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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

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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

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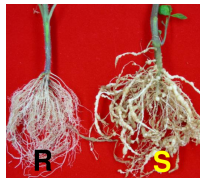
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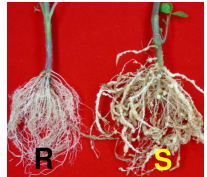
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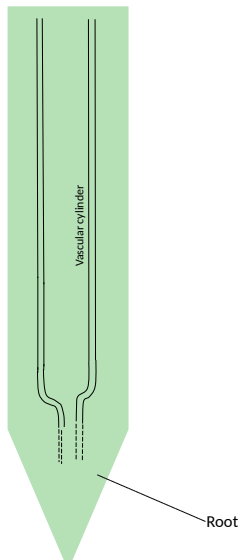
RKN Life Cycle

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



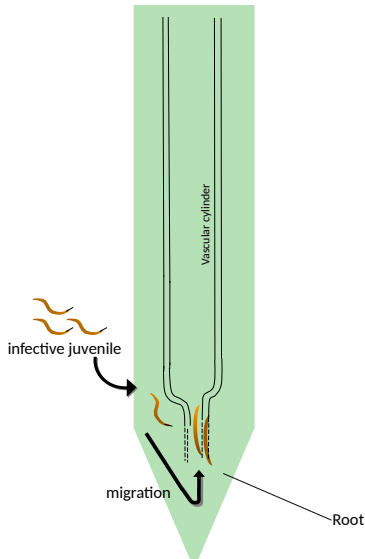
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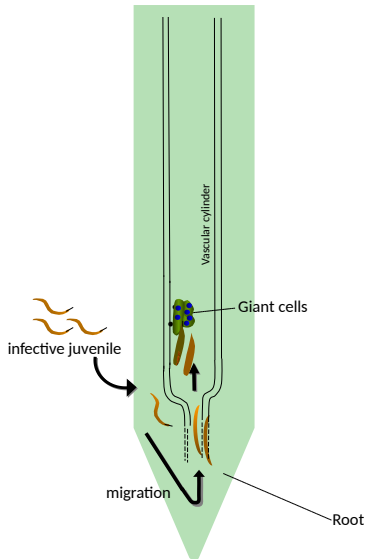
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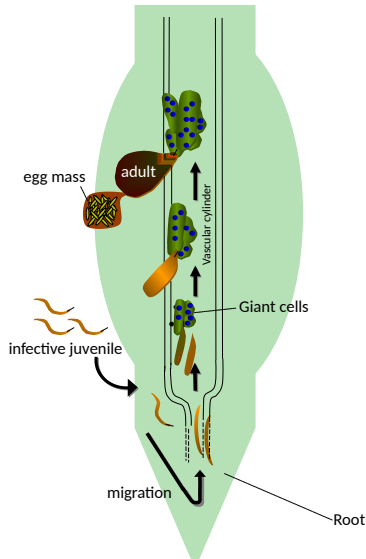
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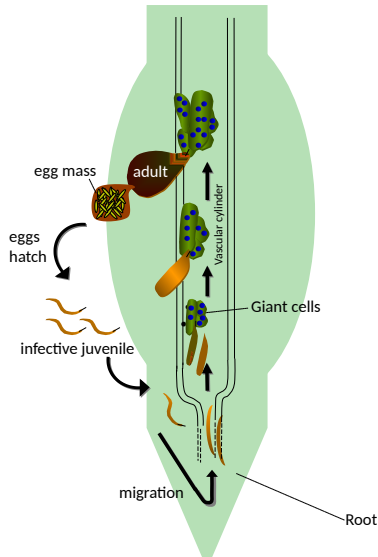
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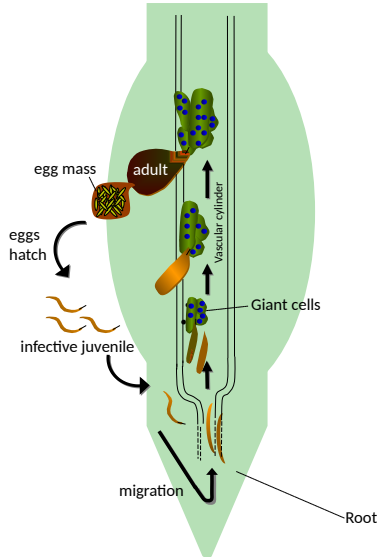
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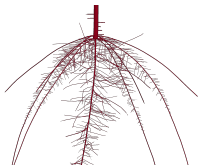


An epidemic among a growing population



Along the course of a season

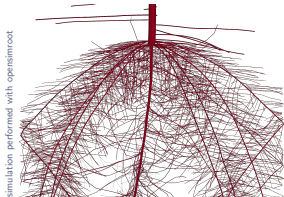
- plant root system grows
- recruits new infective nematodes



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

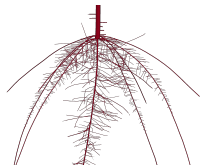


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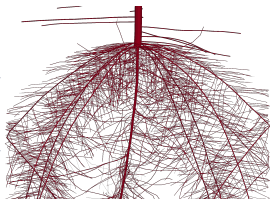


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Nematode infection represses plant roots development



simulation performed with opensimroot

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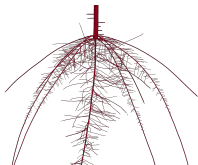
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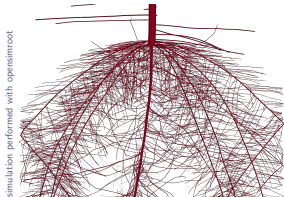
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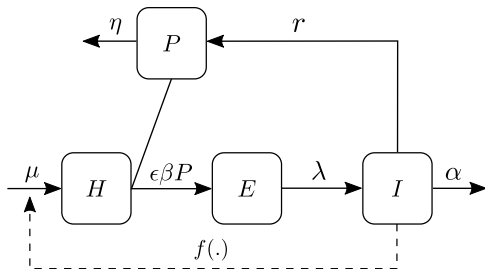
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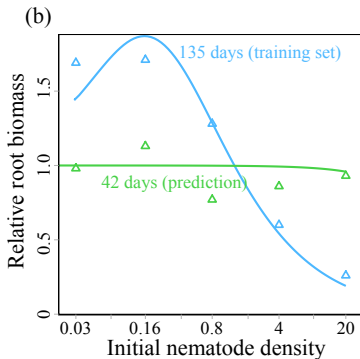
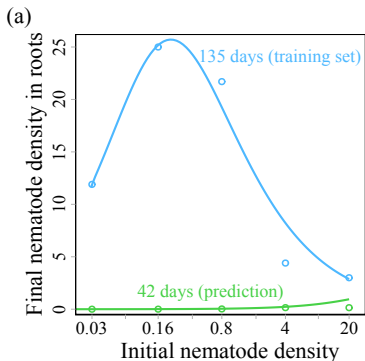
Compartmental model



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

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

Model fitting



data : Ehwaeti et al. 1998, 2000

Parameterization

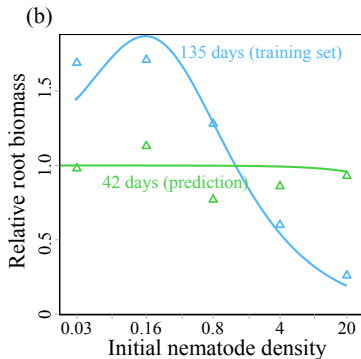
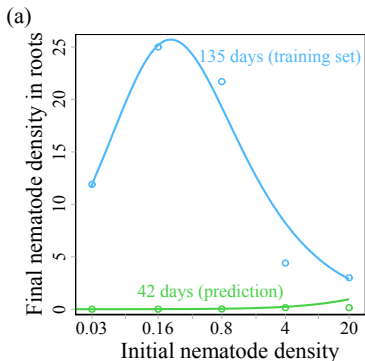
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- some had to be estimated from experimental data: β , $f(.)$

Scenarios derivation

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



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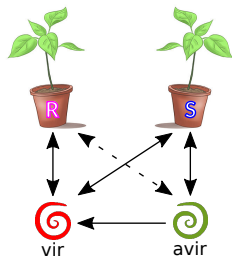
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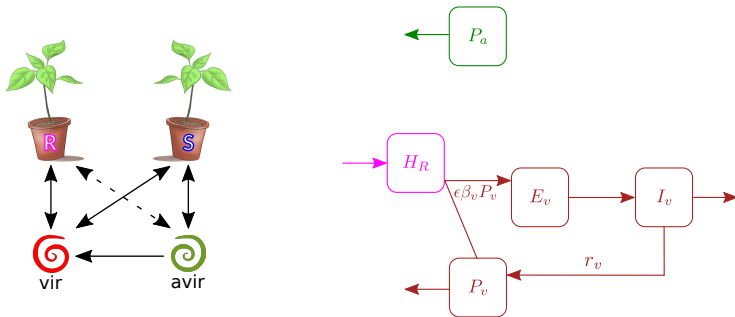
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Plant resistance, nematode virulence

 P_a P_v

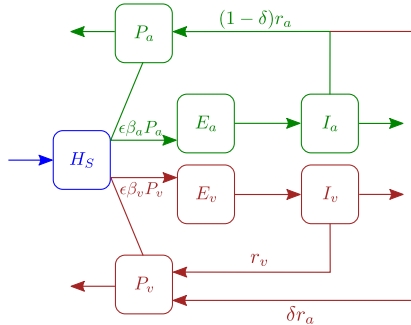
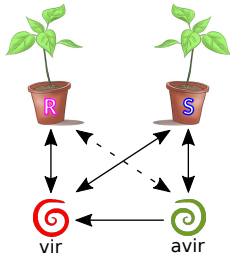
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- nematode pop. structured in **avirulent** and **virulent** phenotypes
 - **avirulents** do not develop on **R** plants
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 - a fraction δ of **avirulent** offspring turns into **virulent**

Plant resistance, nematode virulence



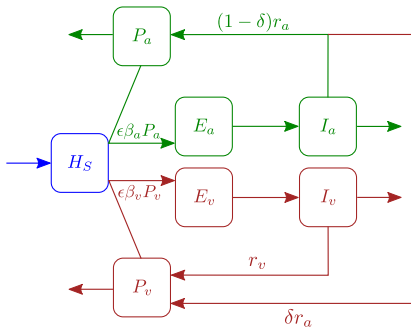
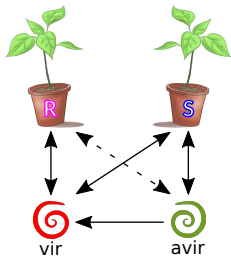
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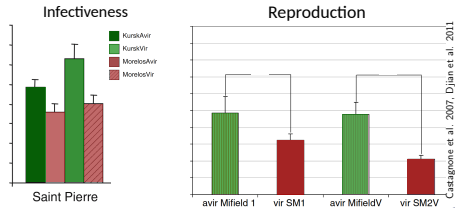
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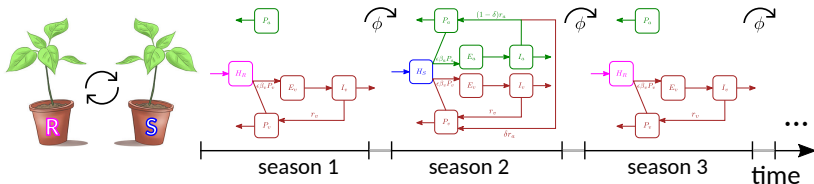


Fitness costs of virulence

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



Seasonal context, crop rotations, optimization



Seasonal agrosystems

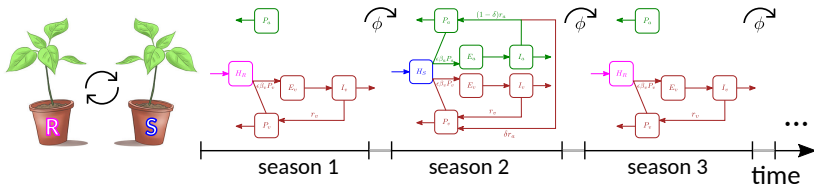
- crops planted and harvested sequentially over time
- cultivar rotations to enhance crop yield (vs. pure S and pure R)

Yield proxy

- Cumulated Healthy Root Density

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

Seasonal context, crop rotations, optimization



Seasonal agroecosystems

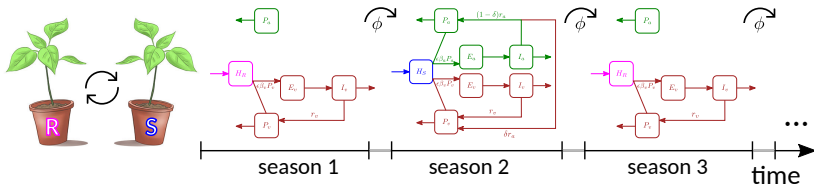
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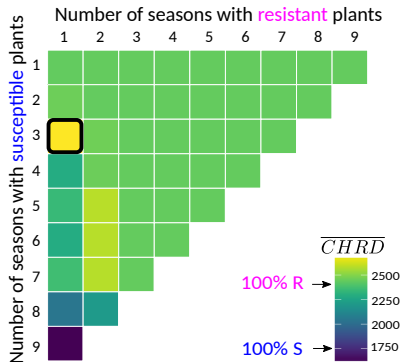
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Optimal cultivar rotation

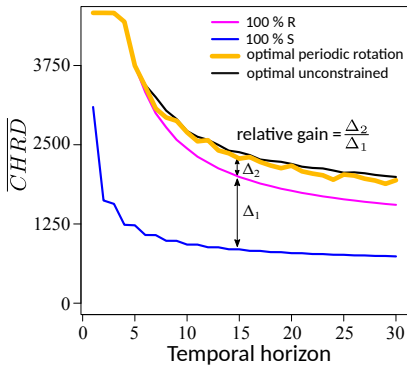
default scenario, 10 seasons



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

Optimal cultivar rotation

default scenario

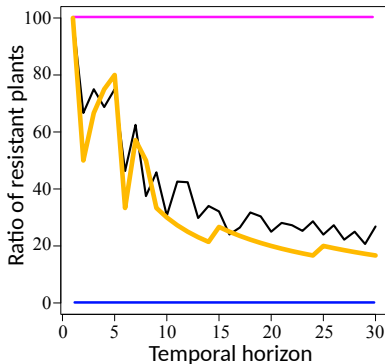
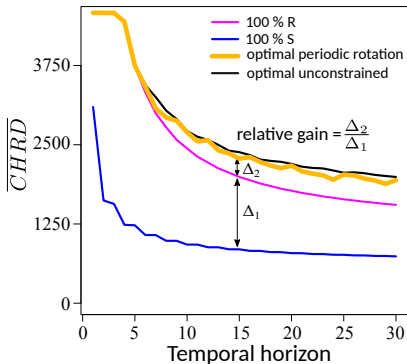


- R efficacy quickly drops with temporal horizon
- optimal periodic rotation nearly as efficient as the best strategy

- optimal R plants ratio much lower than agricultural practice (pure R)

Optimal cultivar rotation

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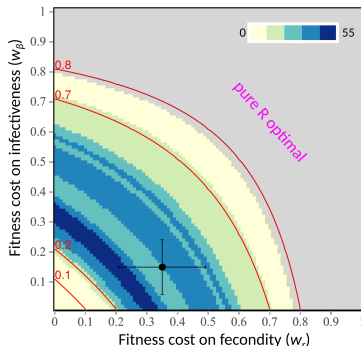


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R characteristics: fitness costs of virulence

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

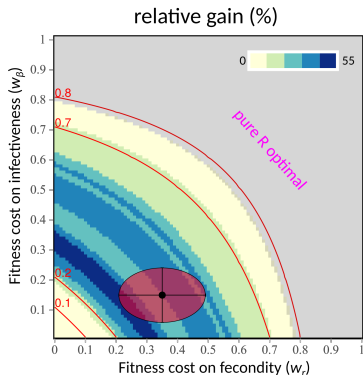
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$$R_{0,v} = f(1 - (1 - w_\beta)(1 - w_r)) = f(w)$$



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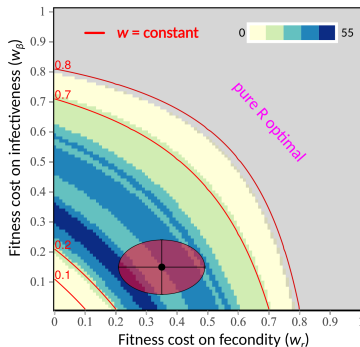
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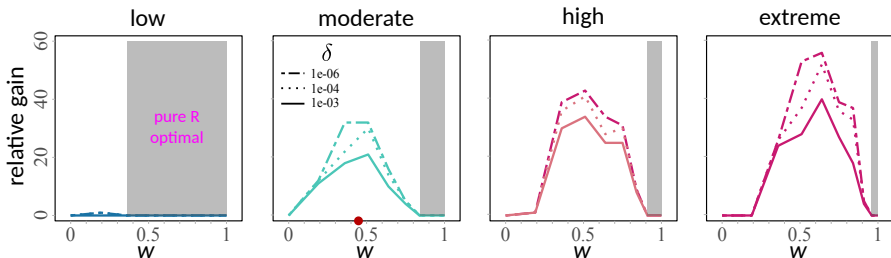
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Fitness cost $\times$ epidemiological scenarios

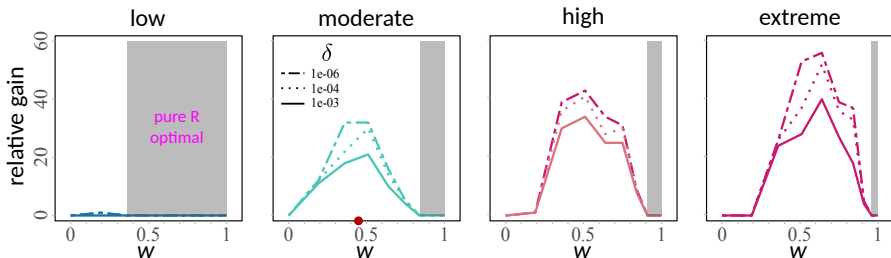
15 seasons, different virulence emergence rates



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

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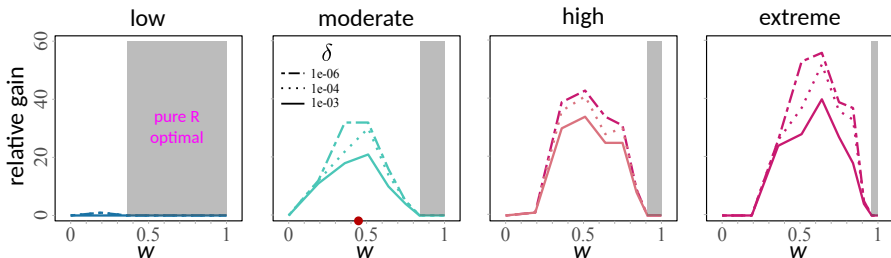
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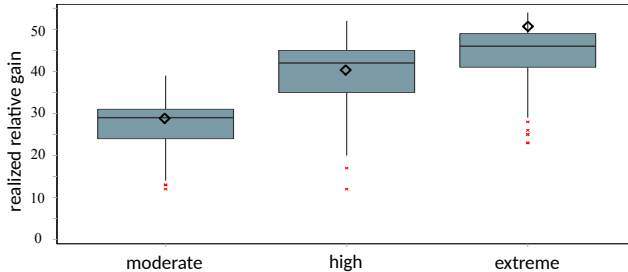
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Robustness

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)

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- optimal rotation efficacy preserved despite uncertainty in model parameter estimates



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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