Modelling plant-nematode interactions to understand plant tolerance

Joseph Penlap, Suzanne Touzeau, Frédéric Grognard, Valentina Baldazzi

MacBiosCore seminar 2023

Outline

1. Context
2. Plant model
3. Plant-Nematode interactions
4. Model calibration

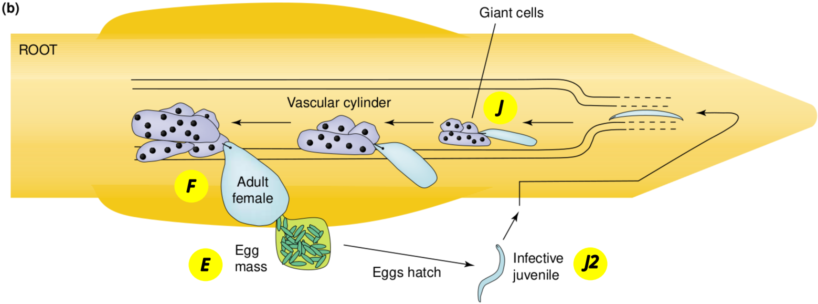
Context

Root-knot nematodes

- microscopic endoparasites feeding on plant roots
- more than 5000 host species concerned
  - changes in root architecture
  - wilting of vegetative part, yield reduction
- 14% of global crop losses worldwide

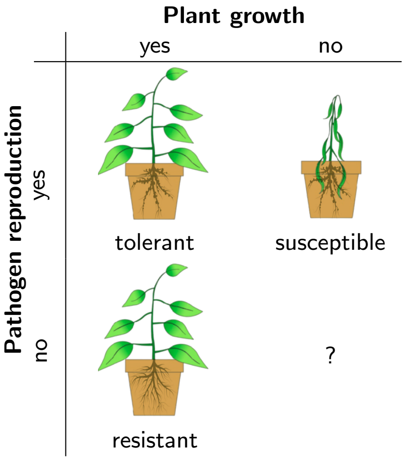
Root-knot nematodes

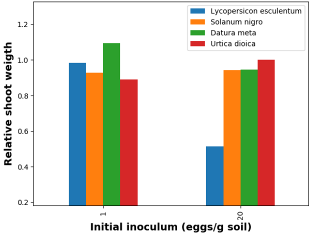
- microscopic endoparasites feeding on plant roots
- more than 5000 host species concerned
  - changes in root architecture
  - wilting of vegetative part, yield reduction
- 14% of global crop losses worldwide



Phenotypic variability

- **Strong variations** in the extent of damages within and among plant species

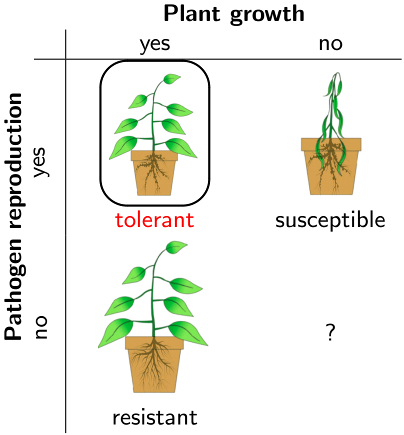


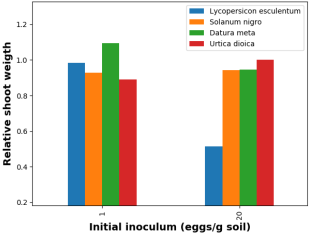


- Resistance is efficient but
  - few resistant genes identified
  - only for a few species
  - may favour the emergence of virulent nematodes
- Interest for tolerance
- Several possible mechanisms reported
  - high root growth rate
  - better water and nutrients uptake
  - delayed senescence ...

Phenotypic variability

- **Strong variations** in the extent of damages within and among plant species





- Resistance is efficient but
  - few resistant genes identified
  - only for a few species
  - may favour the emergence of virulent nematodes
- Interest for tolerance
- Several possible mechanisms reported
  - high root growth rate
  - better water and nutrients uptake
  - delayed senescence ...

Phenotypic variability

Aim

Better understand the mechanisms behind (differential) plant susceptibility to nematodes

Phenotypic variability

Aim

Better understand the mechanisms behind (differential) plant susceptibility to nematodes

Research question

Which are the **physiological mechanisms** behind **plant tolerance**?

Phenotypic variability

Aim

Better understand the mechanisms behind (differential) plant susceptibility to nematodes

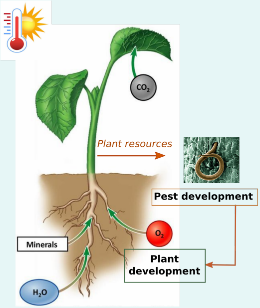
Research question

Which are the **physiological mechanisms** behind **plant tolerance**?

Approach

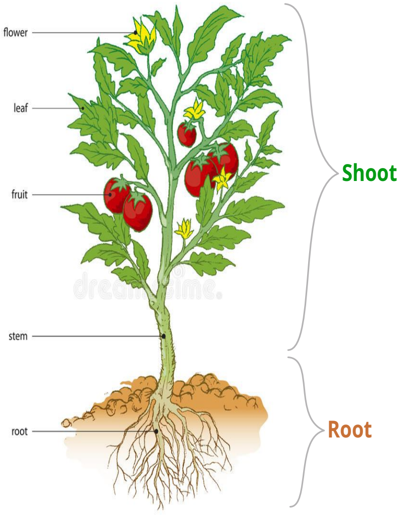
Coupled modeling of plant physiology and pest population dynamics

- better representation of pathosystem dynamics
  - interplay between plant and pest dynamics
- better prediction of plant growth rate and yield
- screening of interesting plant phenotypic traits



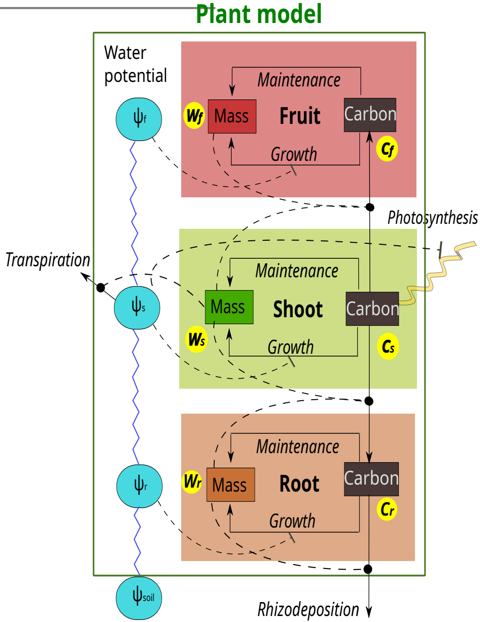
Plant model

Plant description



The basic structure of plant (tomato).

VS

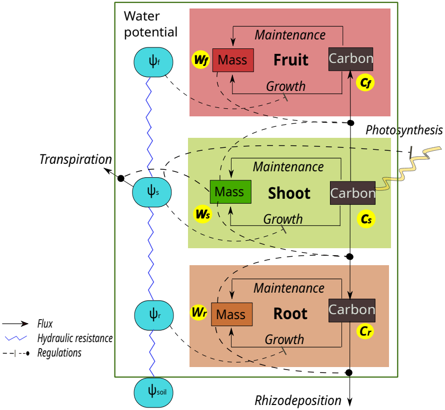


Plant description

- 3 plant compartments:
  - shoots
  - roots
  - **fruits**
- 2 resources:
  - carbon (structural and free)
  - water
- Uptake, transport and allocation through plant compartments
  - growth and respiration processes
  - regulatory functions with respect to the water status of the plant

Thornley (1972), Dewar (1991)

Plant model



Mathematical equations

$$\text{Shoot}\begin{cases}\dfrac{dW_s}{dt} = \\[2em] \dfrac{dC_s}{dt} = \\[2em]\end{cases}$$

$$\text{Root}\begin{cases}\dfrac{dW_r}{dt} = \\[2em] \dfrac{dC_r}{dt} = \\[2em]\end{cases}$$

$$\text{Fruit}\begin{cases}\dfrac{dW_f}{dt} = \\[2em] \dfrac{dC_f}{dt} = \\[2em]\end{cases}$$

Mathematical equations

$$\text{Shoot}\begin{cases} \dfrac{dW_s}{dt} = \\ \dfrac{dC_s}{dt} = \underbrace{\sigma_c f(\psi_s)}_{\text{Uptake}} \quad - \underbrace{\dfrac{1}{W_s}\dfrac{dW_s}{dt}C_s}_{\text{Dilution}} \end{cases}$$

$$\text{Root}\begin{cases} \dfrac{dW_r}{dt} = \\ \dfrac{dC_r}{dt} = \quad - \underbrace{\dfrac{1}{W_r}\dfrac{dW_r}{dt}C_r}_{\text{Dilution}} \end{cases}$$

$$\text{Fruit}\begin{cases} \dfrac{dW_f}{dt} = \\ \dfrac{dC_f}{dt} = \quad - \underbrace{\dfrac{1}{W_f}\dfrac{dW_f}{dt}C_f}_{\text{Dilution}} \end{cases}$$

Mathematical equations

$$\text{Shoot}\begin{cases} \dfrac{dW_s}{dt} = \\[2em] \dfrac{dC_s}{dt} = \underbrace{\sigma_c f(\psi_s)}_{\text{Uptake}} - \dfrac{1}{W_s}\underbrace{(T_r + T_f + \mathrm{T}_a)}_{\text{Transport}} \qquad - \underbrace{\dfrac{1}{W_s}\dfrac{dW_s}{dt}C_s}_{\text{Dilution}} \end{cases}$$

$$\text{Root}\begin{cases} \dfrac{dW_r}{dt} = \\[2em] \dfrac{dC_r}{dt} = \dfrac{1}{W_r}\underbrace{T_r}_{\text{Transport}} \qquad - \underbrace{\dfrac{1}{W_r}\dfrac{dW_r}{dt}C_r}_{\text{Dilution}} \end{cases}$$

$$\text{Fruit}\begin{cases} \dfrac{dW_f}{dt} = \\[2em] \dfrac{dC_f}{dt} = \dfrac{1}{W_f}\underbrace{(T_f + \mathrm{T}_a)}_{\text{Transport}} \qquad - \underbrace{\dfrac{1}{W_f}\dfrac{dW_f}{dt}C_f}_{\text{Dilution}} \end{cases}$$

Mathematical equations

$$
\text{Shoot}\begin{cases}
\dfrac{dW_s}{dt} = \underbrace{k_s f(\psi_s)\dfrac{C_s}{K_s + C_s}W_s}_{\text{Growth}} \\[2ex]
\dfrac{dC_s}{dt} = \underbrace{\sigma_c f(\psi_s)}_{\text{Uptake}} - \dfrac{1}{W_s}\underbrace{(T_r + T_f + \mathrm{T}_a)}_{\text{Transport}} - \underbrace{(f_c \qquad) k_s f(\psi_s)\dfrac{C_s}{K_s + C_s}}_{\text{Growth}} \qquad - \underbrace{\dfrac{1}{W_s}\dfrac{dW_s}{dt}C_s}_{\text{Dilution}}
\end{cases}
$$

$$
\text{Root}\begin{cases}
\dfrac{dW_r}{dt} = \underbrace{k_r f(\psi_r)\dfrac{C_r}{K_r + C_r}W_r}_{\text{Growth}} \\[2ex]
\dfrac{dC_r}{dt} = \dfrac{1}{W_r}\underbrace{T_r}_{\text{Transport}} - \underbrace{(f_c \qquad) k_r f(\psi_r)\dfrac{C_r}{K_r + C_r}}_{\text{Growth}} \qquad - \underbrace{\dfrac{1}{W_r}\dfrac{dW_r}{dt}C_r}_{\text{Dilution}}
\end{cases}
$$

$$
\text{Fruit}\begin{cases}
\dfrac{dW_f}{dt} = \underbrace{k_f f(\psi_f)\dfrac{C_f}{K_f + C_f}W_f}_{\text{Growth}} \\[2ex]
\dfrac{dC_f}{dt} = \dfrac{1}{W_f}\underbrace{(T_f + \mathrm{T}_a)}_{\text{Transport}} - \underbrace{(f_c \qquad) k_f f(\psi_f)\dfrac{C_f}{K_f + C_f}}_{\text{Growth}} \qquad - \underbrace{\dfrac{1}{W_f}\dfrac{dW_f}{dt}C_f}_{\text{Dilution}}
\end{cases}
$$

Mathematical equations

$$
\text{Shoot}\begin{cases}
\dfrac{dW_s}{dt} = \underbrace{k_s f(\psi_s)\dfrac{C_s}{K_s + C_s}W_s}_{\text{Growth}} \\
\dfrac{dC_s}{dt} = \underbrace{\sigma_c f(\psi_s)}_{\text{Uptake}} - \dfrac{1}{W_s}\underbrace{(T_r + T_f + \mathrm{T}_a)}_{\text{Transport}} - \underbrace{(f_c + r_{g,s})\, k_s f(\psi_s)\dfrac{C_s}{K_s + C_s}}_{\text{Respiration growth}} - \underbrace{r_{m,s}\left(\dfrac{C_s^n}{K_m^n + C_s^n}\right)}_{\text{Maintenance respiration}} - \underbrace{\dfrac{1}{W_s}\dfrac{dW_s}{dt}C_s}_{\text{Dilution}}
\end{cases}
$$

$$
\text{Root}\begin{cases}
\dfrac{dW_r}{dt} = \underbrace{k_r f(\psi_r)\dfrac{C_r}{K_r + C_r}W_r}_{\text{Growth}} \\
\dfrac{dC_r}{dt} = \dfrac{1}{W_r}\underbrace{T_r}_{\text{Transport}} - \underbrace{(f_c + r_{g,r})\, k_r f(\psi_r)\dfrac{C_r}{K_r + C_r}}_{\text{Respiration growth}} - \underbrace{r_{m,r}\left(\dfrac{C_r^n}{K_m^n + C_r^n}\right)}_{\text{Maintenance respiration}} - \underbrace{\dfrac{1}{W_r}\dfrac{dW_r}{dt}C_r}_{\text{Dilution}}
\end{cases}
$$

$$
\text{Fruit}\begin{cases}
\dfrac{dW_f}{dt} = \underbrace{k_f f(\psi_f)\dfrac{C_f}{K_f + C_f}W_f}_{\text{Growth}} \\
\dfrac{dC_f}{dt} = \dfrac{1}{W_f}\underbrace{(T_f + \mathrm{T}_a)}_{\text{Transport}} - \underbrace{(f_c + r_{g,f})\, k_f f(\psi_f)\dfrac{C_f}{K_f + C_f}}_{\text{Respiration growth}} - \underbrace{r_{m,f}\left(\dfrac{C_f^n}{K_m^n + C_f^n}\right)}_{\text{Maintenance respiration}} - \underbrace{\dfrac{1}{W_f}\dfrac{dW_f}{dt}C_f}_{\text{Dilution}}
\end{cases}
$$

Mathematical equations

$$\text{Shoot}\begin{cases} \dfrac{dW_s}{dt} = \underbrace{k_s f(\psi_s)\dfrac{C_s}{K_s + C_s}W_s}_{\text{Growth}} \\ \dfrac{dC_s}{dt} = \underbrace{\sigma_c f(\psi_s)}_{\text{Uptake}} - \dfrac{1}{W_s}\underbrace{(T_r + T_f + \mathrm{T}_a)}_{\text{Transport}} - \underbrace{(f_c + r_{g,s})\, k_s f(\psi_s)\dfrac{C_s}{K_s + C_s}}_{\text{Growth}} - \underbrace{r_{m,s}\left(\dfrac{C_s^n}{K_m^n + C_s^n}\right)}_{\text{Maintenance respiration}} - \underbrace{\dfrac{1}{W_s}\dfrac{dW_s}{dt}C_s}_{\text{Dilution}} \end{cases}$$

$$\text{Root}\begin{cases} \dfrac{dW_r}{dt} = \underbrace{k_r f(\psi_r)\dfrac{C_r}{K_r + C_r}W_r}_{\text{Growth}} \\ \dfrac{dC_r}{dt} = \dfrac{1}{W_r}\underbrace{T_r}_{\text{Transport}} - \underbrace{(f_c + r_{g,r})\, k_r f(\psi_r)\dfrac{C_r}{K_r + C_r}}_{\text{Growth}} - \underbrace{r_{m,r}\left(\dfrac{C_r^n}{K_m^n + C_r^n}\right)}_{\text{Maintenance respiration}} - \underbrace{c_{rh}\dfrac{1}{W_r^{1-\beta}}C_r}_{\text{Rhizodeposition}} - \underbrace{\dfrac{1}{W_r}\dfrac{dW_r}{dt}C_r}_{\text{Dilution}} \end{cases}$$

$$\text{Fruit}\begin{cases} \dfrac{dW_f}{dt} = \underbrace{k_f f(\psi_f)\dfrac{C_f}{K_f + C_f}W_f}_{\text{Growth}} \\ \dfrac{dC_f}{dt} = \dfrac{1}{W_f}\underbrace{(T_f + \mathrm{T}_a)}_{\text{Transport}} - \underbrace{(f_c + r_{g,f})\, k_f f(\psi_f)\dfrac{C_f}{K_f + C_f}}_{\text{Growth}} - \underbrace{r_{m,f}\left(\dfrac{C_f^n}{K_m^n + C_f^n}\right)}_{\text{Maintenance respiration}} - \underbrace{\dfrac{1}{W_f}\dfrac{dW_f}{dt}C_f}_{\text{Dilution}} \end{cases}$$

Mathematical equations

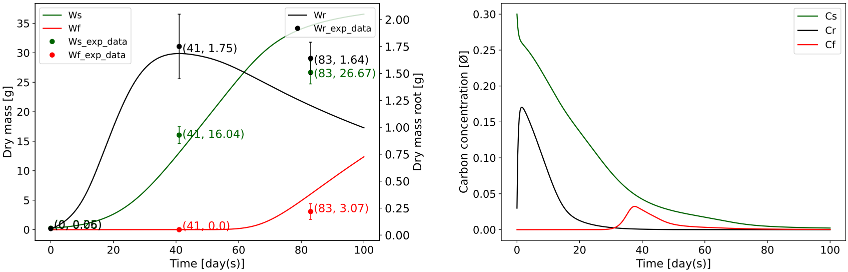
$$
\text{Shoot}\begin{cases}
\dfrac{dW_s}{dt} = \underbrace{k_s f(\psi_s)\dfrac{C_s}{K_s + C_s}W_s}_{\text{Growth}} - \underbrace{\gamma_s W_s}_{\text{Natural senescence}} - \underbrace{\gamma_s \left(\dfrac{K_m^n}{K_m^n + C_s^n}\right) W_s,}_{\text{Additional drop due to carbon shortage}} \\[2ex]
\dfrac{dC_s}{dt} = \underbrace{\sigma_c f(\psi_s)}_{\text{Uptake}} - \dfrac{1}{W_s}\underbrace{(T_r + T_f + \mathrm{T}_a)}_{\text{Transport}} - \underbrace{(f_c + r_{g,s})\, k_s f(\psi_s)\dfrac{C_s}{K_s + C_s}}_{\text{Growth}} - \underbrace{r_{m,s}\left(\dfrac{C_s^n}{K_m^n + C_s^n}\right)}_{\text{Maintenance respiration}} - \underbrace{\dfrac{1}{W_s}\dfrac{dW_s}{dt}C_s}_{\text{Dilution}}
\end{cases}
$$

$$
\text{Root}\begin{cases}
\dfrac{dW_r}{dt} = \underbrace{k_r f(\psi_r)\dfrac{C_r}{K_r + C_r}W_r}_{\text{Growth}} - \underbrace{\gamma_r W_r}_{\text{Natural senescence}} - \underbrace{\gamma_r \left(\dfrac{K_m^n}{K_m^n + C_r^n}\right) W_r,}_{\text{Additional drop due to carbon shortage}} \\[2ex]
\dfrac{dC_r}{dt} = \dfrac{1}{W_r}\underbrace{T_r}_{\text{Transport}} - \underbrace{(f_c + r_{g,r})\, k_r f(\psi_r)\dfrac{C_r}{K_r + C_r}}_{\text{Growth}} - \underbrace{r_{m,r}\left(\dfrac{C_r^n}{K_m^n + C_r^n}\right)}_{\text{Maintenance respiration}} - \underbrace{c_{rh}\dfrac{1}{W_r^{1-\beta}}C_r}_{\text{Rhizodeposition}} - \underbrace{\dfrac{1}{W_r}\dfrac{dW_r}{dt}C_r}_{\text{Dilution}}
\end{cases}
$$

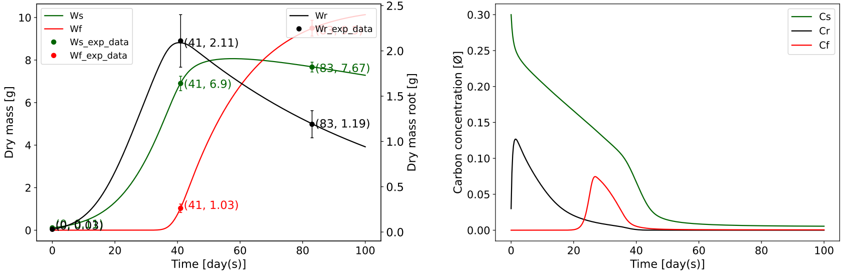
$$
\text{Fruit}\begin{cases}
\dfrac{dW_f}{dt} = \underbrace{k_f f(\psi_f)\dfrac{C_f}{K_f + C_f}W_f}_{\text{Growth}} - \underbrace{\gamma_f W_f}_{\text{Natural senescence}} - \underbrace{\gamma_f \left(\dfrac{K_m^n}{K_m^n + C_f^n}\right) W_f,}_{\text{Additional drop due to carbon shortage}} \\[2ex]
\dfrac{dC_f}{dt} = \dfrac{1}{W_f}\underbrace{(T_f + \mathrm{T}_a)}_{\text{Transport}} - \underbrace{(f_c + r_{g,f})\, k_f f(\psi_f)\dfrac{C_f}{K_f + C_f}}_{\text{Growth}} - \underbrace{r_{m,f}\left(\dfrac{C_f^n}{K_m^n + C_f^n}\right)}_{\text{Maintenance respiration}} - \underbrace{\dfrac{1}{W_f}\dfrac{dW_f}{dt}C_f}_{\text{Dilution}}
\end{cases}
$$

Plant dynamics

Tomato plants



Pepper plants

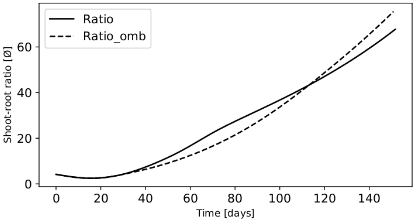


Test of plant model: environmental scenarios

The model is able to react correctly to a panel of environmental scenarios:

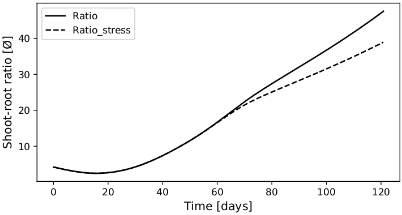
- allocation towards the most limiting resource

Shading



$$\sigma_c \rightarrow \sigma_c/2$$

Water stress



$$\Psi_{soil} \rightarrow -200 MPa$$

$$\boxed{Ratio = \frac{W_s}{W_r}}$$

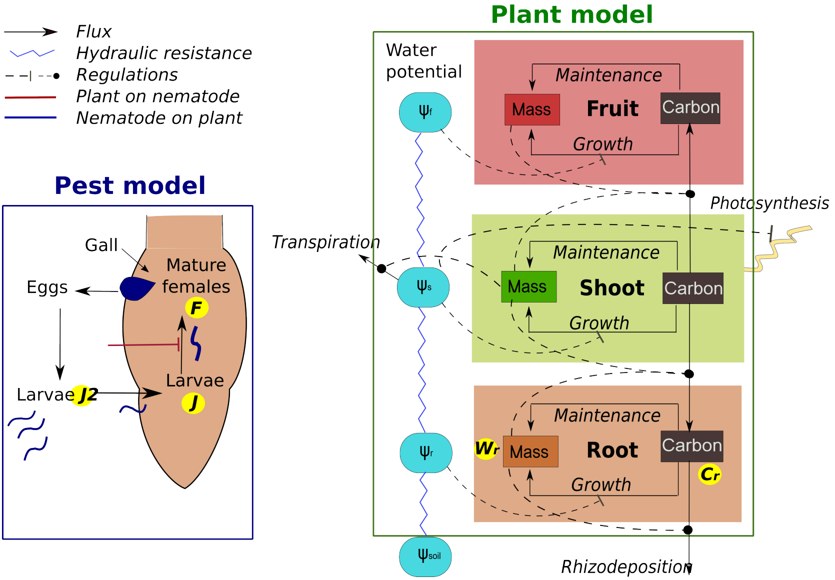
Plant-Nematode interactions

Reported effects and model hypotheses

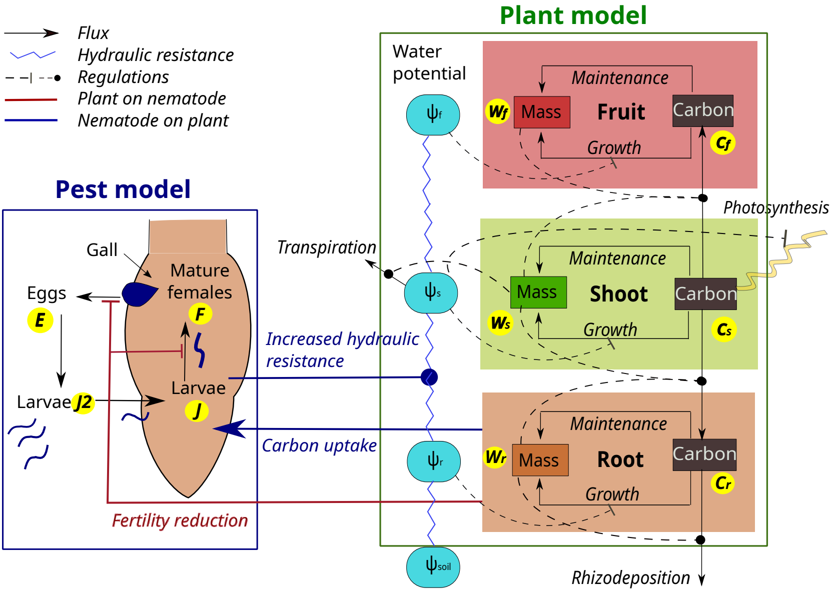
- Hijack of cell machinery amplifies **carbon sink in root galls** - *M.G.K. Jones. et al. 1981*
- **Increased hydraulic resistance** - *R. Dorhout, F.J. Gommers, 1991*
- Change in plant vascularization - *Bartlem et al. 2014*
- **Inhibition of photosynthesis** by water stress and/or interference between synthesis and translocation of growth hormones - *B. Loveys and A. F. Bird, 1994*
- Decrease of respiration intensity - *T. Mateille, 1994*
- Changes in glucose metabolism, nucleogenesis, proteogenesis... - *T. Mateille, 1994*

- Nematode growth rate and body size depend on food supply - *McLeod et al. 2001*
- **Host physiological stress affects egg production and sex ratio** -*Ferris et al. 1984, Snyder et al. 2006*
- **No effect of nitrogen fertilization** on nematodes development - *Spiegel et al. 1982*

Plant-nematode model



Plant-nematode model



Mathematical equations

RKN model:

$$\text{Free}\begin{cases}\dfrac{dE}{dt} = \underbrace{r\,F}_{\text{Egg laying}} - \underbrace{h\,E}_{\text{Egg hatching}} - \underbrace{\mu_e\,E}_{\text{Mortality}}\\[2ex] \dfrac{dJ_2}{dt} = \underbrace{h\,E}_{\text{Egg hatching}} - \underbrace{\beta\,J_2\,W_r}_{\text{Larvae infection}} - \underbrace{\mu_{J_2}\,J_2}_{\text{Mortality}}\end{cases}$$

$$\text{Inside root}\begin{cases}\dfrac{dJ}{dt} = \underbrace{\beta\,J_2 W_r}_{\text{RKN entry}} - \underbrace{\eta\,J}_{\text{Maturation}} - \underbrace{\mu_j J}_{\text{Mortality}}\\[2ex] \dfrac{dF}{dt} = \underbrace{\eta\,J}_{\text{Maturation}} - \underbrace{\mu_F F}_{\text{Mortality}}\end{cases}$$

Plant roots:

$$\text{Root}\begin{cases}\dfrac{dW_r}{dt} = \underbrace{k_r f(\psi_r)\dfrac{C_r}{K_r + C_r} W_r}_{\text{Growth}} - \underbrace{\gamma_r W_r}_{\text{Natural senescence}} - \underbrace{\gamma_r\left(\dfrac{K_m^n}{K_m^n + C_r^n}\right) W_r}_{\text{Additional drop due to carbon shortage}}\\[3ex] \dfrac{dC_r}{dt} = \dfrac{1}{W_r}\underbrace{T_r}_{\text{Transport}} \underbrace{-(f_c + r_{g,r})\,k_r f(\psi_r)\dfrac{C_r}{K_r + C_r}}_{\text{Growth}} \underbrace{-\,r_{m,r}\left(\dfrac{C_r^n}{K_m^n + C_r^n}\right)}_{\text{Maintenance respiration}} \underbrace{-\,c_{rh}\dfrac{1}{W_r^{(1-\beta)}}C_r}_{\text{Rhizodeposition}} \underbrace{-\,\dfrac{1}{W_r}\dfrac{dW_r}{dt}C_r}_{\text{dilution}}\end{cases}$$

Mathematical equations

RKN model:

Free
$$\begin{cases} \dfrac{dE}{dt} = \underbrace{r(C_r)\,F}_{\text{Egg laying}} - \underbrace{h\,E}_{\text{Egg hatching}} - \underbrace{\mu_e\,E}_{\text{Mortality}} \\ \dfrac{dJ_2}{dt} = \underbrace{h\,E}_{\text{Egg hatching}} - \underbrace{\beta\,J_2\,W_r}_{\text{Larvae infection}} - \underbrace{\mu_{J_2}\,J_2}_{\text{Mortality}} \end{cases}$$

Inside root
$$\begin{cases} \dfrac{dJ}{dt} = \underbrace{\Omega(C_r)\,\beta\,J_2 W_r}_{\text{RKN entry}} - \underbrace{\eta\,J}_{\text{Maturation}} - \underbrace{(\mu_j+\mu_r)\,J}_{\text{Mortality}} \\ \dfrac{dF}{dt} = \underbrace{(1-\theta(C_r))\,\eta\,J}_{\text{Maturation}} - \underbrace{(\mu_F+\mu_r)\,F}_{\text{Mortality}} \end{cases}$$

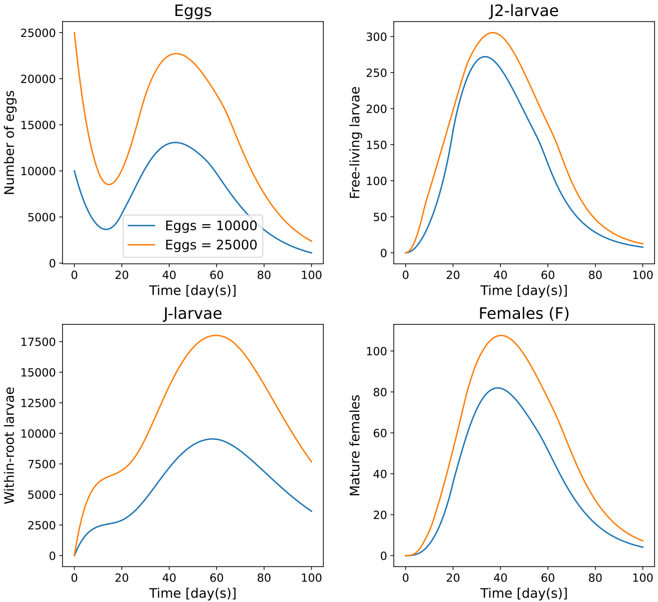
Plant roots:

Root
$$\begin{cases} \dfrac{dW_r}{dt} = \underbrace{k_r f(\psi_r)\dfrac{C_r}{K_r+C_r}W_r}_{\text{Growth}} - \underbrace{\gamma_r W_r}_{\text{Natural senescence}} - \underbrace{\gamma_r\left(\dfrac{K_m^n}{K_m^n+C_r^n}\right)W_r}_{\text{Additional drop due to carbon shortage}} - \underbrace{\Omega(C_r)\epsilon\beta J_2\ W_r}_{\text{Successfully infected roots}} \\ \dfrac{dC_r}{dt} = \dfrac{1}{W_r}\underbrace{T_r}_{\text{Transport}} - \underbrace{(f_c+r_{g,r})\,k_r f(\psi_r)\dfrac{C_r}{K_r+C_r}}_{\text{Growth}} - \underbrace{r_{m,r}\left(\dfrac{C_r^n}{K_m^n+C_r^n}\right)}_{\text{Maintenance respiration}} - \underbrace{c_{rh}\dfrac{1}{W_r^{(1-\beta)}}C_r}_{\text{Rhizodeposition}} - \underbrace{\dfrac{1}{W_r}\dfrac{dW_r}{dt}C_r}_{\text{dilution}} \\ \qquad - \underbrace{\gamma\dfrac{C_r}{C_r+K_\gamma}F}_{\text{Nematode feeding}} - \underbrace{\rho\Omega(C_r)\beta\ J_2}_{\text{Gall formation}} \end{cases}$$

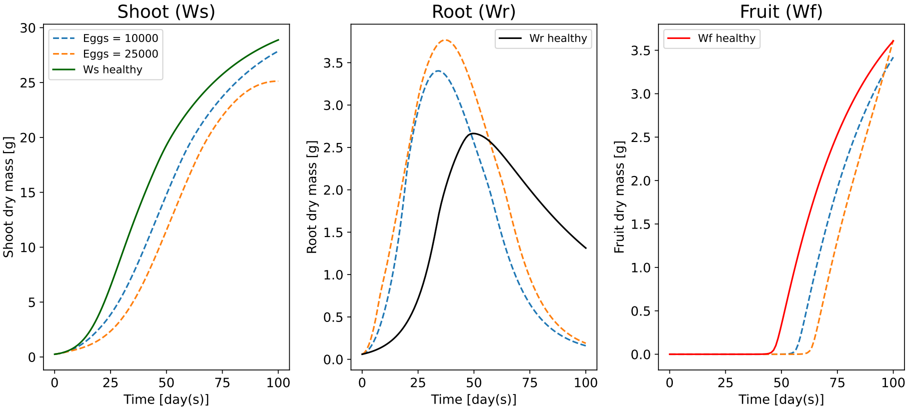
Plant $\rightarrow$ Nematodes effects

Nematodes $\rightarrow$ Plant effects

Preliminary Simulation plant-pest model



Preliminary Simulation plant-pest model



Model calibration

Calibration strategy

- Highly complex and non-linear model
- More than 30 parameters
- Few data available in literature

Calibration strategy

- Highly complex and non-linear model
- More than 30 parameters
- Few data available in literature

- Dedicated experiments

- 2-steps calibration strategy:

1. Calibration of the plant model on data from healthy plants
   - data processing
   - global sensitivity analysis
   - numerical estimation of sensitive parameters

2. Calibration of the plant-nematode model on data from infected plants
   - global sensitivity analysis: nematode parameters
   - numerical estimation of sensitive parameters

Plant model Calibration

- Dedicated experiments

- 2-step calibration strategy:

1. Calibration of the plant model on data from healthy plants
    - data processing
    - global sensitivity analysis
    - numerical estimation of sensitive parameters

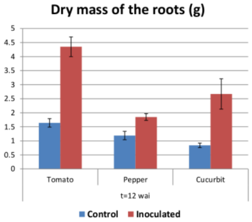
2. Calibration of the plant-nematode model on data from infected plants
    - global sensitivity analysis: nematode parameters
    - numerical estimation of sensitive parameters

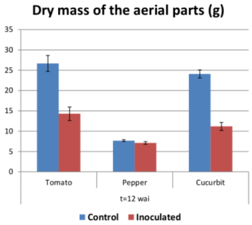
Plant Model Calibration

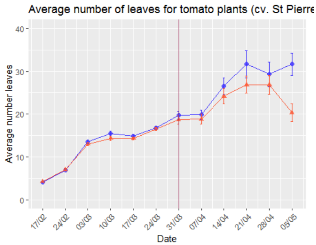
ArchiNem project (INRAE 2020-21)

Experimental data available on **3 contrasted species** (tomato, pepper, curcubit)

- Plant growth, physiology (healthy and infected)
  - Shoot, root, fruit dry mass (destructive): **3 time-points**
  - Leaf number: **12 time-points**
- 6 replicates per time-point







Collaboration with C. Caporalino (INRAE)

Data processing

Objective: increase the number of data points by exploiting non-destructive measurements (leaf number)

Allometric relation: shoot weight vs leaf number

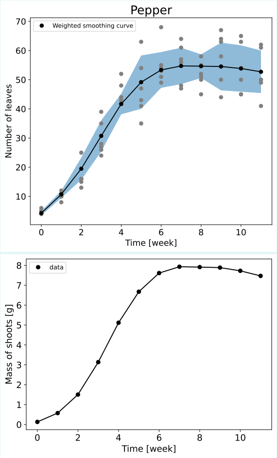
- Spline smoothing of leaf data
  - average dynamics
- Calibration of a general allometric relation (3 time-points x 3 species)

$$M = a_i L^b, \quad i = \text{species}\, 1, 2, 3$$

M = shoot dry mass, L= number of leaves

$$\Downarrow$$

- Prediction of shoot dry mass from leaf data at 12 time-points



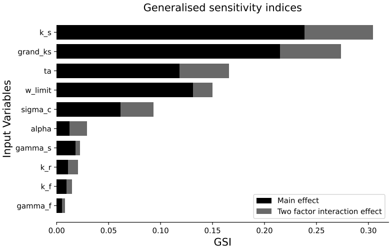
Multi-variate global sensitivity analysis

inputs : 26 parameters, reference value $\pm 30\%$
outputs : Shoot and root dry masses *dynamics* (vector)
method: R `multisensi` package (PCA- and ANOVA-based)

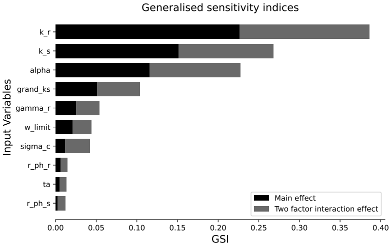
Multi-variate global sensitivity analysis

inputs : 26 parameters, reference value $\pm 30\%$
outputs : Shoot and root dry masses *dynamics* (vector)
method: R `multisensi` package (PCA- and ANOVA-based)

Shoot growth



Root growth



8 sensitive parameters (1 parameter fixed from litterature data):

- k_s shoot growth rate
- k_r root growth rate
- σ_c shoot carbon fixation rate
- K_s shoot growth dynamics
- t_a active C transport to fruit
- γ_r root senescence rate
- α vascular architecture
- w_{limit} water stress sensitivity

Numerical parameter estimation

- 1 calibration per species considered
- Estimation of 7 (sensitive) parameters
- Weighted (π) least-square function for real and reconstructed mass data:

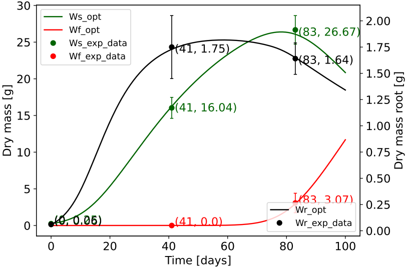
$$\underbrace{\frac{\pi}{N_i}\sum_{i=1}^{N_i}\left(\frac{M_{sol}^{i}-M_{data}^{i}}{std^{i}}\right)^2}_{Dry\ mass\ data}+\underbrace{\frac{(1-\pi)}{N_j}\sum_{j=1}^{N_j}\left(\frac{M_{sol}^{j}-M_{pred}^{j}}{M_{pred}^{j}}\right)^2}_{Reconstructed\ data\ from\ leaf\ number}$$

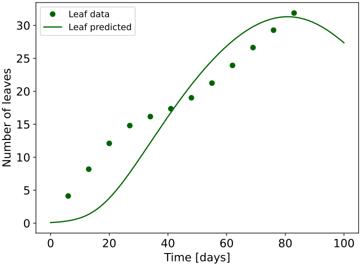
2-step estimation strategy:

1. Global search (differential evolution algorithm)
2. Local search around solution of step 1 (least square)

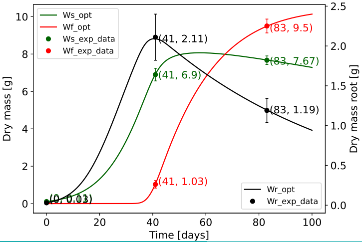
Calibrated plant model

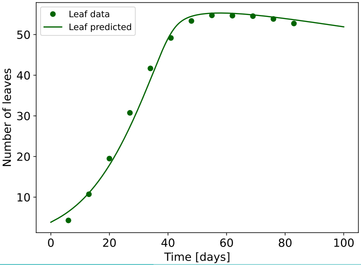
Tomato plants





Pepper plants





On-going work and perspectives

- Calibration of RKN-related parameters on data from infected plants
- Identification of key physiological and architectural traits underlying **plant tolerance** to RKN infestation
- **Multi-seasonal**[2] effect of plant tolerance: **crop rotations** (tolerant, susceptible and resistant plants), management practices, effect of environmental conditions...

[2] Nilusmas et al., *Evolutionary Applications*, 2020

Collaborators:

INRAE collegues:

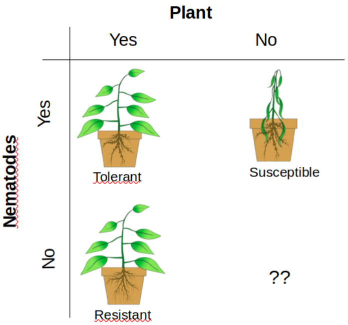
- C. Caporalino
- L. Pagès
- C. Doussan

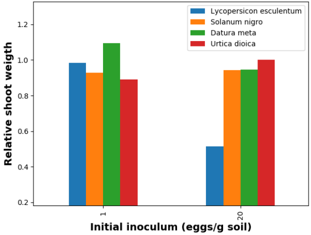
Master students

- T. Brenière
- N. Juazion-Graverolle
- C. Bourgade
- E. Ceci
- A. Canaud

Phenotypic variability

- **Strong variations** in the extent of damages within and among plant species





- Resistance is efficient but
  - few resistant genes identified
  - only for a few species
  - may favour the emergence of virulent nematodes
- Interest for tolerance
- Several possible mechanisms reported
  - high root growth rate
  - better water and nutrients uptake
  - delayed senescence ...

Aim

Better understand the mechanisms behind (differential) plant susceptibility to nematodes

Resource transport resistances

Water transport

$$R_{sr} = r_{sr}\left(Wr\ +\ G\right)^{-\alpha_r} \tag{1}$$

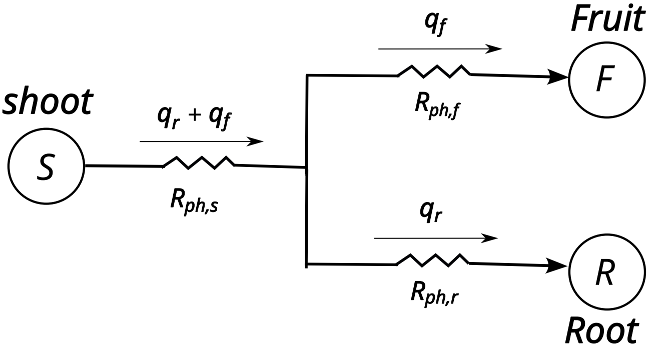
$$R_{xy} = \frac{r_{xy}}{W_r^{\alpha_r}} + \frac{r_{xy}}{W_s^{\alpha s}} \tag{2}$$

Carbon transport

$$R_{ph} = \frac{r_{ph}}{W_s^{\alpha_s}} + \frac{r_{ph}}{(W_r + G)^{\alpha_r}} \tag{3}$$

Carbon transport (T)

The carbon flow[3] T in phloem vessels $T = q\ C_s$, with q the volume flow rate,



Therefore,

$$\begin{cases} (q_r + q_f)R_{ph,s} + q_r\ R_{ph,r} = (C_s - C_r) \\ (q_r + q_f)R_{ph,s} + q_f\ R_{ph,f} = (C_s - C_f) \end{cases}$$

$$\begin{cases} T_r = q_r C_s \\ T_f = \left(\dfrac{W_s^n}{I^n + W_s^n}\right) q_f C_s \end{cases}$$

[3]Minchin et al., *Journal of Experimental Botany*, 1993

Male proportion

$$\theta(C_r) = \theta_{\max} \frac{K_\theta}{C_r + K_\theta} \tag{4}$$

Reproduction rate

$$r(C_r) = r_{\min} + \frac{(r_{\max} - r_{\min})\ C_r}{C_r + K_{repro}} \tag{5}$$

Establishment of the feeding site

$$\Omega(C_r) = \frac{Wcr^\kappa}{Wcr^\kappa + K_\Omega^\kappa} \tag{6}$$

Global sensitivity analysis

Goal: Identifying the most influential parameters

inputs : 26 parameters, **outputs** : dry masses along time (vector)

Method

1. fractional factorial design to explore parameter space
2. PCA to reduce output and capture its variability
3. ANOVA to compute sensitivity indices (SI)

$$SI_{..} = \frac{SS_{..}}{TSS}, \qquad GSI = \sum_{k=1}^{components} SI_k \times inertia_k$$

SS = sum of squares, TSS = total sum of squares

Parameter set

TABLE 1 – Standard values for sensitivity analysis

Parameters	Description	Value	Interval
σ_C	Specific carbon fixation rate by the aerial part	0.4	$\pm$ 30%
σ_W	Specific transpiration rate of aerial part	1.2	$\pm$ 30%
$r_{ph,s}$, $r_{ph,r}$, $r_{ph,f}$	Xylem resistance coefficients to water flow	0.5, 0.5, 0.005	$\pm$ 30%
$r_{xy,s}$, $r_{xy,r}$, $r_{xy,f}$	Phloem resistance coefficients to sap flow	5, 5, 0.1	$\pm$ 30%
r_{sr}	Coefficient of resistance to water absorption by the roots	1	$\pm$ 30%
k_s, k_r, k_f	Specific growth rates	0.14, 0.12, 0.6	$\pm$ 30%
K_s, K_r, K_f	Half-saturation constants related to growth rate	0.1, 0.05, 0.01	$\pm$ 30%
γ_s, γ_r, γ_f,	Mortality and leaf fall coefficients	0.1, 0.01, 0.001	$\pm$ 30%
n, n_c, n_p, n_{hill}	Hill coefficients for transition, growth, photosynthesis and water regulation	10, 10, 10, 10	$\pm$ 30%
W_{limit}	Transition coefficient from vegetative to reproductive phase	15	$\pm$ 30%
K_c, K_p	Half-saturation constants related to the effect of water on growth and photosynthesis	-1400, -1600	3 fixed values
α_s, α_r, α_f	Allometric coefficients	2/3, 2/3, 2/3	$\pm$ 30%
$r_{s,m}$, $r_{r,m}$, $r_{f,m}$	Maintenance respiration coefficients for aerial, root and fruit compartments	0.001, 0.001, 0.001	$\pm$ 30%
$r_{s,g}$, $r_{r,g}$, $r_{f,g}$	Growth respiration coefficients of aerial, root and fruit compartments	0.01, 0.01, 0.01	$\pm$ 30%
c_{rh}	Rhizodeposition coefficient	0.1	$\pm$ 30%
ta	concentration rate of carbon related to active transport	0.5	$\pm$ 30%

- 26 parameters
- 3 levels for each parameter (reference value and $\pm$30% of reference value)
- some reference values from literature