European Xylella conference on 2019

An epidemiological model for the short-range spread of *Xylella fastidiosa* and the assessment of eradication management measures

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EFSA WG on ‘Xylella fastidiosa pest risk assessment’

Main Objectives

- Potential establishment
- Asymptomatic period
- Short- and long-range spread modelling
- Impact
- Risk Reduction Options

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Update of the Scientific Opinion on the risks to plant health posed by *Xylella fastidiosa* in the EU territory

EFSA Panel on Plant Health (PLH),
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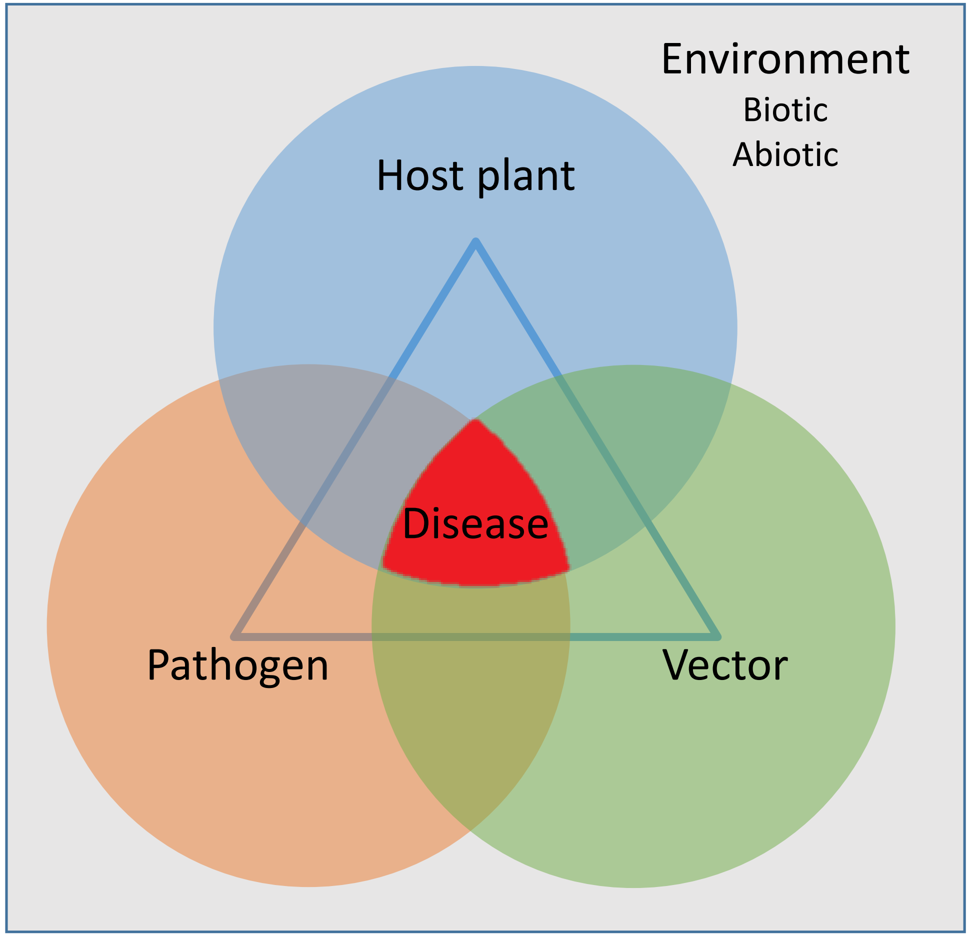
Complexity in plant epidemiology modelling

- Plant-vector-bacteria: the disease triangle
  - Complexity in disease dynamics and gaps in knowledge make it difficult the analysis of epidemiological systems and the definition of effective control strategies to contain or eradicate new emerging diseases
  - Epidemiological dynamics requires the consideration of interactions among the components of the disease tringle in a specific environmental context
  - Need of multidisciplinary skills integrated into a unified methodological approach, e.g. biology, agronomy, ecology, mathematics and model design



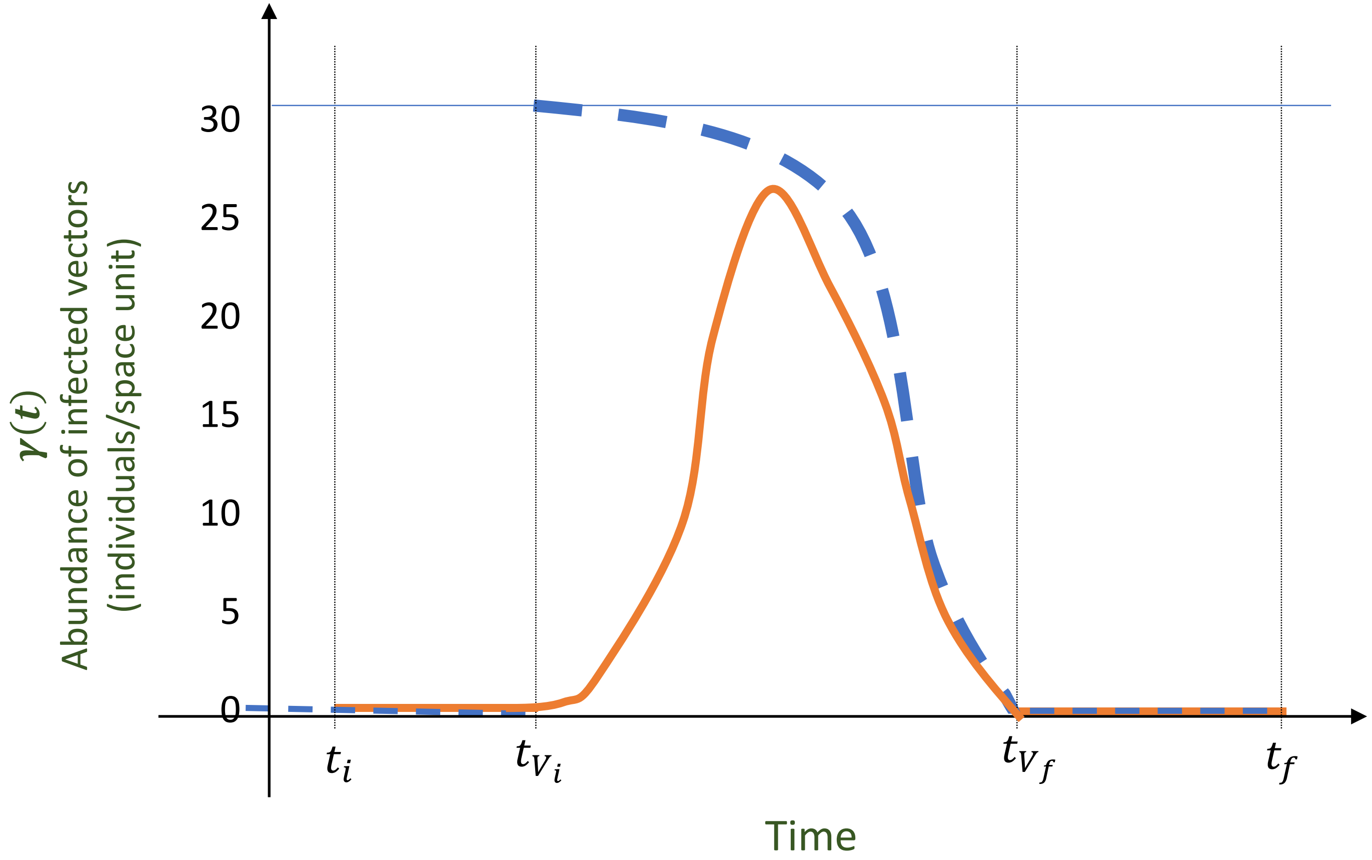
Modelling approach in *X. fastidiosa* epidemiological system

- Disease triangle (pathogen, host plant and vector) in the *X. fastidiosa* (*Xf*) epidemiology
    - In the epidemiology of *Xf* all three components are characterized by high variability and heterogeneity affecting the presence, prevalence and spread of *Xf* both in space and time
    - Models should consider the relationships among the components of the system as well as the influence of the environment (landscape, land-use, biotic and abiotic factors)
- Approaches to the epidemiology of *Xf* [*White et al. 2017*]
    - Species distribution modelling [e.g, *Bosso et al. 2016a, b*]
    - Directly-measured model parameters [e.g, *Parnell et al. 2015*]
    - Mechanistic model [e.g, *Chapman et al. 2015*]
    - Models targeted on supporting the strategies to control [e.g, *Fierro et al. 2019*]
- Approaches specific to disease spread
    - Statistical approaches [e.g, *Gilbert et al. 2004*]
    - Explicit [e.g, *White et al. 2017*] or implicit [e.g, *Jeger et al. 2007*] spatially dependent approaches

Short-Range Spread model (SRS)

- We developed a general spatial-explicit eco-epidemiological model describing the dynamics of vector-borne plant diseases
- SRS model describes the epidemiological dynamics of *Xf* and its vectors
  - At high resolution both in space (single plant, meters) and time (days)
  - Only the local spread (i.e., within the orchard) is considered in the model: *Xf* is propagated only by the feeding activity and the natural spread of its infected vectors
  - Long jumps of the disease, due to human-assisted spread of the infected vectors or infected host plants, are not included in the SRS.
- SRS model considers the interactions between vector, host plant and pathogen
  - Transmission processes
    - The transmission of the pathogen from the vector to the plant (including host susceptibility)
    - The acquisition of the pathogen by the vector from the infected plant
  - Disease growth in the host plant
  - Demography of vector population
  - Vector dispersal behaviour
  - Impact of environmental drivers on disease dynamics

Vector population abundance dynamics



$k_{v,max}$

$k_v(t)$ = carrying capacity

γ(t) = abundance of infected vectors

t_i	initial time of the period
t_{V_i}	time of vectors emergence
t_{V_f}	time at which vectors disappear
t_f	final time of the period

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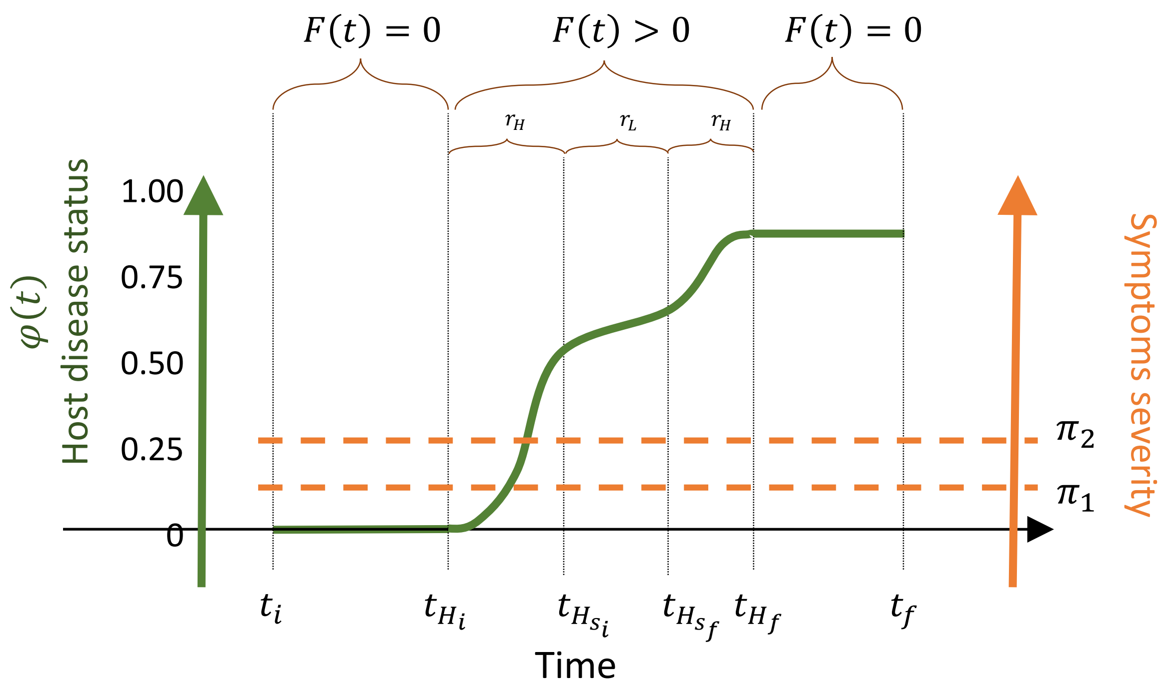
Disease dynamics



— φ(t) = Host disease status

$F(t)$ = bacterial growth in the infected plant
If $F(t)$>0 transmission ‘vector to host’ and ‘host to vector’ is possible

r_H = high rate of the bacterial growth
r_L = low rate of the bacterial growth

π_1 = threshold for molecular detectability of the bacterium
π_2 = threshold for visual detectability of the bacterium

t_i	initial time of the period
t_{H_i}	*for deciduous host* → initial time in which leaves are present and potentially infectious *for evergreen host* → initial time in which temperatures allow the growth of disease agent
t_{H_f}	*for deciduous host* → final time in which leaves are present and potentially infectious *for evergreen host* → final time in which temperatures allow the growth of disease agent
t_f	final time of the period

Formal model

- The space-time spread of the disease induced by *Xf* bacteria is described as a function of
  - the health status of the host plant (φ)
  - the abundance of infected vectors (γ)
- Through a nonlinear system composed of
  - a parabolic partial differential equation for γ
  - a first-order ordinary differential equation for φ

$$\dot{\gamma} = a\Delta\gamma - M\gamma + b(k_v(t) - \gamma)\varphi$$

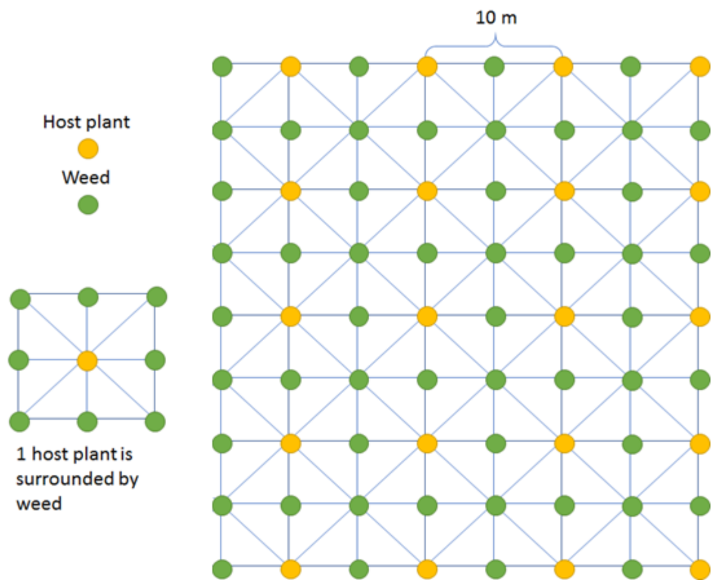
$$\varphi = [s\, l\, \gamma + F(t)\varphi](1 - \varphi)$$

$$\varphi(0) = \varphi_0, \qquad \gamma(0) = \gamma_0$$

- $\varphi(0)$ and $\gamma(0)$ represent the initial condition, i.e. the status of the system at $t = 0$

Parameter	Name	Description
φ	Health status of the host plant	$\varphi = 0$: healthy plant; $\varphi > 0$: infected plants; $\varphi = 1$: the bacterial load in the host plant is at its maximum level
γ	Infected vector abundance	γ should be lower or equal to $k_v(t)$
Δ	Laplacian operator	The mathematical operator defining how the vectors spread in the space Ω
a	Spread scalar parameter	Parameter of the Laplacian operator, directly proportional to vector spread capability
M	Natural mortality	Mortality rate of the vector population due to natural mortality
b	Acquisition rate	Acquisition rate of the disease by the vector when feeding on the infected plant
$k_v(t)$	Instant local carrying capacity	Carrying capacity at time t in the point (x,y) of the space Ω
s	Susceptibility rate	Rate of susceptibility of the host plant to the bacterium
l	Bacterium load	Bacterial load transmitted by the vector in a feeding day on a plant
$F(t)$	Disease growth	It describes the growth of the disease in an infected plant

Case study: Apulian olive orchards



- Landscape is a simplified representation of a large olive grove
  - Maximum extent of 10 000 x 10 000 m with reflecting boundary conditions (Neumann homogeneous boundary conditions).
  - Susceptible plants are in centre of the nodes of a regular grid 10 x 10 m
- Spatial and temporal epidemiological dynamics is followed considering the establishment on a new outbreak in the centre of free area.

- Time scale: ten years for the epidemiological dynamics, efficacy of the eradication strategy is assessed five years after the detection
- Time resolution: one day.
- Environmental conditions are those typical of a Mediterranean area
  - The role of climate is considered by assigning different patterns in the year to the disease growth in the plant and to the phenology and the density of the vectors.
  - The same patterns are repeated every year of the simulation.

Epidemiological and management scenarios

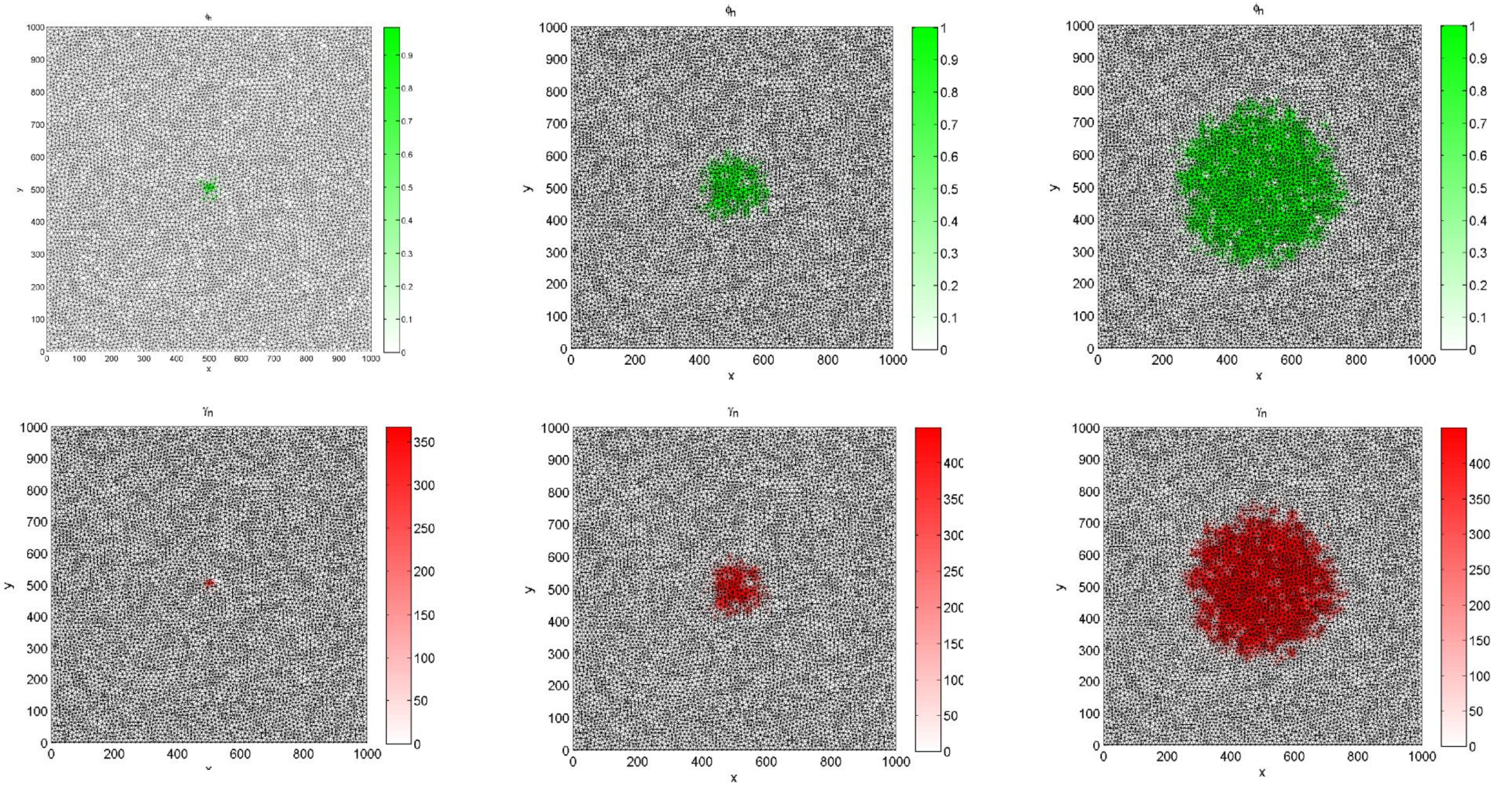
- Four scenarios to assess the epidemiological dynamics based on
  - Maximum vector density
    - High (20 adults/m^2) / Low (1 adult/m^2)
  - Susceptibility of the host plant
    - High (reference cultivar *Ogliarola*) / Low (reference cultivar *Leccino*)
- Variables used to define scenarios of detection and the eradication strategies
  - Vector control efficacy (both adult vector and weed control)
    - High (80% of nymphs mortality, 90% of adult mortality) / Low (60% of nymphs mortality, 50% of adult mortality)
  - Cutting radius
    - High (100 m) / Low (50 m)
  - Time to detection
    - Early (3 years after the inoculum) / Late (4 years after the inoculum)
  - Time to intervention
    - Delay of the intervention (days from the detection)
- Efficacy of the eradication strategy were tested in the worst case scenario of epidemiological dynamics

Spread dynamics

2nd year **5th year** **10th year**

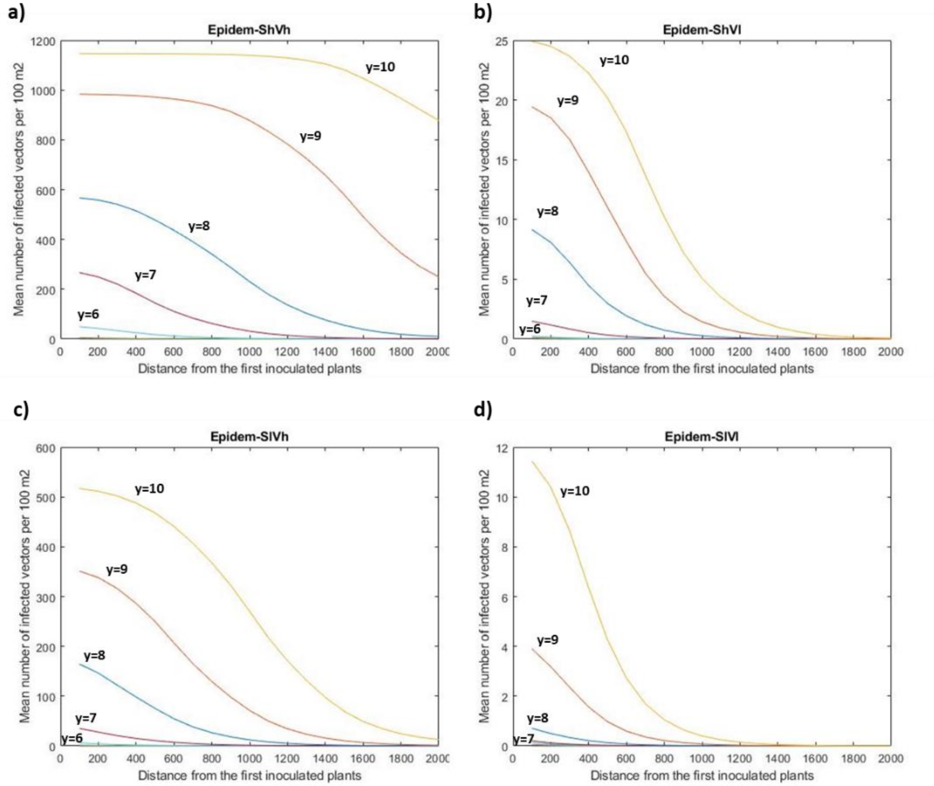
Vector

Disease (*Xf*)

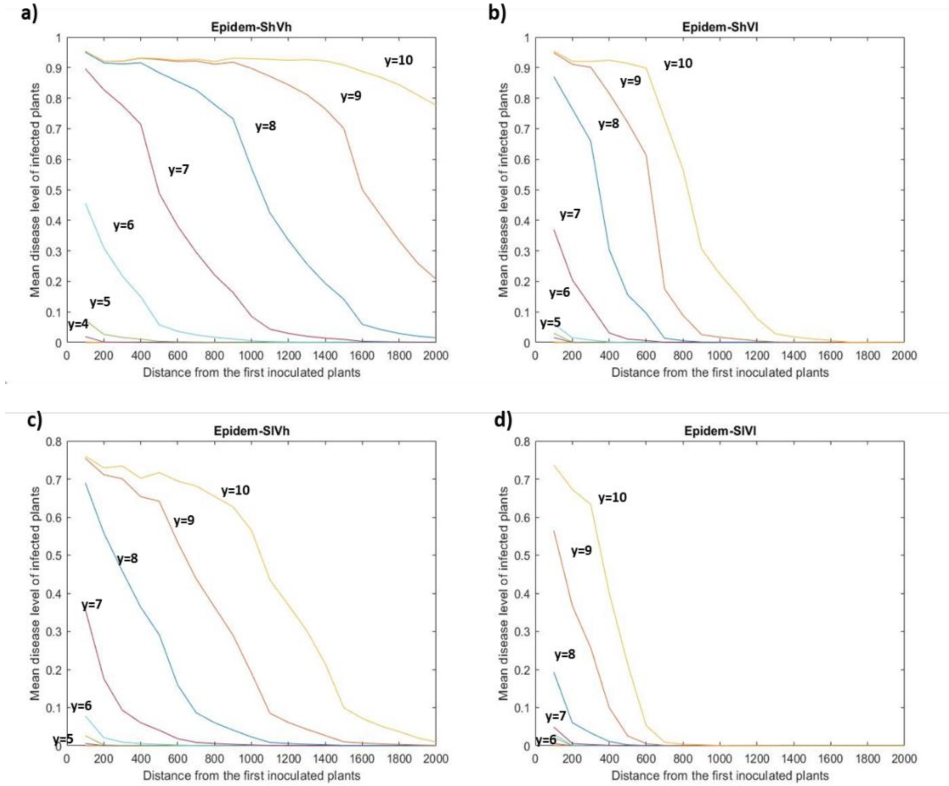


Simulation results: Epidemiological dynamics

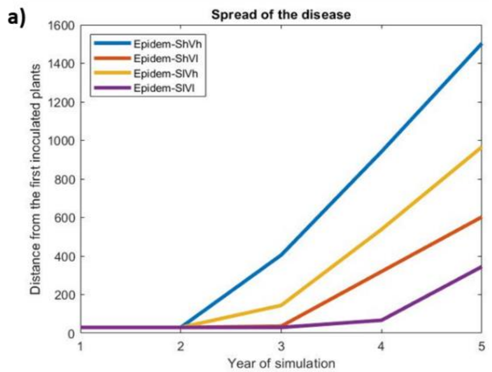
Mean infected vector density (adults/100m2)

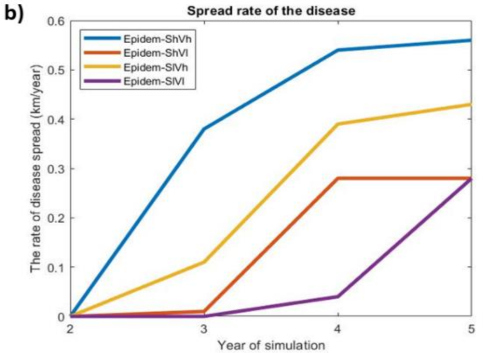


Mean disease level in the infected plants



Spread of disease front (m)





Spread Rate (km/y)

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Simulation results: Management strategies

Scenario components				Scenario outcomes			
Vector control efficacy	Cut radius	Time to detection (years after inoculation)	Delay of the intervention (days from the detection)	Outcome of the control	Infected area (in km^2) at the end of the simulation period	Infected plants in the buffer zone at the end of the simulation period	Maximum distance of plants removed (in m from the point of initial outbreak)
H	100	3	30	eradicated at year 4	2.97	0	1003.2
			65	eradicated at year 5	3.03	0	1024.9
H	100	4	30	eradicated at year 4	6.99	0	1591.8
			65	eradicated at year 5	7.05	0	1595.2
H	50	3	30	eradicated at year 4	2.48	0	957.7
			65	eradicated at year 5	2.73	0	976.37
H	50	4	30	eradicated at year 4	5.91	0	1544.3
			65	eradicated at year 5	6.92	0	1644.4
L	100	3	30	eradicated at year 5	3.07	0	1037.0
			65	not eradicated	4.35	896	1247.8
L	100	4	30	not eradicated	8.59	176	1772.0
			65	not eradicated	10.40	856	1905.0
L	50	3	30	not eradicated	3.36	7292	1198.7
			65	not eradicated	4.10	12104	1328.3
L	50	4	30	not eradicated	8.52	17052	1926.3
			65	not eradicated	8.85	32128	1998.3

Main factor:
Control efficacy

Main factor:
Cut radius and early detection / intervention

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Simulation results

- Key factors for a successful eradication of an outbreak in a free area

  Factor 1: Vector control

  - The application of highly effective nymphs and adults vector control

  Factor 2: Delay

  - Short delay from infection to detection
  - Short delay from detection to implementation of control measures (e.g. removing plants)

  Factor 3: Cut radius

  - With a small cut radius (<100m) it was possible to achieve an effective eradication of the disease if high efficacy of nymphs and adults control is guaranteed.
  - A cut radius of 100m is more efficient in eradication but it could still fail in the situation where the vector is poorly controlled and detection and instigation of control were too slow.

Short-Range Spread models (SRS): Model uncertainties and improvement

Source of uncertainty	How to evaluate the impact of uncertainty and expected consequences
Spread rate of the vector and the pattern of the vector dispersal movement	▪ An uncertainty distribution for the vector dispersal kernel is available and can be explored by the simulation model ▪ Variation in the spread rate could have influence on the growth rate and on the spread of the disease, and in turn on the effectivity of control measures ▪ Inhomogeneity in the pattern of the vector dispersal could lead to inhomogeneity in the distribution of the disease, affecting the uncertainty for assessing the cut radius.
Vector acquisition rate of the bacteria	▪ The vector acquisition rate could be affected by within- and between-species variability in the feeding rate and preference. This could result in increasing the spatial variability of disease. ▪ The model can include element of stochasticity in the feeding behaviour of the vectors and explore the consequences.
Vector population density that is known to be highly variable in a given area.	▪ This factor resulted one of the most important driver for the spread of the disease. ▪ The spatial and temporal variability of vector density could affect the risk of disease spread in an area as well as the temporal dynamics of the symptom appearance. ▪ The density also affects the possibility of eradicate the disease. ▪ Also the phenology of the vector could have large impact on disease spread and control. ▪ The model can account for variability in the density and the phenology of the vector changing the parameters related to those factors.

Short-Range Spread models (SRS): uncertainties and improvement

Source of uncertainty	How to evaluate the impact of uncertainty and expected consequences
Susceptibility of the host plant	▪ Together with vector density this is the most important factor influencing disease spread and control. ▪ Variability in the host susceptibility highly affect the growth rate of the disease in the plant with consequences on the spatial and temporal pattern of the disease. ▪ Susceptibility influences also the asymptomatic period, the detectability of the plants and the severity of the symptoms.
Diseased plant detection	▪ The deterministic nature of the model produces regularity and homogeneity in the temporal and spatial patterns of the disease level and symptoms severity. This also makes the pattern of detection homogenous for small areas. The role of spatial variability in disease presence and severity is not explored in its consequences on the probability of detection. ▪ Only the stochastic formulation of the model could allow a full exploration of a probabilistic approach to plant detection.
Vector control	▪ Some important aspects related to vector control are not explored like for example the long term impact of chemical control and weed removal, the difficulty to access or doing vector control in some areas (private gardens, forestry areas or urban areas). ▪ These factors could affect the outcome of the control measures. ▪ The role of uncertainty in the vector control efficacy and in the availability of refugees for the vector population can be explored by the model considering suitable parametrization of the mortality function and appropriate definition of the landscape structure.
Outcome of the eradication process	▪ With respect to eradication indications emerging from model simulations show dichotomous system behaviour: disease eradicated or not eradicated. ▪ Since there is a stochastic component in the detection of infected plants the level of confidence associated to the outcome of control is not the same for all the scenarios. ▪ For the scenarios where the transition from eradication to non eradication occurs there is a possibility of a random variation in the outcome of the control. The level of confidence in this case is lower than for the remaining scenarios where a clear outcome is observed for all the realizations (i.e., repeated simulations for the same scenario). ▪ To account for this uncertainty the model has run several times, particularly for the scenarios characterised by a significant level of uncertainty and the most probable outcome is considered.

Short-Range Spread models (SRS): Exploitation

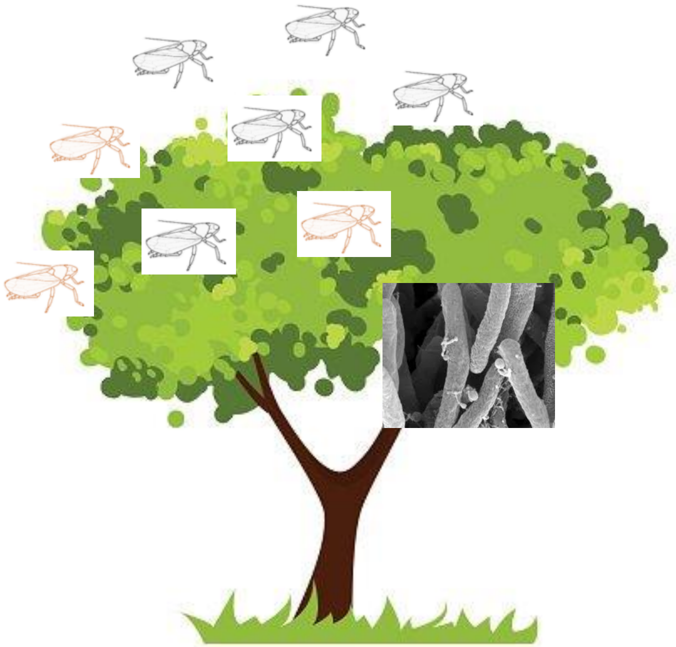
- The eco-epidemiological approach adopted allows to model wide range of conditions to account for
    - Different vector species, *X. fastidiosa* sub-species and strains
    - Mixed plant communities (species with different susceptibility)
    - Scenarios on landscapes (homogeneous, heterogeneous but continuous, patchy)
    - Combinations of management options

- SRS is suitable
    - To explore theoretical scenarios for epidemiological analysis
    - To support decision making for the definition and management of emergency plans related to new outbreaks

- Need for model improvement

Future direction: composite modelling approach

Step 1:
i-state modelling

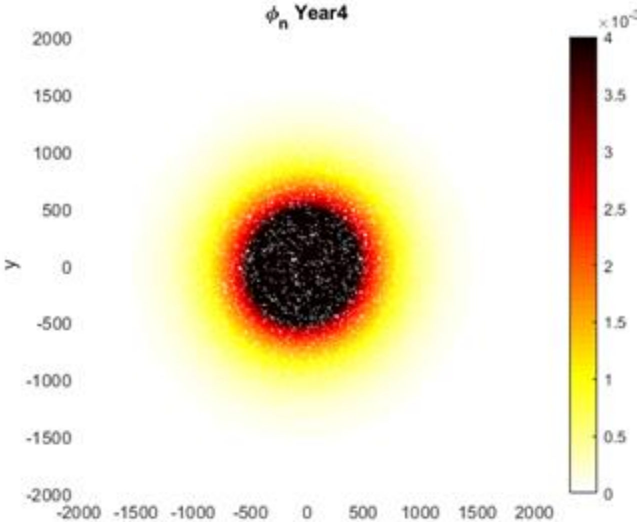


Step 2:
Landscape and drivers

Step 3:
Lumped-parameter estimation

Parameter	Name
φ	Health status of the host plant
γ	Infected vector abundance
Δ	Laplacian operator
a	Spread scalar parameter
M	Natural mortality
$k_v(t)$	Instant local carrying capacity
b	Acquisition rate
s	Susceptibility rate
l	Bacterium load
$F(t)$	Disease growth

Step 4:
Eco-epidemiological model



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Many thanks!