



HAL
open science

A demo-genetic model of root-knot nematod dynamics with applications to the deployment of plant resistance

Ludovic Mailleret, Samuel Nilusmas, Suzanne Touzeau, Vincent Calcagno, Caroline Djian-Caporalino, Philippe Castagnone-Sereno

► To cite this version:

Ludovic Mailleret, Samuel Nilusmas, Suzanne Touzeau, Vincent Calcagno, Caroline Djian-Caporalino, et al.. A demo-genetic model of root-knot nematod dynamics with applications to the deployment of plant resistance. Journée MODECO - Modélisation des Dynamiques Ecologiques, Jul 2019, Nice, France. hal-02393318

HAL Id: hal-02393318

<https://inria.hal.science/hal-02393318v1>

Submitted on 6 Dec 2019

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

A demo-genetic model of root-knot nematode dynamics with applications to the deployment of plant resistance

Ludovic Mailleret

with S. Nilusmas, S. Touzeau, V. Calcagno,
C. Caporalino, P. Castagnone

M2P2 & IPN, UMR ISA, INRA, CNRS, Université Côte d'Azur
Biocore, Inria Sophia Antipolis Méditerranée



Introduction



Nematodes

- very small slender worms (0.1-2.5 mm)
- over 40,000 species, present in virtually any ecosystem
- free living and parasites of animals and plants

Plant parasitic nematodes

- ~ 4,000 species, causing billions of dollars of crop losses each year (temperate & tropical agrosystems)
- root knot nematodes (RKN) rank first in terms of damage at the world scale

Root knot nematodes

- polyphagous (> 5,000 host plants), distributed worldwide, but sedentary
- cause galls on roots, which alter plants development



Introduction



Nematodes

- very small slender worms (0.1-2.5 mm)
- over 40,000 species, present in virtually any ecosystem
- free living and parasites of animals and plants

Plant parasitic nematodes

- ~ 4,000 species, causing billions of dollars of crop losses each year (temperate & tropical agrosystems)
- root knot nematodes (RKN) rank first in terms of damage at the world scale

Root knot nematodes

- polyphagous (> 5,000 host plants), distributed worldwide, but sedentary
- cause galls on roots, which alter plants development



Introduction



Nematodes

- very small slender worms (0.1-2.5 mm)
- over 40,000 species, present in virtually any ecosystem
- free living and parasites of animals and plants

Plant parasitic nematodes

- ~ 4,000 species, causing billions of dollars of crop losses each year (temperate & tropical agrosystems)
- root knot nematodes (RKN) rank first in terms of damage at the world scale

Root knot nematodes

- polyphagous (> 5,000 host plants), distributed worldwide, but sedentary
- cause galls on roots, which alter plants development

RKN control methods

Long relied on hardcore chemical use

- soil fumigation
- restricted or banned

Biological control offers limited options

Resistant plant based control

- powerful eco-friendly method
- few R-genes
- R can be broken down by virulent strains, which limits the durability of the method

Aim of this work

- understand if and how it is possible to optimize the use of resistant cultivars to control RKN in seasonal agrosystems (market gardening)



RKN control methods

Long relied on hardcore chemical use

- soil fumigation
- restricted or banned

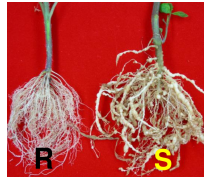
Biological control offers limited options

Resistant plant based control

- powerful eco-friendly method
- few R-genes
- R can be broken down by virulent strains, which limits the durability of the method

Aim of this work

- understand if and how it is possible to optimize the use of resistant cultivars to control RKN in seasonal agrosystems (market gardening)



RKN control methods

Long relied on hardcore chemical use

- soil fumigation
- restricted or banned

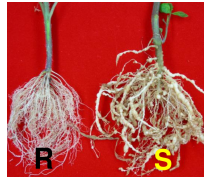
Biological control offers limited options

Resistant plant based control

- powerful eco-friendly method
- few R-genes
- R can be broken down by virulent strains, which limits the durability of the method

Aim of this work

- understand if and how it is possible to optimize the use of resistant cultivars to control RKN in seasonal agrosystems (market gardening)



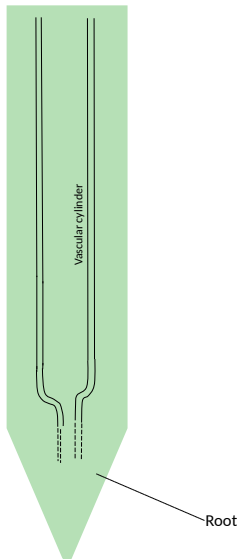
RKN Life Cycle

In the soil, near a plant root

- free living infective juveniles
- contact with the root and penetrate it
- giant cells formation
- mature and produce eggs (clonal)
- released into the soil and hatch

At the plant root system scale

- parasites with a free-living stage
- causing an epidemic within a population of roots



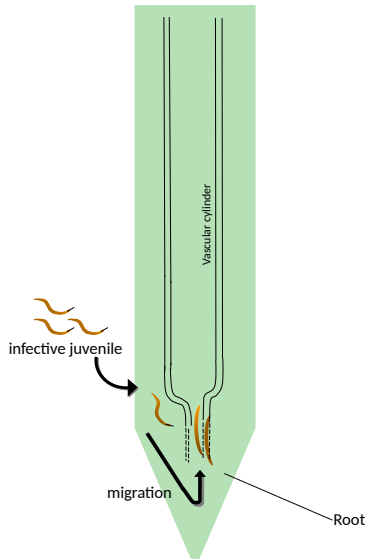
RKN Life Cycle

In the soil, near a plant root

- free living infective juveniles
- contact with the root and penetrate it
- giant cells formation
- mature and produce eggs (clonal)
- released into the soil and hatch

At the plant root system scale

- parasites with a free-living stage
- causing an epidemic within a population of roots



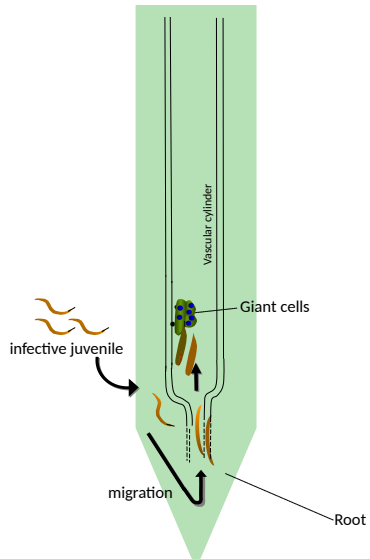
RKN Life Cycle

In the soil, near a plant root

- free living infective juveniles
- contact with the root and penetrate it
- giant cells formation
- mature and produce eggs (clonal)
- released into the soil and hatch

At the plant root system scale

- parasites with a free-living stage
- causing an epidemic within a population of roots



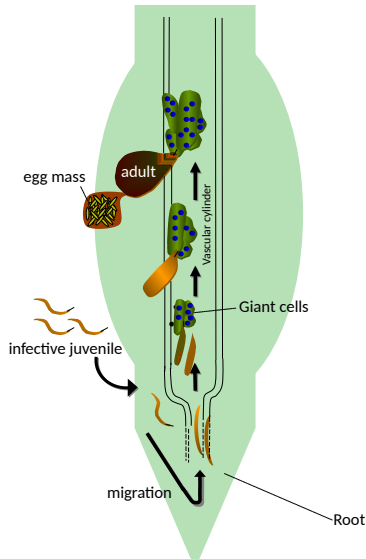
RKN Life Cycle

In the soil, near a plant root

- free living infective juveniles
- contact with the root and penetrate it
- giant cells formation
- mature and produce eggs (clonal)
- released into the soil and hatch

At the plant root system scale

- parasites with a free-living stage
- causing an epidemic within a population of roots



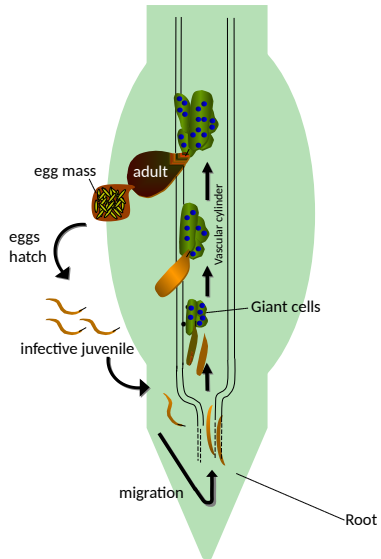
RKN Life Cycle

In the soil, near a plant root

- free living infective juveniles
- contact with the root and penetrate it
- giant cells formation
- mature and produce eggs (clonal)
- released into the soil and hatch

At the plant root system scale

- parasites with a free-living stage
- causing an epidemic within a population of roots



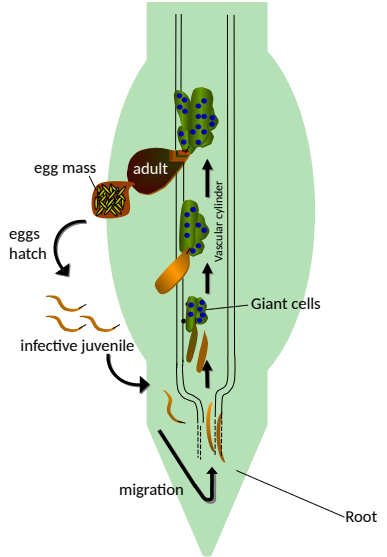
RKN Life Cycle

In the soil, near a plant root

- free living infective juveniles
- contact with the root and penetrate it
- giant cells formation
- mature and produce eggs (clonal)
- released into the soil and hatch

At the plant root system scale

- parasites with a free-living stage
- causing an epidemic within a population of roots

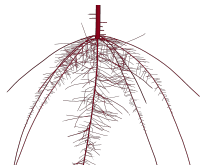


An epidemic among a growing population



Along the course of a season

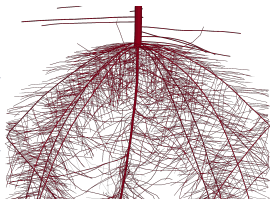
- plant root system grows
- recruits new infective nematodes



Nematode infection represses plant roots development

An unusual epidemic

- parasites with a free-living stage
- developing on a growing population
- whose growth is negatively affected by infection
- in a seasonal context



simulation performed with openSimroot

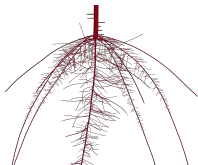


An epidemic among a growing population



Along the course of a season

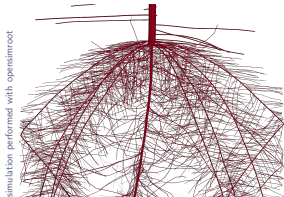
- plant root system grows
- recruits new infective nematodes



Nematode infection represses plant roots development

An unusual epidemic

- parasites with a free-living stage
- developing on a growing population
- whose growth is negatively affected by infection
- in a seasonal context



simulation performed with openSimroot

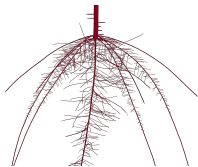


An epidemic among a growing population



Along the course of a season

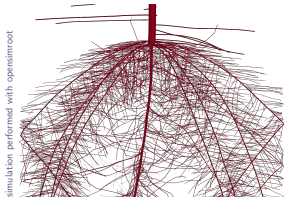
- plant root system grows
- recruits new infective nematodes



Nematode infection represses plant roots development

An unusual epidemic

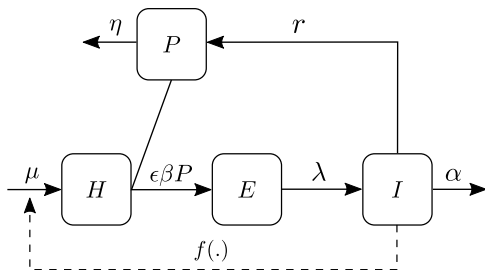
- parasites with a free-living stage
- developing on a growing population
- whose growth is negatively affected by infection
- in a seasonal context



simulation performed with openseimroot



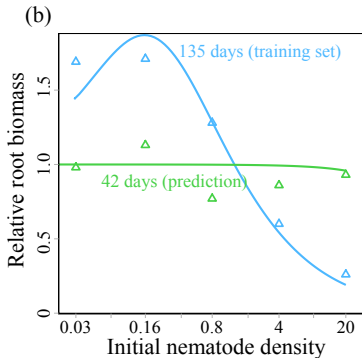
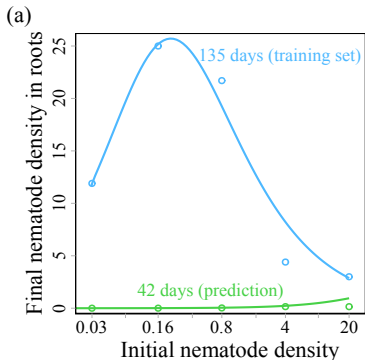
Compartmental model



$$\begin{cases} \dot{P} = -\beta PH - \eta P + rI \\ \dot{H} = \mu f(H, E, I) - \epsilon\beta PH \\ \dot{E} = \epsilon\beta PH - \lambda E \\ \dot{I} = \lambda E - \alpha I \end{cases}$$

- P free living nematodes
- H healthy root sites
- E maturing nematodes
- I egg laying nematodes

Model fitting



data : Ehwaeti et al. 1998, 2000

Parameterization

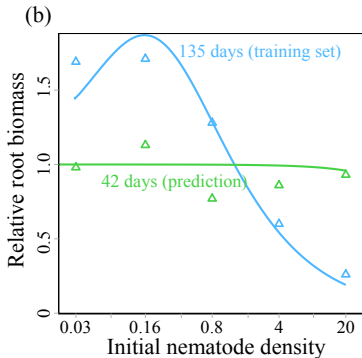
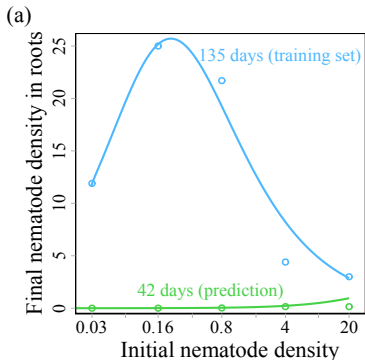
- most parameter values were found in literature
- some had to be estimated from experimental data: β , $f(\cdot)$

Scenarios derivation

- $\pm 30\%$ parameters
- low, medium (default), high, extreme scenarios



Model fitting



data : Ehwaeti et al. 1998, 2000

Parameterization

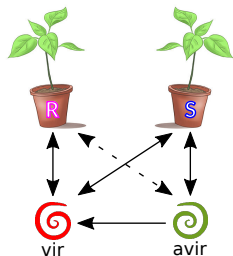
- most parameter values were found in literature
- some had to be estimated from experimental data: β , $f(\cdot)$

Scenarios derivation

- $\pm 30\%$ parameters
- low, medium (default), high, extreme scenarios



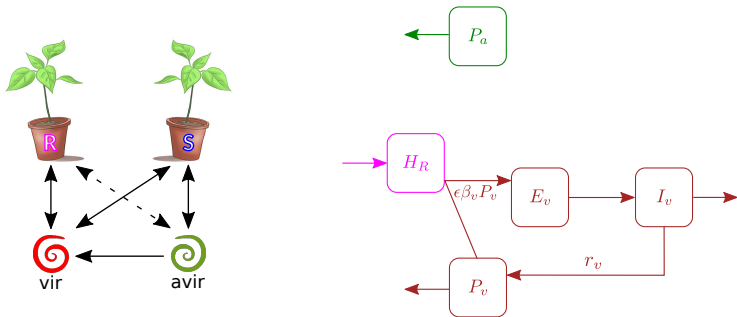
Plant resistance, nematode virulence

 P_a P_v

- plants are either R or S
- nematode pop. structured in avirulent and virulent phenotypes
- avirulents do not develop on R plants
- both avirulents and virulents develop on S plants
- a fraction δ of avirulent offspring turns into virulent

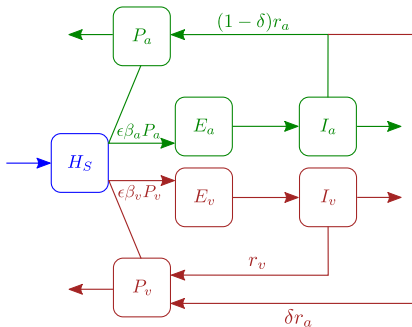
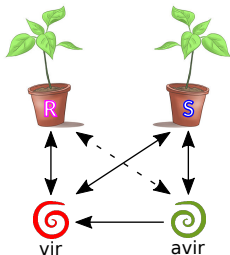


Plant resistance, nematode virulence



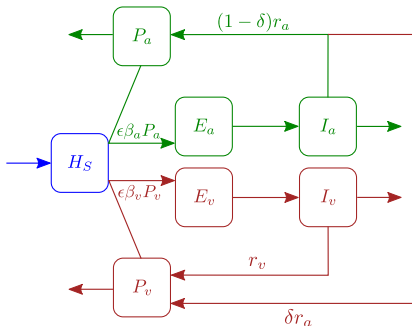
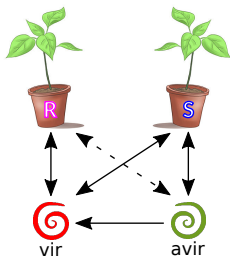
- plants are either **R** or **S**
- nematode pop. structured in **avirulent** and **virulent** phenotypes
- **avirulents** do not develop on **R** plants
 - both **avirulents** and **virulents** develop on **S** plants
 - a fraction δ of **avirulent** offspring turns into **virulent**

Plant resistance, nematode virulence



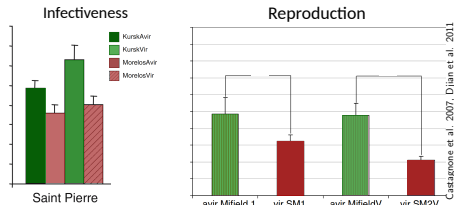
- plants are either R or S
- nematode pop. structured in avirulent and virulent phenotypes
- avirulents do not develop on R plants
- both avirulents and virulents develop on S plants
- a fraction δ of avirulent offspring turns into virulent

Plant resistance, nematode virulence

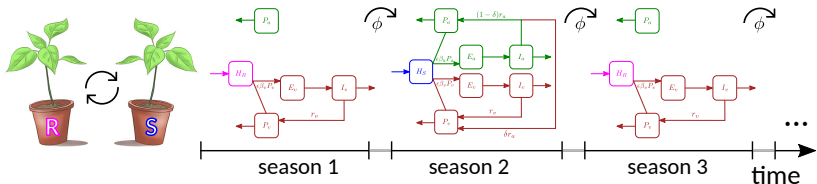


Fitness costs of virulence

- infectiveness: $\beta_v = (1 - w_\beta)\beta_a$
- reproduction: $r_v = (1 - w_r)r_a$



Seasonal context, crop rotations, optimization



Seasonal agrosystems

- crops planted and harvested sequentially over time
- cultivar rotations to enhance crop yield (vs. pure S and pure R)

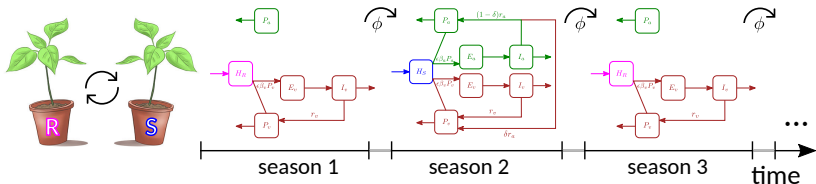
Yield proxy

- Cumulated Healthy Root Density

$$\overline{CHR D} = \frac{1}{n} \sum_{\text{seasons}} \int_0^T H(\tau) d\tau$$



Seasonal context, crop rotations, optimization



Seasonal agrosystems

- crops planted and harvested sequentially over time
- cultivar rotations to enhance crop yield (vs. pure S and pure R)

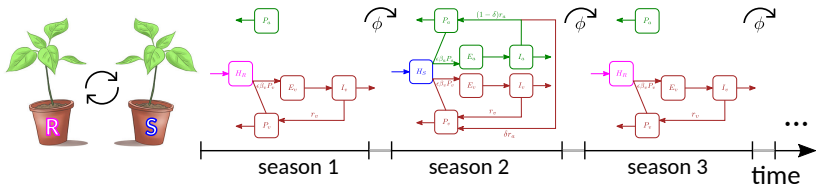
Yield proxy

- Cumulated Healthy Root Density

$$\overline{CHR D} = \frac{1}{n} \sum_{\text{seasons}} \int_0^T H(\tau) d\tau$$



Seasonal context, crop rotations, optimization



Seasonal agrosystems

- crops planted and harvested sequentially over time
- cultivar rotations to enhance crop yield (vs. pure S and pure R)

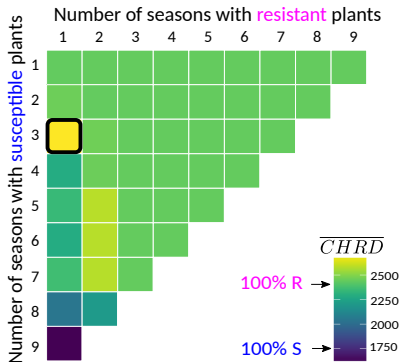
Yield proxy

- Cumulated Healthy Root Density

$$\overline{CHR D} = \frac{1}{n} \sum_{\text{seasons}} \int_0^T H(\tau) d\tau$$

Optimal cultivar rotation

default scenario, 10 seasons

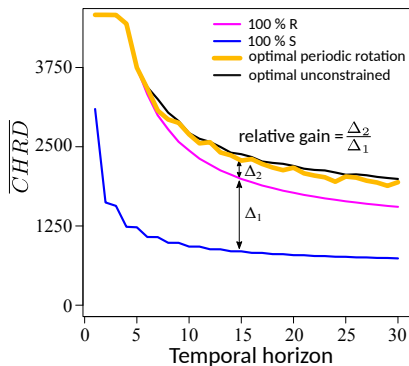


- computation of all periodic crop rotations over given time horizon
- best rotation > pure R > pure S



Optimal cultivar rotation

default scenario

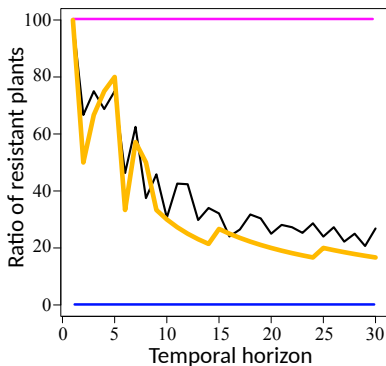
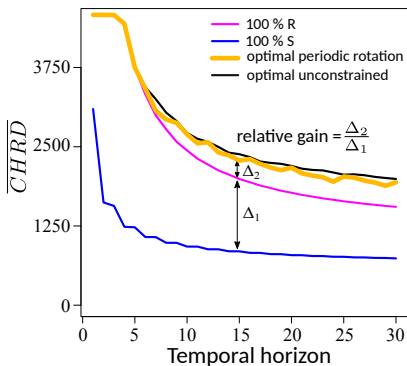


- R efficacy quickly drops with temporal horizon
- optimal periodic rotation nearly as efficient as the best strategy
- optimal R plants ratio much lower than agricultural practice (pure R)



Optimal cultivar rotation

default scenario



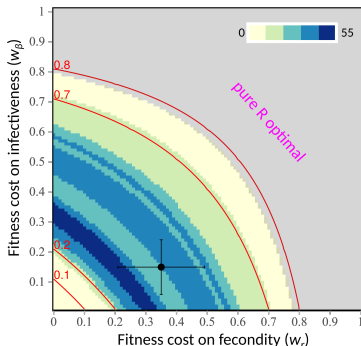
- R efficacy quickly drops with temporal horizon
- **optimal periodic rotation** nearly as efficient as the best strategy
- **optimal** R plants ratio much lower than agricultural practice (**pure R**)



R characteristics: fitness costs of virulence

default scenario, 15 seasons

relative gain (%)



Castagnone et al. 2007, Djian Cap. et al. 2011

- no advantage of rotations when high or low fitness costs
- experimental data (*Mi*-tomato): >30% gain with optimal rotations

- w_r and w_β have symmetrical influence but interact negatively

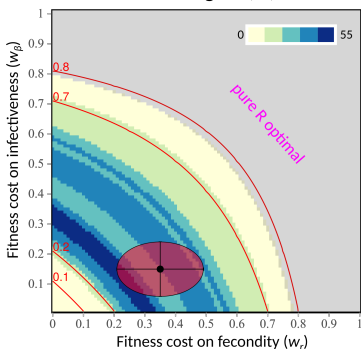
$$R_{0,v} = f(1 - (1 - w_\beta)(1 - w_r)) = f(w)$$



R characteristics: fitness costs of virulence

default scenario, 15 seasons

relative gain (%)



- no advantage of rotations when high or low fitness costs
- **experimental data (Mi-tomato):**
>30% gain with optimal rotations

- w_r and w_β have symmetrical influence but interact negatively

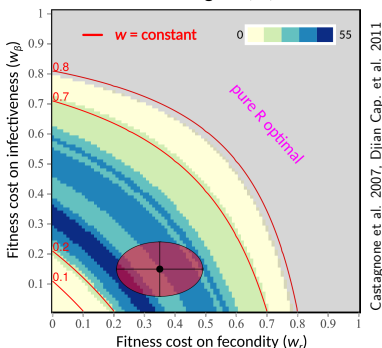
$$R_{0,v} = f(1 - (1 - w_\beta)(1 - w_r)) = f(w)$$



R characteristics: fitness costs of virulence

default scenario, 15 seasons

relative gain (%)



- no advantage of rotations when high or low fitness costs
- **experimental data** (*Mi*-tomato):
>30% gain with optimal rotations

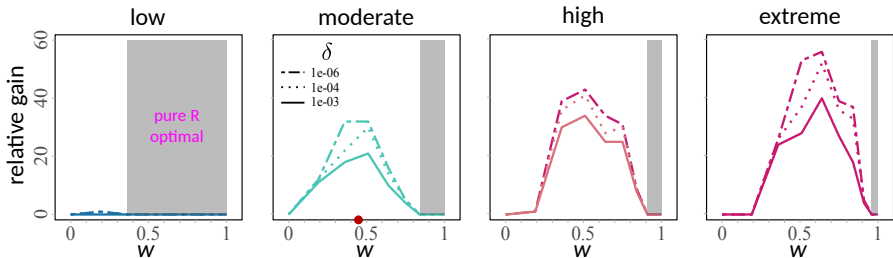
- w_r and w_β have symmetrical influence but interact negatively

$$R_{0,v} = f(1 - (1 - w_\beta)(1 - w_r)) = f(w)$$



Fitness cost \times epidemiological scenarios

15 seasons, different virulence emergence rates

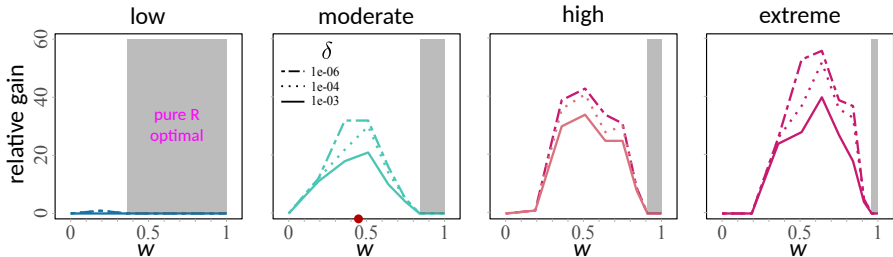


- strong influence of disease severity on advantage of rotations: increases with severity
- gain maximized for medium fitness costs
- mild influence of virulence emergence rate on advantage of rotations: decreases with rate



Fitness cost \times epidemiological scenarios

15 seasons, different virulence emergence rates

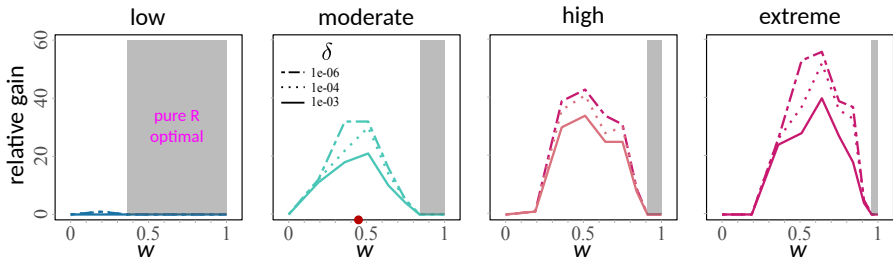


- strong influence of disease severity on advantage of rotations: increases with severity
- gain maximized for medium fitness costs
- mild influence of virulence emergence rate on advantage of rotations: decreases with rate



Fitness cost \times epidemiological scenarios

15 seasons, different virulence emergence rates

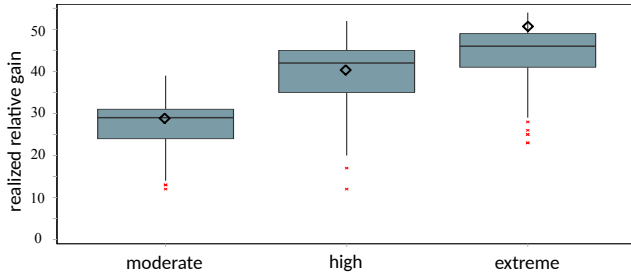


- strong influence of disease severity on advantage of rotations: increases with severity
- gain maximized for medium fitness costs
- mild influence of virulence emergence rate on advantage of rotations: decreases with rate



Robustness

15 seasons, $\pm 10\%$ on all parameter values



- sub-optimal rotations always outperform pure R strategies
- benefit of optimal rotations little affected by uncertainty on parameters

Using plant Resistance against RKN

Alternating R and S cultivars

- more efficient than classical agricultural practice
- optimal periodic rotations approach best deployment performance

Fitness costs of virulence

- interact negatively
- 1 large cost + 1 small cost > 2 medium costs

Optimal rotations significantly outperform pure R

- when nematode infestation is moderate to severe
- when fitness costs are medium
- over longer time scales (not shown)

Robustness

- optimal rotation efficacy preserved despite uncertainty in model parameter estimates



Using plant Resistance against RKN

Alternating R and S cultivars

- more efficient than classical agricultural practice
- optimal periodic rotations approach best deployment performance

Fitness costs of virulence

- interact negatively
- 1 large cost + 1 small cost $>$ 2 medium costs

Optimal rotations significantly outperform pure R

- when nematode infestation is moderate to severe
- when fitness costs are medium
- over longer time scales (not shown)

Robustness

- optimal rotation efficacy preserved despite uncertainty in model parameter estimates



Using plant Resistance against RKN

Alternating R and S cultivars

- more efficient than classical agricultural practice
- optimal periodic rotations approach best deployment performance

Fitness costs of virulence

- interact negatively
- 1 large cost + 1 small cost $>$ 2 medium costs

Optimal rotations significantly outperform pure R

- when nematode infestation is moderate to severe
- when fitness costs are medium
- over longer time scales (not shown)

Robustness

- optimal rotation efficacy preserved despite uncertainty in model parameter estimates



Using plant Resistance against RKN

Alternating R and S cultivars

- more efficient than classical agricultural practice
- optimal periodic rotations approach best deployment performance

Fitness costs of virulence

- interact negatively
- 1 large cost + 1 small cost $>$ 2 medium costs

Optimal rotations significantly outperform pure R

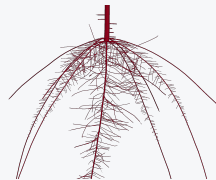
- when nematode infestation is moderate to severe
- when fitness costs are medium
- over longer time scales (not shown)

Robustness

- optimal rotation efficacy preserved despite uncertainty in model parameter estimates



Thank You !



any questions?



Appendix: $R_{0,v}$

Season-to-season basic reproduction number of virulent nematodes

$$R_{0,v} = \phi \exp \left(\left[\left((1 - w_\beta)(1 - w_r) \frac{\epsilon r}{\alpha} - 1 \right) \left(H_0 + \frac{\mu T}{2} \right) \beta - \eta \right] T \right)$$

- obtained from the \dot{P}_v/P_v dynamics
- in the limit $P_a, P_v \rightarrow 0$
- assuming E and I at quasi-equilibrium

