Modelling interference between vectors plant viruses to identify effective control strategies

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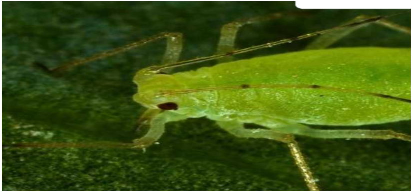
The genesis of the work

PhD thesis on the peach *Prunus persica* - green aphid *Myzus persicae* pathosystem

- *M. persica* does not affect peach production, why it is a threat ?
- Because green aphid is an excellent vector of plant viruses !
- But, if it is a "resident" aphid, it does not visit different plants!
- Right...let's read more and ask for help



State of the art and research questions

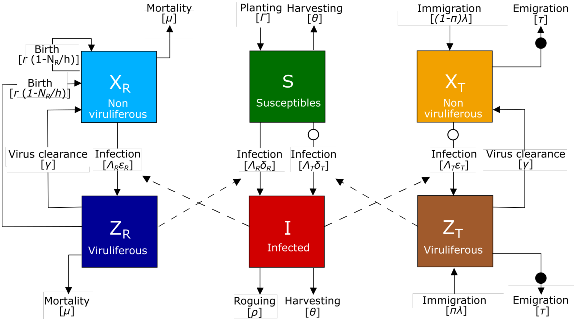
We learned that

- **Transient** aphids are commonly considered the principal vectors of viruses
- **Resident** aphids can also transmit viruses when they are induced to change their host
- The presence of resident aphids may affect transient aphids' behavior

Research questions

- Which is the role of possible inter-specific aphid interference on viral crop diseases spread
- Which is the effect of common agricultural practices, such as fertilization, pesticide application and rouging?

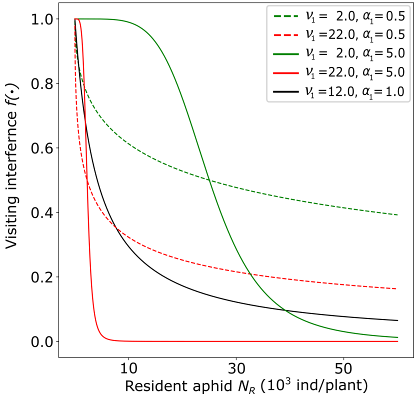
Model outlines and assumptions



$$
\begin{cases}
\dot{S} = \Gamma - [\Lambda_R \delta_R Z_R + \Lambda_T \delta_T f(\cdot) Z_T] S - \theta S \\
\dot{I} = [\Lambda_R \delta_R Z_R + \Lambda_T \delta_T f(\cdot) Z_T] S - [\rho + \theta] I \\
\dot{X_R} = r N_R [1 - \frac{N_R}{h}] - \mu X_R - \Lambda_R \epsilon_R \frac{I}{S+I} X_R + \gamma Z_R \\
\dot{Z_R} = \Lambda_R \epsilon_R \frac{I}{S+I} X_R - [\gamma + \mu] Z_R \\
\dot{X_T} = [1 - \pi] \lambda - \Lambda_T \epsilon_T f(\cdot) \frac{I}{S+I} X_T + \gamma Z_T - \tau g(\cdot) X_T \\
\dot{Z_T} = \pi \lambda + \Lambda_T \epsilon_T f(\cdot) \frac{I}{S+I} X_T - \gamma Z_T - \tau g(\cdot) Z_T
\end{cases}
$$

Interference functions (direct or not)

The role of ecology



Visiting direct interference

$$f(N_R = X_R + Z_R) = \frac{1}{1 + \left(\nu_1 \frac{N_R}{h}\right)^{\alpha_1}}$$

Transient aphids visit more plants per day but they might avoid already colonized plants: $\dot{S} = \Gamma - [\Lambda_R \delta_R Z_R + \Lambda_T \delta_T f(\cdot) Z_T] S - \theta$

Model parameters

The role of agricultural practices and disease control

- Fertilization or irrigation increase the abundance of resident aphids dwelling on the plants (plant hosting capacity h)
- Pesticides increase of resident aphid mortality μ
- Roguing removes infected plants and replace them with healthy ones ρ (with planting rate $\Gamma = \theta S + [\rho + \theta I]$)

$$\begin{cases} \dot{S} = \Gamma - [\Lambda_R \delta_R Z_R + \Lambda_T \delta_T f(\cdot) Z_T] S - \theta S \\ \dot{I} = [\Lambda_R \delta_R Z_R + \Lambda_T \delta_T f(\cdot) Z_T] S - [\rho + \theta] I \\ \dot{X}_R = r N_R [1 - \frac{N_R}{h}] - \mu X_R - \Lambda_R \epsilon_R \frac{I}{S+I} X_R + \gamma Z_R \\ \dot{Z}_R = \Lambda_R \epsilon_R \frac{I}{S+I} X_R - [\gamma + \mu] Z_R \\ \dot{X}_T = [1 - \pi] \lambda - \Lambda_T \epsilon_T f(\cdot) \frac{I}{S+I} X_T + \gamma Z_T - \tau g(\cdot) X_T \\ \dot{Z}_T = \pi \lambda + \Lambda_T \epsilon_T f(\cdot) \frac{I}{S+I} X_T - \gamma Z_T - \tau g(\cdot) Z_T \end{cases}$$

Model overview: state variables and parameters

Table 1. Model state variables and parameters.

Variable	Description	Dimensions		
S	Susceptible plants	plant ha^{-1}		
I	Infected plants	plant ha^{-1}		
X_R	Non viruliferous resident aphids	aphid plant^{-1}		
Z_R	Viruliferous resident aphids	aphid plant^{-1}		
X_T	Non viruliferous transient aphids	aphid plant^{-1}		
Z_T	Viruliferous transient aphids	aphid plant^{-1}		
Parameter	**Description**	**Dimensions**	**Values**	**Source**
Γ	Planting rate	plant day^{-1}	$\theta S + (\rho + \theta)I$	
Λ_R	Number of plants visited by a resident aphid	plant aphid^{-1} day^{-1}	0.05	Fixed
Λ_T	Number of plants visited by a transient aphid	plant aphid^{-1} day^{-1}	8.5	Fixed
δ_R	Probability of virus transmission from the resident aphid to the plant	dimensionless	0.04	[34]
δ_T	Probability of virus transmission from the transient aphid to the plant	dimensionless	0.04	[34]
ε_R	Probability of virus transmission from the plant to the resident aphid	dimensionless	0.02	[34]
ε_T	Probability of virus transmission from the plant to the transient aphid	dimensionless	0.02	[34]
α_1	Visiting interference curvature	dimensionless	1.00	Fixed
ν_1	Visiting interference strength (for direct interference)	dimensionless	12.0	Fixed
α_2	Emigration interference curvature	dimensionless	1.00	Fixed
ν_2	Emigration interference strength (for direct interference)	dimensionless	12.0	Fixed
ρ	Infected plant roguing rate	day^{-1}	0.02	[35, 36]
θ	Plant harvesting rate	day^{-1}	0.003	[37]
r	Intrinsic growth rate of resident aphids	day^{-1}	0.21	[37]
h	Plant hosting capacity	aphid plant^{-1}	50,000	[38]
h_R	Reference plant hosting capacity	aphid plant^{-1}	50,000	Fixed
μ	Mortality rate of resident aphids	day^{-1}	0.08	Fixed
γ	Virus clearance rate in aphid vectors	day^{-1}	4	[34]
λ	Average number of transient aphids immigrating per plant	aphid plant^{-1} day^{-1}	$\tau T = 250$	Derived
π	Fraction of viruliferous transient aphids entering the system	dimensionless	0	Fixed
τ	Transient aphids emigration rate in absence of resident aphids	day^{-1}	0.5	[35, 39]
N_P	Total number of plants	plant ha^{-1}	720	[40]
T	Average number of transient aphids per plant in absence of resident aphids	aphid plant^{-1}	500	Fixed

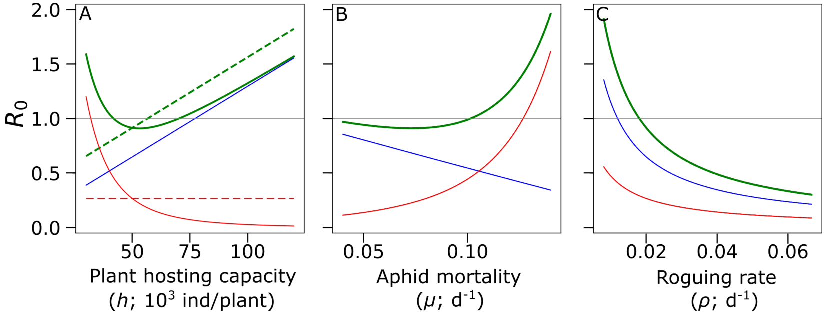
Source: Fixed: fixed to an arbitrary, biologically-plausible reference value.

Equilibrium analysis and basic reproduction number

Viruliferous aphids enter the system ($\pi > 0$)	Resident aphids are present ($\mu < r$)	Basic reproduction number (Eq 6)	$(\bar{S}, \bar{I}, \bar{X}_R, \bar{Z}_R, \bar{X}_T, \bar{Z}_T)$
no	no	$R_0 < 1$	(+, 0, 0, 0, +, 0)
no	no	$R_0 > 1$	(+, +, 0, 0, +, +)
no	yes	$R_0 < 1$	(+, 0, +, 0, +, 0)
no	yes	$R_0 > 1$	(+, +, +, +, +, +)
yes	no	- *	(+, +, 0, 0, +, +)
yes	no	- *	(+, +, +, +, +, +)

* The disease is always able to persist, the basic reproduction number is not definable.

The role of fert-irrigation, pesticide and roguing



$$R_0 = \frac{1}{\rho + \theta}\left(\frac{\Lambda_R^2 \delta_R \varepsilon_R \bar{N}_R}{\gamma + \mu} + \frac{\Lambda_T^2 \delta_T \varepsilon_T f(\cdot)^2 \bar{N}_T}{\gamma + \tau g(\cdot)}\right)$$

Conclusions

- Interference mechanisms between vectors matter: formalized for the first time
- A number of simplifying assumptions and “educated” parameter guesses $\rightarrow$ call for dedicated empirical measurements
- Fert-irrigation and pesticide application can have “unexpected” results