemic model

We obtain the following system

Plant population

$$\left\{ \begin{array}{l} \frac{dH_p}{dt} = -\phi b I_v \frac{H_p}{K}, \\ \frac{dL_p}{dt} = \phi b I_v \frac{H_p}{K} - k_1 L_p, \\ \frac{dI_p}{dt} = k_1 L_p - (k_2 + \gamma) I_p, \\ \frac{dR_p}{dt} = k_1 I_p. \end{array} \right. \quad (1)$$

Vector population

$$\left\{ \begin{array}{l} \frac{dS_v}{dt} = \alpha_v V - (\mu_1 + \mu_2 V) S_v - \phi a S_v \frac{I_p}{K} + \delta I_v e^{-\frac{\phi a I_p}{\delta K}}, \\ \frac{dI_v}{dt} = \phi a S_v \frac{I_p}{K} - \delta I_v e^{-\frac{\phi a I_p}{\delta K}} - (\mu_1 + \mu_2 V) I_v \end{array} \right. \quad (2)$$

Using "standard" tools from Mathematical Epidemiology, we are able to study system (1)-(2).

An example of a (noncirculative) epidemic model

Using suitable changes of variables, it suffices to study the simplified system:

$$\left\{\begin{array}{rcl} \frac{dh_p}{dt} & = & -\phi b i_v h_p \rho, \\ \frac{dl_p}{dt} & = & \phi b i_v h_p \rho - k_1 l_p, \\ \frac{di_p}{dt} & = & k_1 l_p - (k_2 + \gamma)\, i_p, \\ \frac{di_v}{dt} & = & \phi a(1 - i_v) i_p - \delta i_v e^{-\frac{\phi a i_p}{\delta}} - \alpha i_v. \end{array}\right. \tag{3}$$

with $\frac{d\rho}{dt} = \beta(\tilde{\rho} - \rho)\rho$ and $\tilde{\rho} = V^*/K$.

Theorem

For any continuous nonnegative function ρ the system of differential equations (3) defines a (positive) dynamical system on the compact domain $\Omega = \left\{x = (h_p, l_p, i_p, i_v)^T \in \mathbb{R}^4; x \geq 0, h_p + l_p + i_p \leq 1; i_v \leq 1\right\}$

The equilibria of the system comprise the set

$$\mathcal{P} = \{x = (h_p, 0, 0, 0) : 0 \leq h_p \leq 1\} \subset \Omega.$$

Analysis of the ODE model

For every $h_p \in \mathcal{P}$ we compute $NGM(h_p)$, and derive the reproduction ratio at h_p

$$\mathcal{R}(h_p) = \sqrt[2]{\frac{\phi^2 ab\tilde{\rho}h_p}{(k_2+\gamma)(\alpha+\delta)}},$$

from which we derive the Basic Reproduction Ratio, when $h_p = 1$:

$$\mathcal{R}_0 = \sqrt[2]{\frac{\phi^2 ab\tilde{\rho}}{(k_2+\gamma)(\alpha+\delta)}},$$

With $\tilde{\rho} = \frac{\alpha_v - \mu_1}{\mu_2 K}$. Let $h_p^* = \frac{(k_2+\gamma)(\alpha+\delta)}{\phi^2 ab\rho}$ such that $\mathcal{R}(h_p^*) = 1$.

Theorem (Stability)

$$\mathcal{P}_s = \{x = (h_p, 0, 0, 0) : 0 \leq h_p \leq \min\{1, h_p^*\}\} \subset \mathcal{P}$$

consists of all stable equilibria of the dynamical system defined via (3). The equilibria in $\mathcal{P}_u = \mathcal{P} \setminus \mathcal{P}_s$ are unstable. The set $\mathcal{P}_s$ is a stable invariant set with basin of attraction $\Omega \setminus \mathcal{P}_u$. More precisely, every trajectory initiated in $\Omega \setminus \mathcal{P}_u$ converges to a point in $\mathcal{P}_s$.

An example of a (noncirculative) epidemic model

We consider the following parameters $\phi = \hat{\rho} = 1$, $a = b = 0.2$, $k_1 = 0.2$, $k_2 = 0.1$, $\alpha_v = 0.05$, $\beta = 0.01$, $\delta = 0.2$.

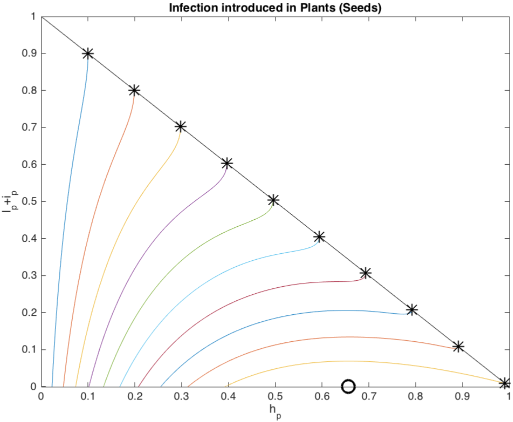


Fig. 2. Infection introduced in plant (through seeds)

All trajectories enter the interval $[0, h_P^*]$.

An example of a (noncirculative) epidemic model

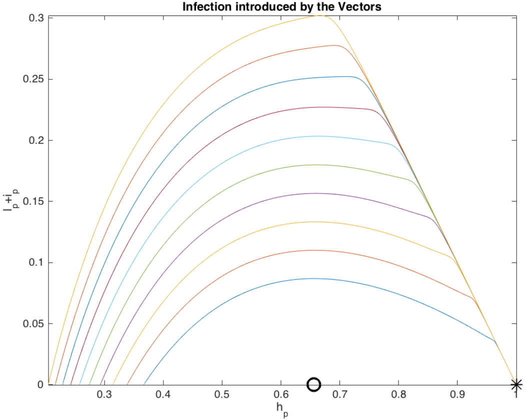
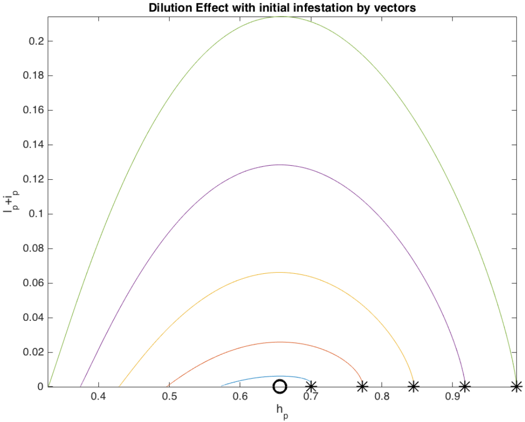


Fig. 3. Infection introduced by vectors

An example of a (noncirculative) epidemic model



"Diluted" crop population effect - the impact of planting a certain percentage of "resistant" plants.

If the proportion of "Diluted plants" is about 20%, then, according to the simulation the loss can be estimated around $\frac{80-50}{80} \times 100 = 37.5\%$.

As usual, based on the Basic Reproduction Ratio

$$\mathcal{R}_0 = \sqrt[2]{\frac{\phi^2 ab\hat{\rho}}{(k_2+\gamma)(\alpha+\delta)}},$$

some "standard" control tools may be useful:

- Insect-proof nets or mineral oils $\longrightarrow$ to decay ϕ.
- Use pesticide $\longrightarrow$ to increase α ... Drawback: spreading, resistance....

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some "standard" control tools may be useful:

- Insect-proof nets or mineral oils $\longrightarrow$ to decay ϕ.
- Use pesticide $\longrightarrow$ to increase α ... Drawback: spreading, resistance....
- Use Barrier Plants, K_b: non-host for the virus and the vectors...$\longrightarrow$ the proportion of infected plants shift from $\dfrac{S}{K}$ to $\dfrac{S}{K+\lambda K_b}$... However, this has also an impact on the disinfecting force too: $e^{-\phi a I_p/(\delta(K+\lambda K_b))}$ (Virus-Sink Hypothesis: when aphids spend sufficient time to become susceptible)... such that $\mathcal{R}_{0,b} < \mathcal{R}_0$...
- Barrier Plants can also be attractive to natural ennemies....

Possible Extension of the Model

Based on the previous Model, several extensions are possible....
The previous Model assume implicitely that Plants and Vectors are homogeneously distributed... which in fact is not true.

Plants cannot move, while Vectors can

Thus a first extension is to assume that the vectors can spread on the domain, leading to a system of ODES-PDES.

We show that adding the spatial component may impact the control strategies.

Vector-borne disease Model with Diffusion

Submodel for the crop (Plant population)

$$
\begin{cases}
\dfrac{\partial H_p}{\partial t} = -\phi b I_v \dfrac{H_p}{K}, \\
\dfrac{\partial L_p}{\partial t} = \phi b I_v \dfrac{H_p}{K} - k_1 L_p, \\
\dfrac{\partial I_p}{\partial t} = k_1 L_p - k_2 I_p - \gamma I_p, \\
\dfrac{\partial R_p}{\partial t} = k_2 I_p.
\end{cases}
\tag{4}
$$

Submodel for the Vector population

$$
\begin{cases}
\frac{\partial S_v}{\partial t} = D \frac{\partial^2 S_v}{\partial x^2} + \alpha_v V - (\mu_1 + \mu_2 V)\, S_v - \phi a S_v \frac{I_p}{K} + \delta I_v e^{-\frac{\phi a I_p}{\delta K}}, \\
\frac{\partial I_v}{\partial t} = D \frac{\partial^2 I_v}{\partial x^2} + \phi a S_v \dfrac{I_p}{K} - \delta I_v e^{-\frac{\phi a I_p}{\delta K}} - (\mu_1 + \mu_2 V)\, I_v
\end{cases}
\tag{5}
$$

with homogeneous Neumann boundary conditions (on a possible infinite 1-dimensional domain) and nonnegative initial conditions.

Theorem (Existence - uniqueness)

Let $H_p(0)$, $L_p(0)$, $I_p(0)$, $R_p(0)) \in L^\infty(0,l)$, and $S_v(0)$, $I_v(0) \in L^2(0,l)$, then a nonnegative bounded solution exists. It is unique.

Large time behavior. Since $H_p + L_p + I_p + R_p = K$ for all $x \in [0,l]$, and $t \geq 0$, we have

- $\lim_{t\to\infty} H_p(x,t) = H_p^*(x)$,
- $\lim_{t\to\infty} L_p(x,t) = 0$,
- $\lim_{t\to\infty} I_p(x,t) = 0$,
- $\lim_{t\to\infty} R_p(x,t) = R_p^*(x)$,

and

- $\lim_{t\to\infty} S_v(x,t) = V^*$,
- $\lim_{t\to\infty} I_v(x,t) = 0$,

Logistic Diffusion in the Vector Population

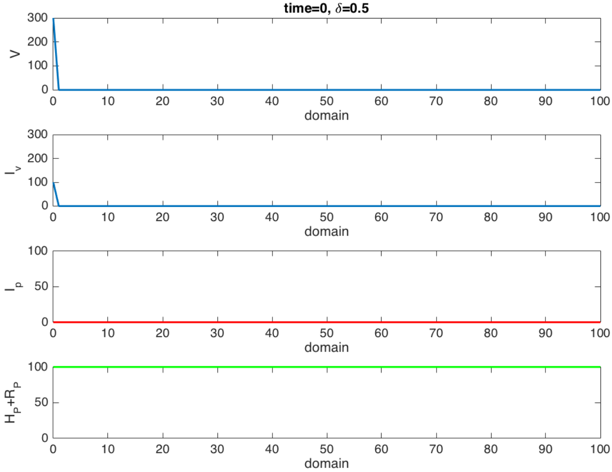
In fact, the vector population, simply follows

$$\begin{cases} \dfrac{\partial V}{\partial t} = D\dfrac{\partial^2 V}{\partial x^2} + \alpha_v V - (\mu_1 + \mu_2 V)\, V, \\ \dfrac{\partial V}{\partial x}(0,t) = \dfrac{\partial V}{\partial x}(L,t) = 0, \\ V(x,0) = V_0(x), \qquad x \in [0,L]. \end{cases} \tag{6}$$

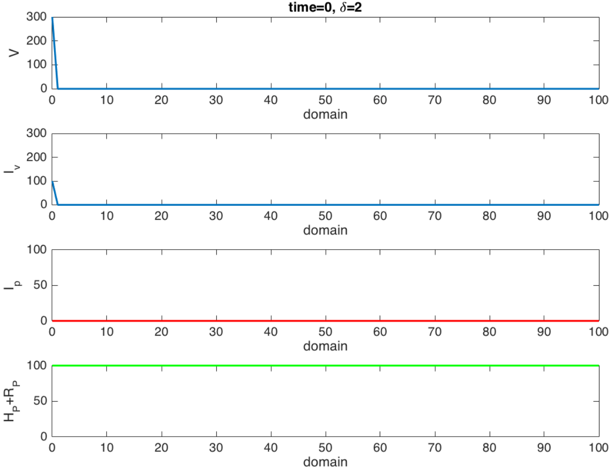
We recognized the well-known Logistic Diffusion Equation, for which we have a certain number of theoretical results

- Two equilibria exist: 0 (unstable) and $V^* = \dfrac{\alpha - \mu_1}{\mu_2}$ (asymptotically stable).
- Travelling-wave solutions $v(x - ct)$ exists, if $c > c^* = 2\sqrt{D(\alpha_v - \mu_1)}$.

initial infective vectors at $x = 0$, $\delta = 0.5$

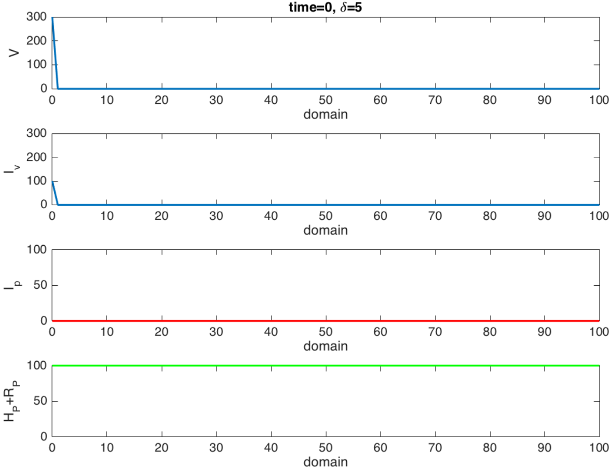


initial infective vectors at $x = 0$, $\delta = 2$



Simulations of Vector spreading when carrying a virus

initial infective vectors at $x = 0$, $\delta = 5$



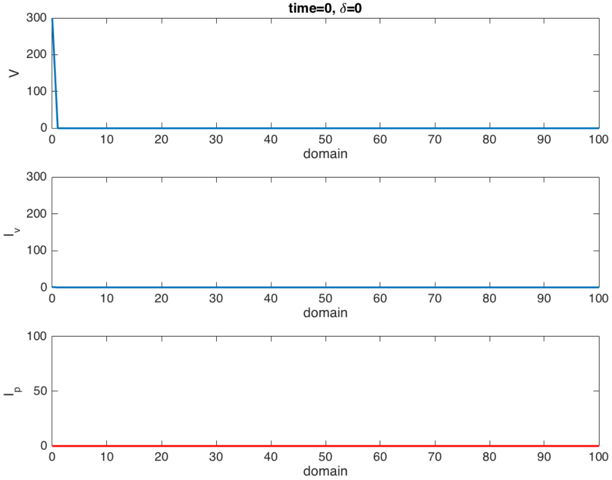
Simplification in the Model

Consider the previous model, with "some simplifications", such that

$$\left\{\begin{aligned} \frac{\partial I_p}{\partial t} &= b\phi\left(1-\frac{I_p}{K}\right)I_v, \\ \frac{\partial I_v}{\partial t} &= D\frac{\partial^2 I_v}{\partial x^2}+\phi a\left(V-I_v\right)\frac{I_p}{K}-\left(\delta e^{-\frac{\phi a I_p}{\delta K}}+\left(\mu_1+\mu_2 V\right)\right)I_v, \\ \frac{\partial V}{\partial t} &= D\frac{\partial^2 V}{\partial x^2}+\alpha_v V-\left(\mu_1+\mu_2 V\right)V, \end{aligned}\right. \tag{7}$$

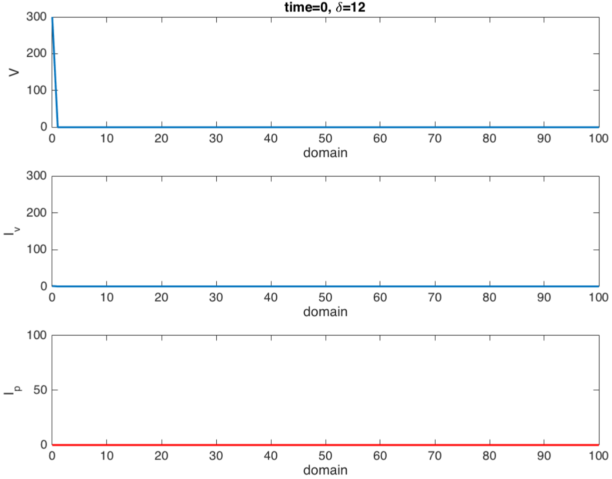
Simulations with the simple model

initial infective vectors at $x = 0$, $\delta = 0$

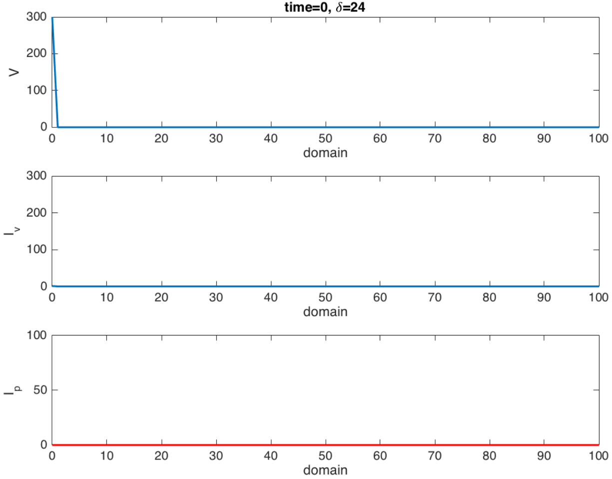


Simulations with the simple model

initial infective vectors at $x = 0$, $\delta = 12$



initial infective vectors at $x = 0$, $\delta = 24$



Discussions....

- In some sense, according to δ (and ϕ), the "invasion" slow down... which, biologically, makes sense.
- Our preliminary results remind me on previous works: see for instance F. Hilker et al. (2005).... Work in progress. Extension to 2D.

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- In some sense, according to δ (and ϕ), the "invasion" slow down... which, biologically, makes sense.
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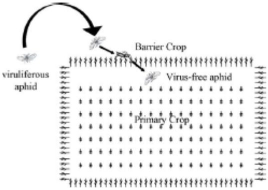

- Implication for Control strategies....
- Barrier Plants, B,
  can appeal to pest landing (colors).... $\Rightarrow$ drift in the model, i.e.

$$\frac{\partial}{\partial x}\left(V\frac{\partial B}{\partial x}\right).$$

  (possible) differential attractivity to infective plants!
- Use of Nets... $\phi = 0$. Where? Ongoing experiments in Kenya....

A M A P

Conclusion: Plant Vector-borne diseases

Modelling Plant Epidemiology can lead to new Models in Mathematical Epidemiology and thus the need of new mathematical results.

Of course, from the modelling point of view, further improvements are possible: distinguish vegetative and reproductive stages, take into account plant growth (photosynthesis...).... Balance between Model tractability and the objectives!

Vector control: the importance of taking into account plant-Pest interactions!

Done in combination with ongoing works and Projects

- Mating Disrupting control and SIT (Fruit flies - South Africa)
- Cacao (Cameroon): Miride (Pest) and Phytospora (fungal pathogen)
- ...
- Plant-Pollinator interactions (Indonesia).

Thank You!

Questions?