Photo: Sylvie Richart-Cervera

Strategies for cultivar deployment in agricultural landscapes: confronting the points of view of breeders and farmers

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Bordeaux

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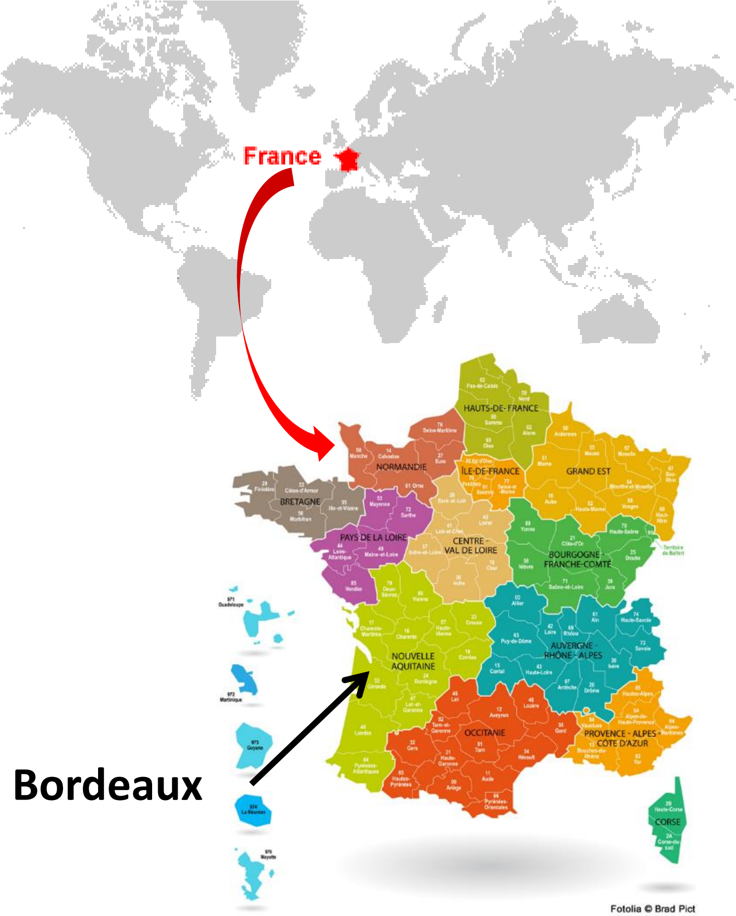


Schedule

- 15 min introduction
- 1h30 serious game (30 min game + 15 min feedback for each round):
  - Round 1: optimising landscape organisation
  - Round 2: optimising deployment strategies and resistance sources

Plant diseases

Rusts
(*Puccinia* spp.)
of cereal crops

Downy mildew
(*Plasmopara viticola*)
on grapevine

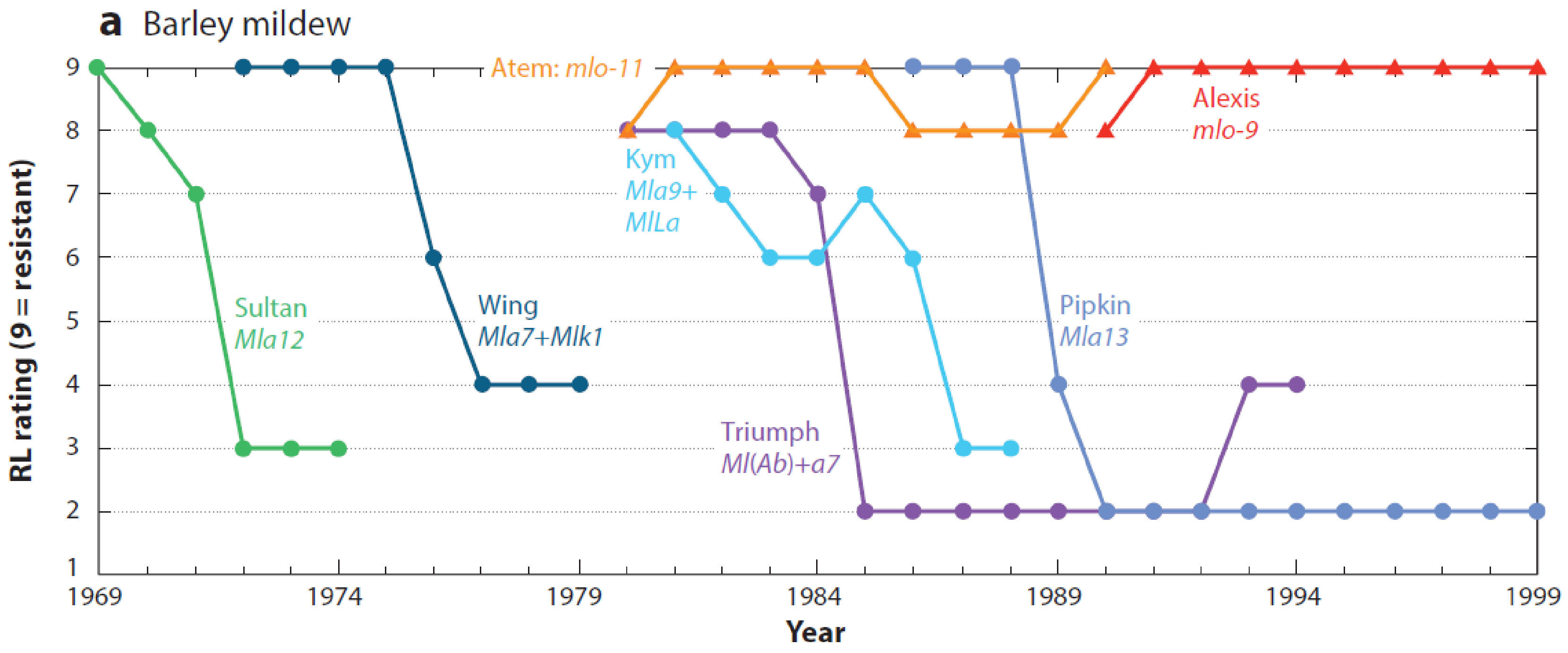
Black sigatoka
(*Pseudocercospora fijiensis*)
on banana

Cucumber mosaic virus
on pepper

Resistance is useful but can be overcome

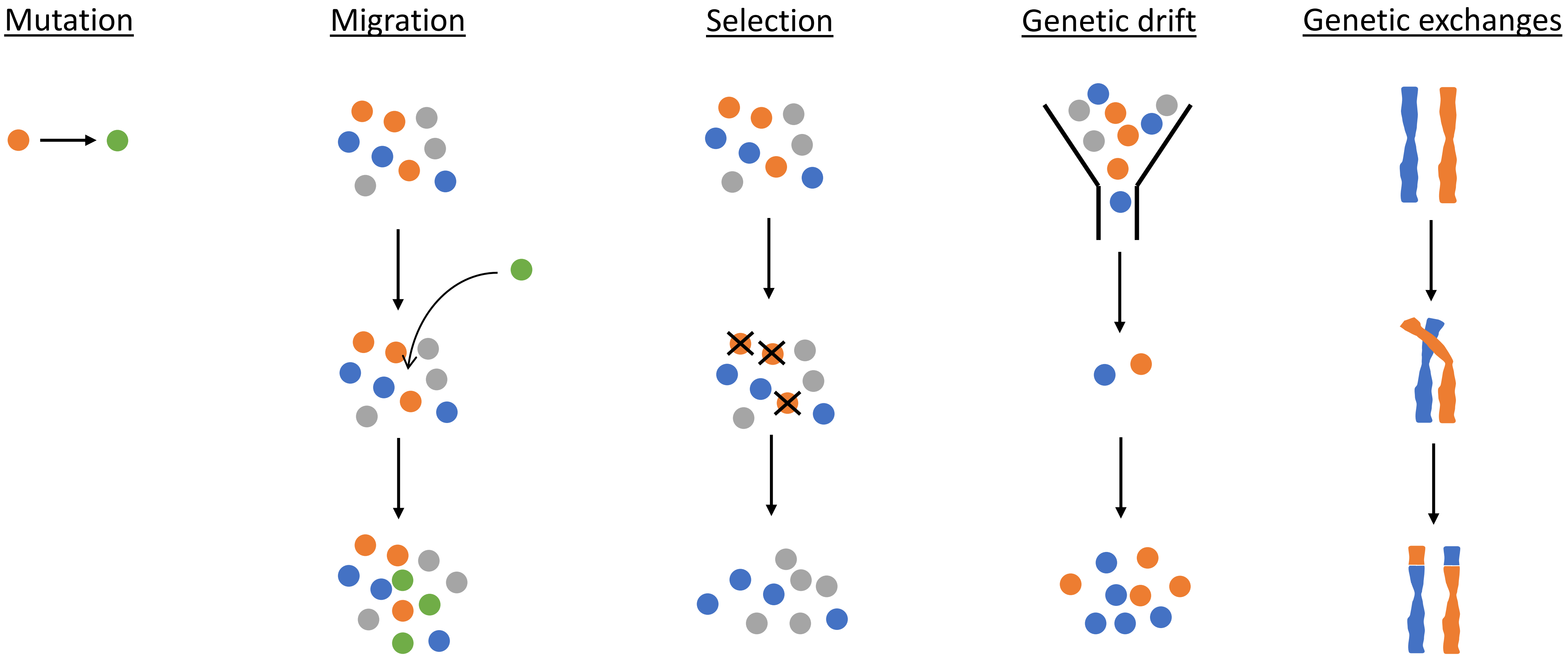
Plant resistance

complete or partial reduction of pathogen infection, growth and spread, hence disease severity

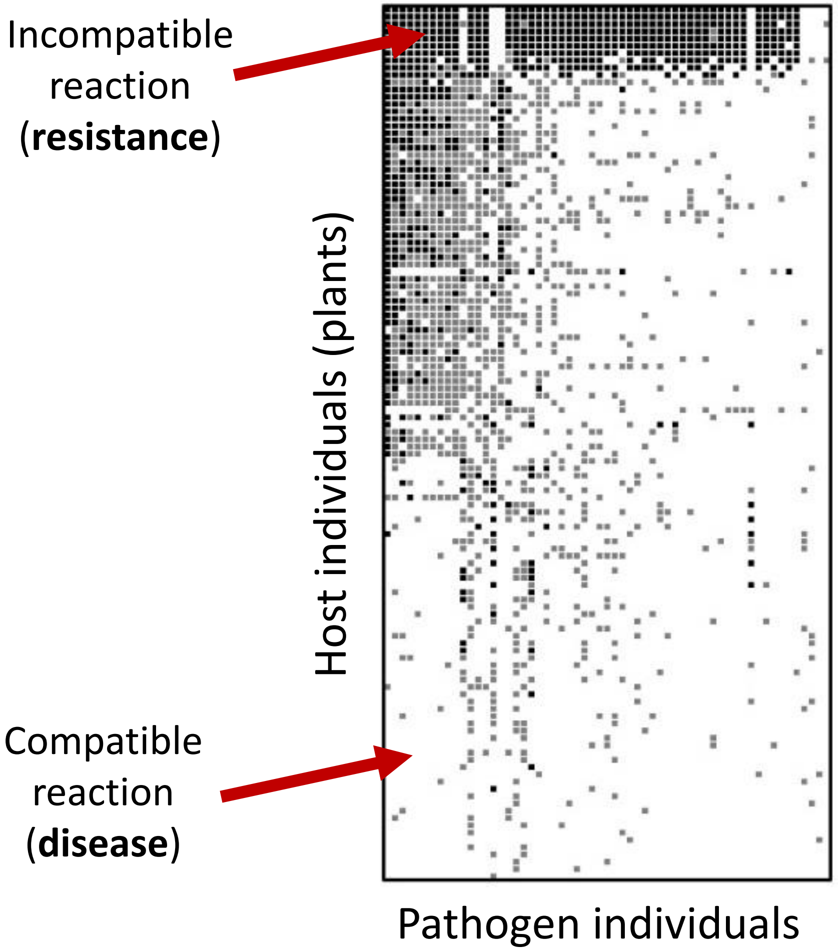


Brown JKM (2015). *Annu. Rev. Phytopathol.* 53:513-539

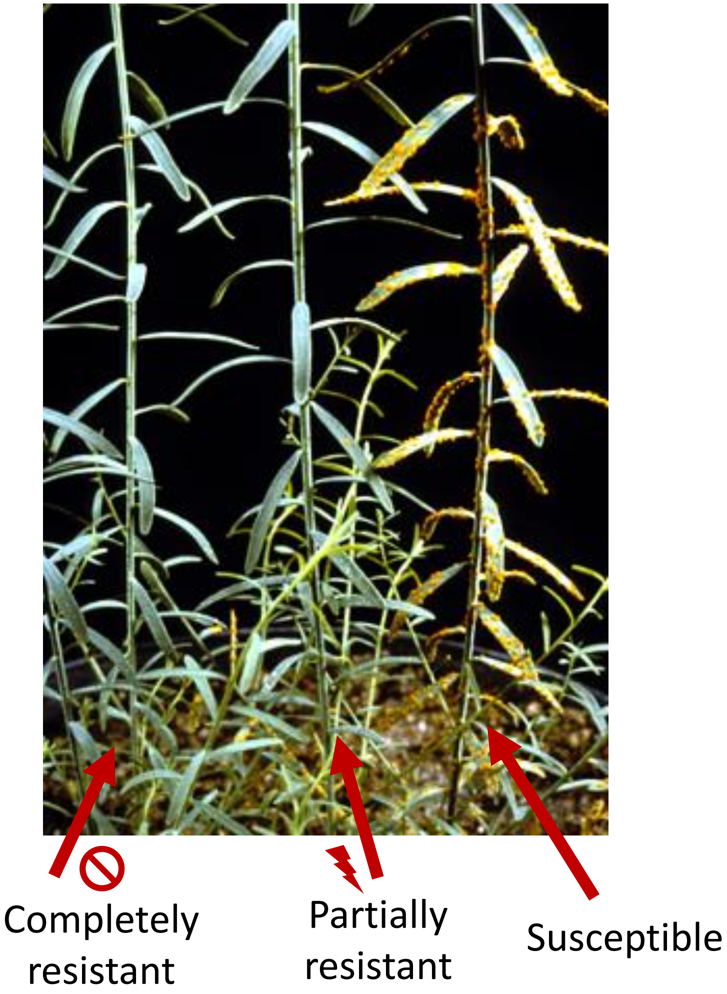
Evolutionary forces



A high diversity in wild plant-pathogen interactions

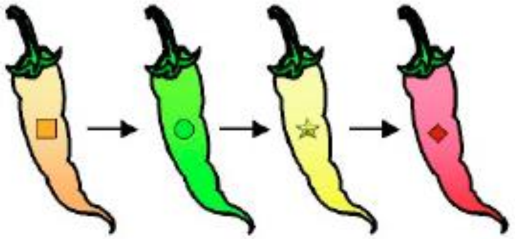


Rust infection of wild flax *Linum marginale*, caused by *Melampsora lini*

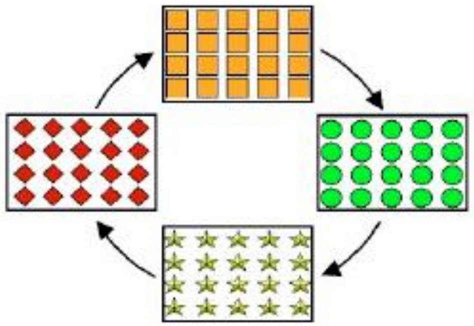


Barrett LG et al. (2008) *Trends Ecol. Evol.* 23:678-685.

What is the best strategy to deploy plant resistance?



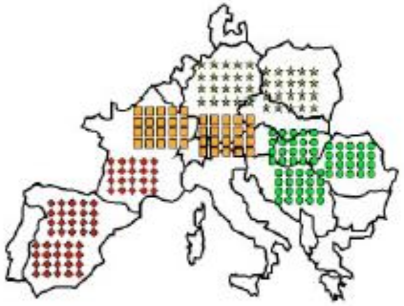
Turn-over (traditional approach)
→ **Boom & bust cycles**



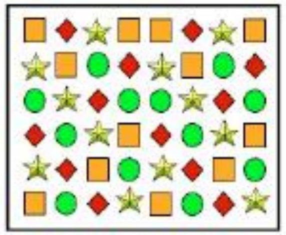
Rotations in time

What are the relative performances of the alternative strategies?

Pyramids



Mosaics (regional deployment)



Cultivar mixtures

McDonald & Linde (2002). *Annu. Rev. Phytopathol.* 40:349-379

What is the best strategy to deploy plant resistance?

Djian-Caporalino et al. BMC Plant Biology 2014, 14:53
http://www.biomedcentral.com/1471-2229/14/53

BMC Plant Biology

RESEARCH ARTICLE — Open Access

Pyramiding, alternating or mixing: comparative performances of deployment strategies of nematode resistance genes to promote plant resistance efficiency and durability

Caroline Djian-Caporalino[1*], Alain Palloix[2], Ariane Fazari[1], Nathalie Marteu[1], Arnaud Barbary[1], Pierre Abad[1], Anne-Marie Sage-Palloix[2], Thierry Mateille[3], Sabine Risso[4], Roger Lanza[4], Catherine Taussig[3] and Philippe Castagnone-Sereno[1]

THE BOTANICAL REVIEW

Vol. 29 — October-December, 1963 — No. 4

CONTROL OF PLANT DISEASES BY CROP ROTATION

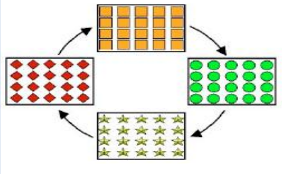
ELROY A. CURL
Department of Botany and Plant Pathology
Auburn University
Auburn, Alabama

Theoretical and Applied Genetics
https://doi.org/10.1007/s00122-017-3043-9

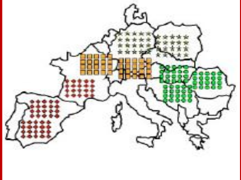
ORIGINAL ARTICLE

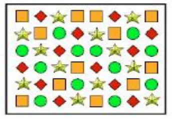
Pyramiding of transgenic *Pm3* alleles in wheat results in improved powdery mildew resistance in the field

Teresa Koller[1] · Susanne Brunner[2] · Gerhard Herren[1] · Severine Hurni[1] · Beat Keller[1]


Rotations in time


Pyramids


Mosaics


Cultivar mixtures

Genetic diversity and disease control in rice

Youyong Zhu*, Hairu Chen*, Jinghua Fan*, Yunyue Wang*, Yan Li*, Jianbing Chen*, JinXiang Fan†, Shisheng Yang‡, Lingping Hu§, Hei Leung‖, Tom W. Mew‖, Paul S. Teng‖, Zonghua Wang‖ & Christopher C. Mundt‖¶

Plant Pathology (2017) 66, 412–422

Efficiency of pyramiding of three quantitative resistance loci to apple scab

G. Laloi, E. Vergne, C. E. Durel, B. Le Cam and V. Caffier*
IRHS, Agrocampus-Ouest, INRA, Université d'Angers, SFR 4207 QuaSaV, 42 rue Georges Morel, Beaucouzé Cedex 49071, France

eLIFE
elifesciences.org

RESEARCH ARTICLE

Pathogen effectors and plant immunity determine specialization of the blast fungus to rice subspecies

Jingjing Liao[1,2†], Huichuan Huang[1,2†], Isabelle Meusnier[3], Henri Adreit[4], Aurélie Ducasse[3], François Bonnot[4], Lei Pan[1,2], Xiahong He[1,2], Thomas Kroj[3], Elisabeth Fournier[3], Didier Tharreau[4], Pierre Gladieux[3], Jean-Benoit Morel[3*]

Contents lists available at SciVerse ScienceDirect

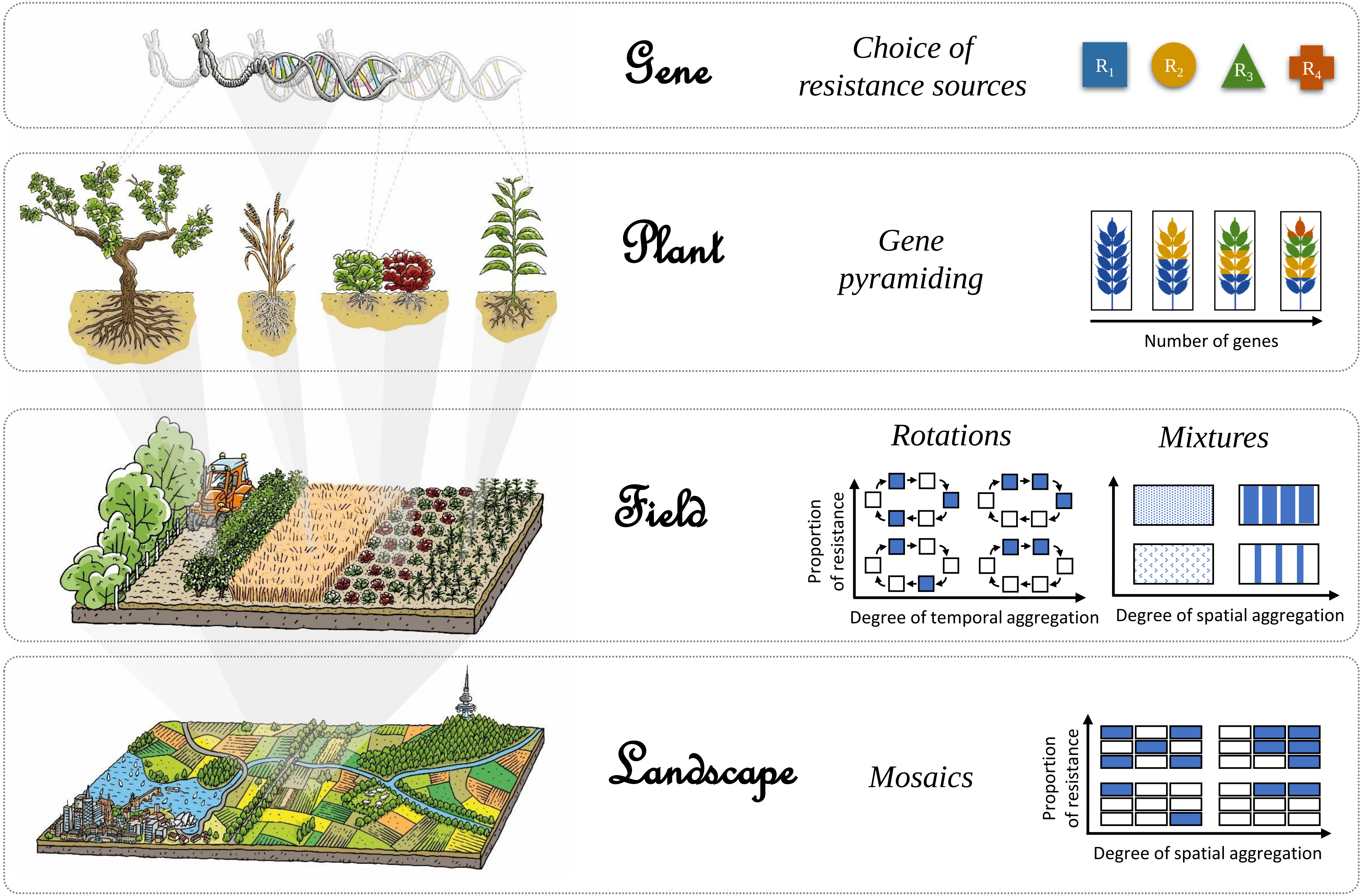
ELSEVIER

Crop Protection

journal homepage: www.elsevier.com/locate/cropro

Effects of wheat cultivar mixtures on stripe rust: A meta-analysis on field trials

Chong Huang, Zhenyu Sun, Haiguang Wang, Yong Luo*, Zhanhong Ma**
Department of Plant Pathology, China Agricultural University, Beijing, China



Adapted from Rimbaud L., Fabre F., Papaïx J., Moury B., Lannou C., Barrett L. and Thrall P. (2021). Models of plant resistance deployment. *Annual Review of Phytopathology* 59:125-152

Spread and evolution of a pathogen

in the agricultural landscape

over multiple cropping seasons

accounting for variability

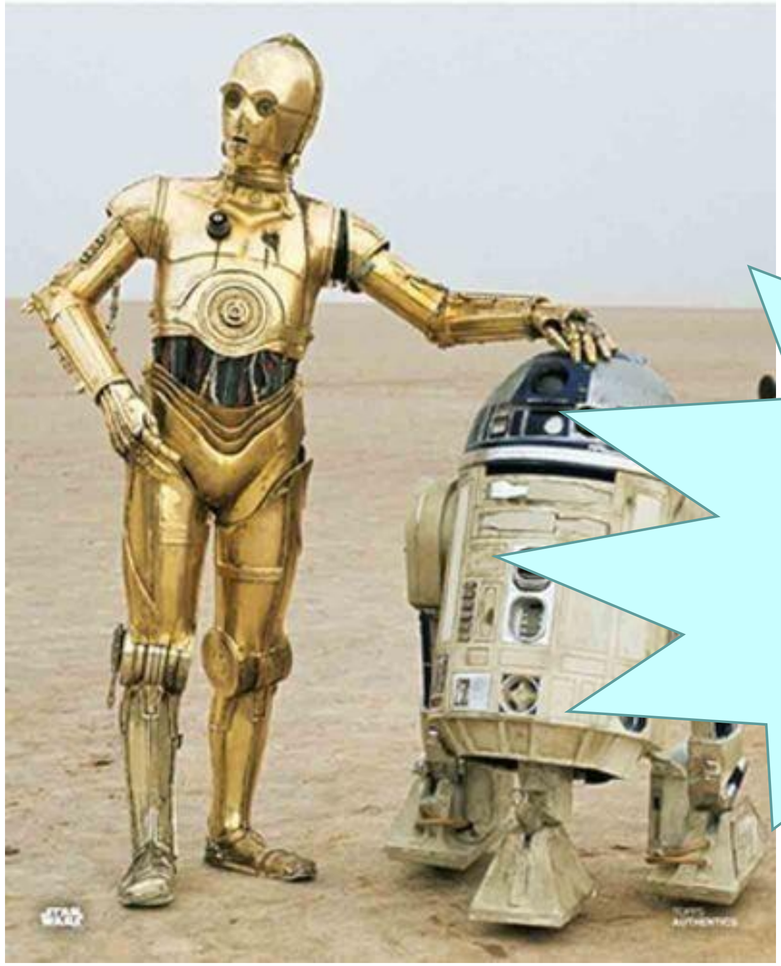
R package
landsepi

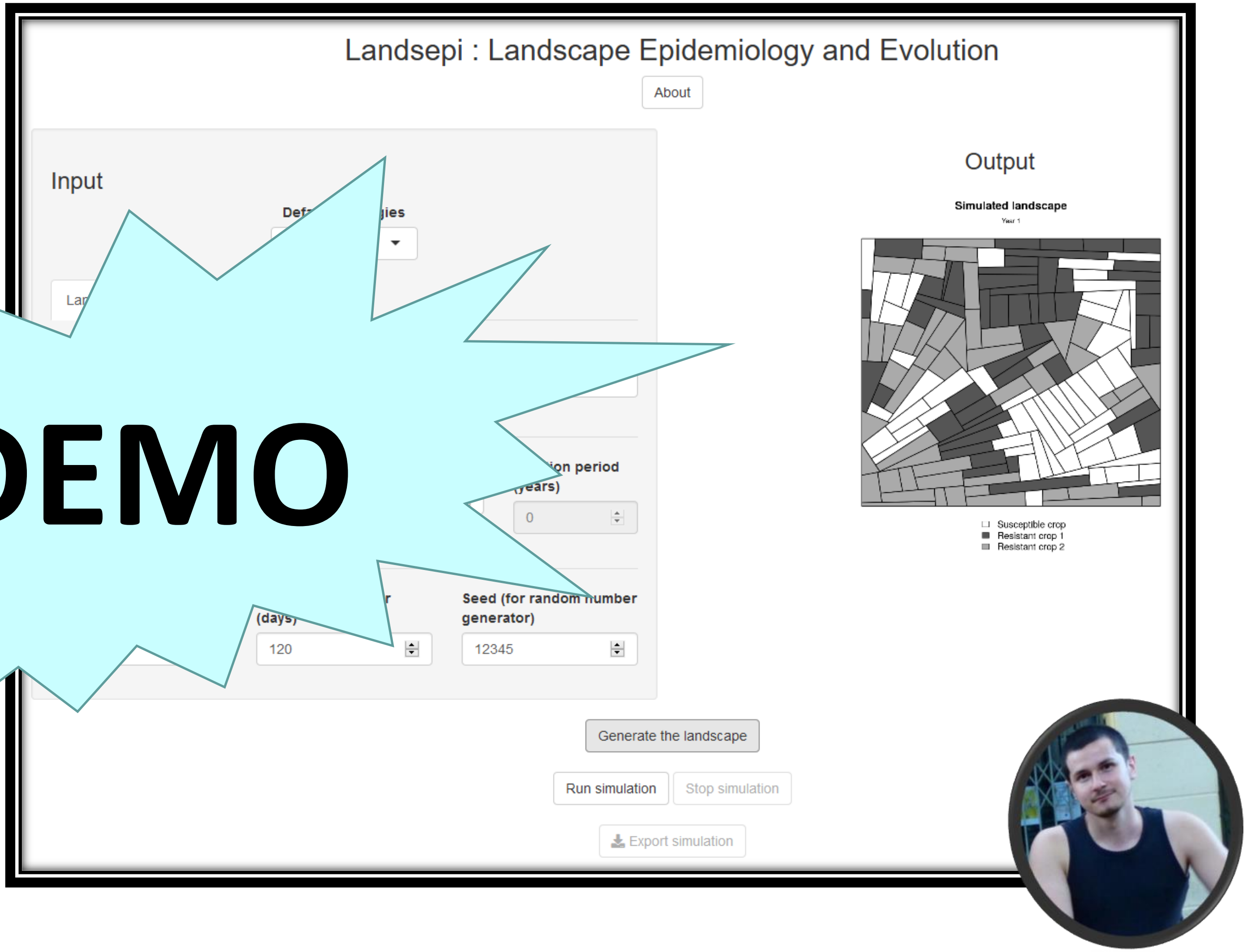
A demo-genetic spatially-explicit temporal stochastic model… to assess disease control and resistance durability

Julien Papaïx
Jean-François Rey
Jean-Loup Gaussen
Marta Zaffaroni

landsepi
Landscape Epidemiology

A web interface destined to broad audience

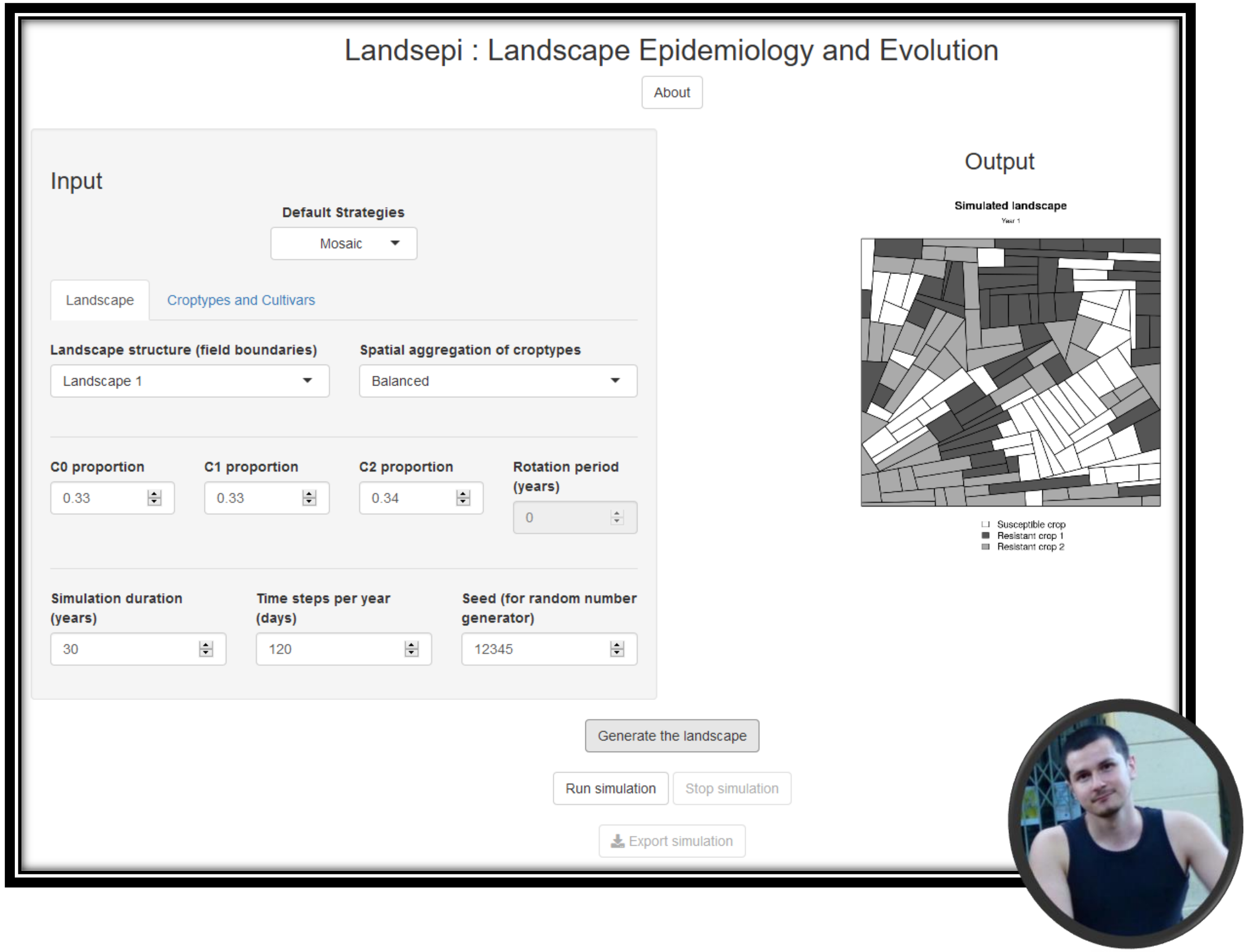




Jean-Loup Gaussen
Master student, 2019

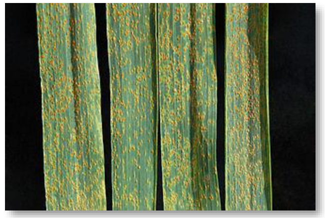
A web interface destined to broad audience

https://shiny.biosp.inrae.fr/app_direct/landsepi/



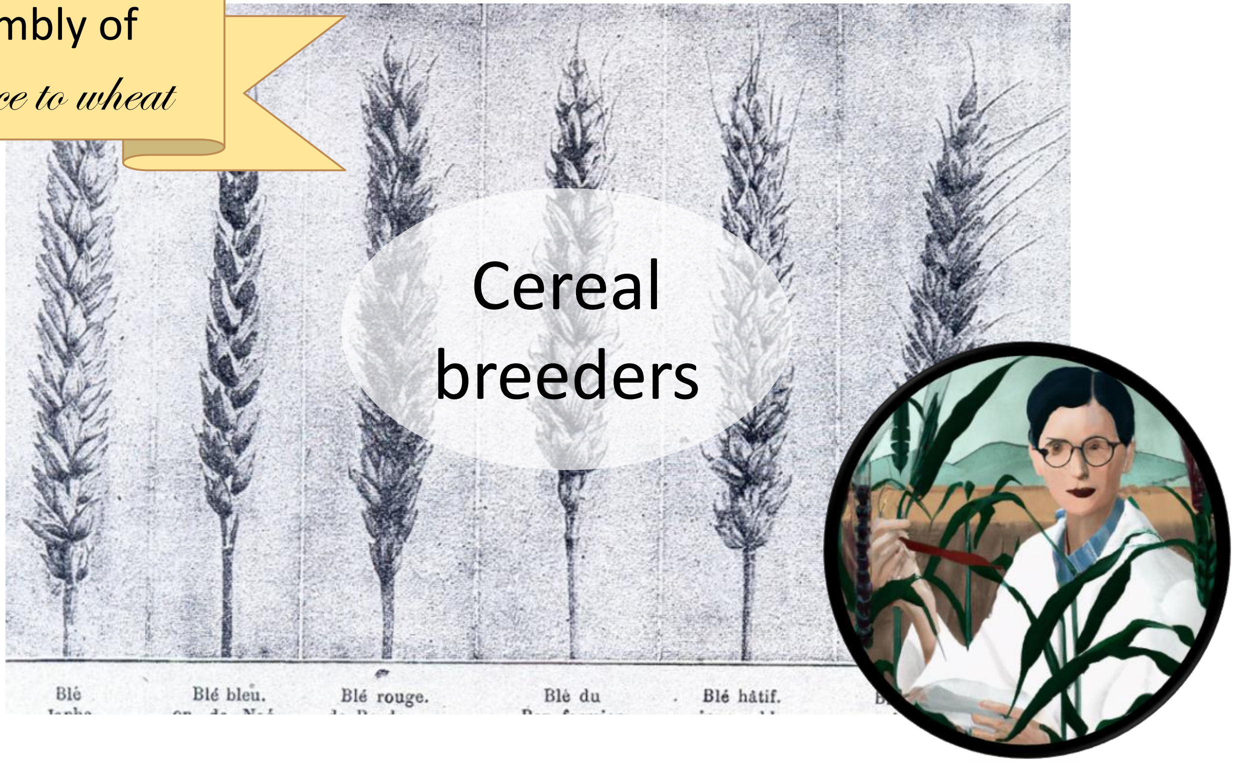
Jean-Loup Gaussen
Master student, 2019

Serious game: Groups




We need you to manage recent and dramatic rust epidemics in France !!!

General assembly of
Beauce, the place to wheat



General assembly of

Beauce, the place to wheat

Landsepi : Landscape Epidemiology and Evolution

About | Advanced Mode On/Off

Input

Default Strategies

Mosaic

Landscape | Cultivars and Genes | Pathogen | Treatment

Landscape structure (field boundaries)

Landscape 1

Spatial aggregation of croptypes

Highly aggregated

Croptypes

croptypeID	croptypeName	Susceptible	Resistant1	Resistant2	Proportions	delete
0	Susceptible crop	1	0	0	0.33	
1	Resistant crop 1	0	1	0	0.33	
2	Resistant crop 2	0	0	1	0.34	

Add line

Rotation period (years)

0

1st configuration : croptypes 0 (**Susceptible crop**) and 1 (**Resistant crop 1**)
2nd configuration : croptypes 0 (**Susceptible crop**) and 2 (**Resistant crop 2**)

Simulation duration (years)

10

Time steps per year (days)

120

Seed (RNG)

1

Generate the landscape

Run simulation | Stop simulation

Download simulation parameters

Round #1

Optimising landscape organisation

Farmers wish to grow 1/3-1/3-1/3 of *Delicate* (susceptible cultivar), *ToughTough* (resistant cultivar with resistance gene 'Lr13') and *Wheateatix* (resistant cultivar with resistance gene 'Lr34') **in a mosaic** during 10 years (120 days/year)

From your perspective, how should they organise the fields in terms of:

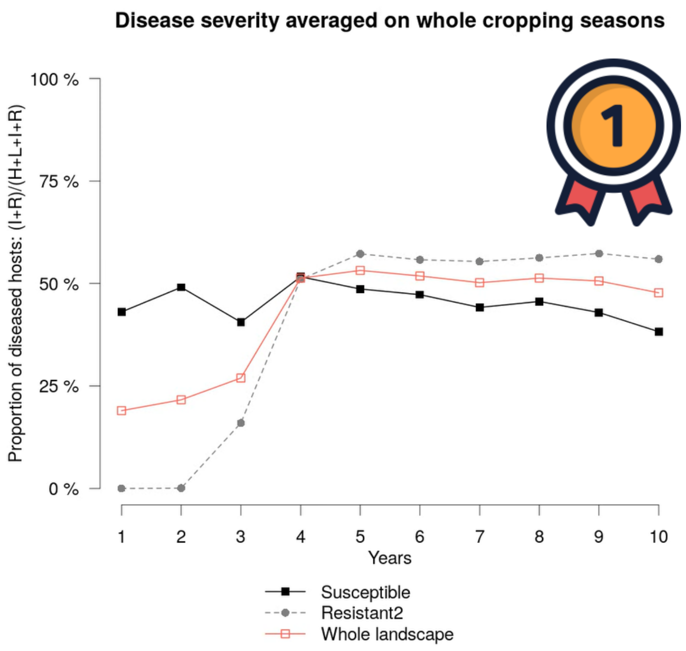
- Field boundaries (landscape structure)?
- Spatial aggregation of the 3 cultivars?

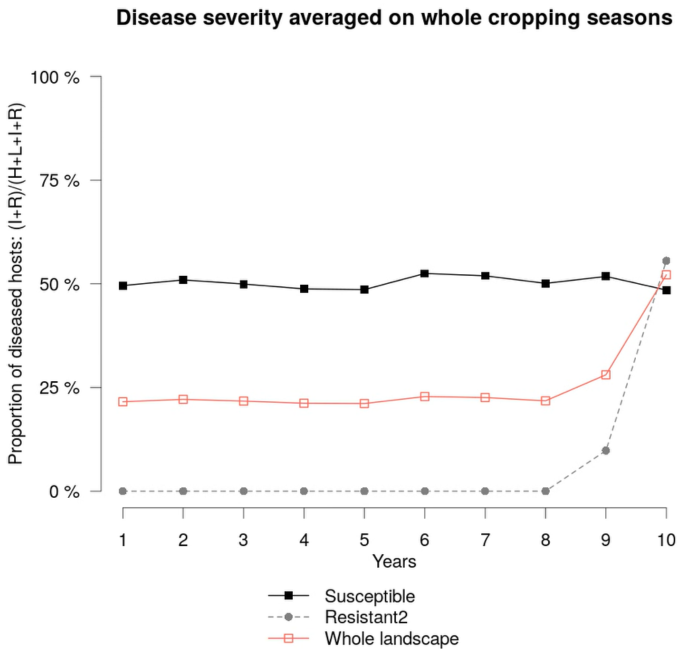
Cereal growers

Your goal is to control epidemics (that is to minimize the proportion of infected plants) on the susceptible *Delicate*, because it is your main cash crop. For this, you must find an appropriate deployment strategy for the resistant ***ToughTough*** and ***Wheateatix*** while maintaining sufficient fields with ***Delicate*** in the landscape.

How does this objective translate into the model outputs? Which of the following is favourable from your point of view?

Minimizing the proportion of diseased **<u>susceptible</u>** hosts (for example the average trend along the 10 simulated years, or the value at year 10)





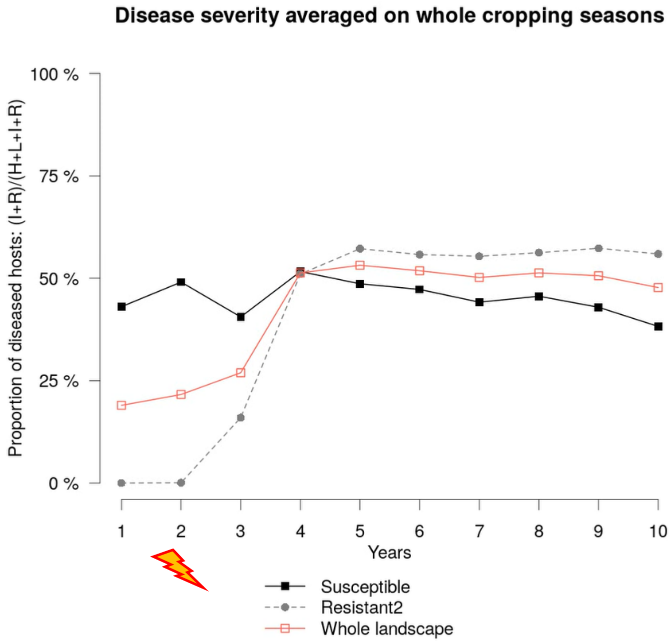
This is the best option for cereal growers, because it minimizes the proportion of diseased susceptible host.

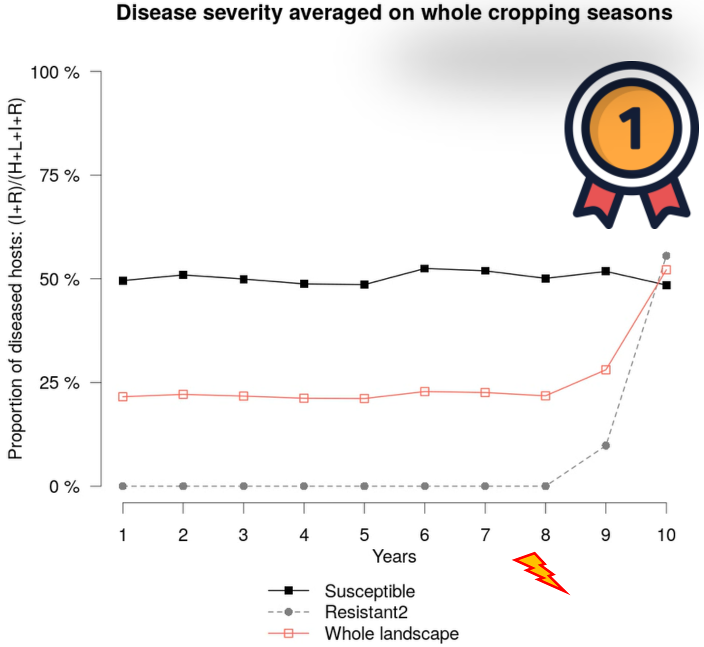
Cereal breeders

Your goal is to avoid a breakdown of resistance genes 'Lr13' and 'Lr34', because it would lead to dramatic epidemics and a loss of at least 10 years of heavy investments in research & development. Thus, ***ToughTough* and *Wheateatix* must be as durable as possible**, that is, the deployment strategy must avoid or at least delay the appearance of adapted pathogens.

How does this objective translate into the model outputs? Which of the following is favourable from your point of view?

Maximizing the number of years before resistance breakdown, that is the moment when the proportion of diseased **<u>resistant</u>** host starts increasing.





This is the best option for cereal breeders, because it maximize the number of years before resistance breakdown


Landscape structure	Spatial aggregation of croptypes	Proportion of diseased <u>susceptible</u> hosts	Years before resistance breakdown
Landscape 1	Highly fragmented		
Landscape 1	Balanced		
Landscape 1	Highly aggregated		
Landscape 2	Highly fragmented		
Landscape 2	Balanced		
Landscape 2	Highly aggregated		
Landscape 3	Highly fragmented		
Landscape 3	Balanced		
Landscape 3	Highly aggregated		
Landscape 4	Highly fragmented		
Landscape 4	Balanced		
Landscape 4	Highly aggregated		
Landscape 5	Highly fragmented		
Landscape 5	Balanced		
Landscape 5	Highly aggregated		

Running the *landsepi* simulator
to get the results for all the
landscape structure X aggregation combinations

Landscape structure	Spatial aggregation of croptypes	Proportion of diseased susceptible hosts 	Years before resistance breakdown 
Landscape 1	Highly fragmented	40%	10 +
Landscape 1	Balanced	50%	3
Landscape 1	Highly aggregated	55%	10 +
Landscape 2	Highly fragmented	45%	10 +
Landscape 2	Balanced	50%	3
Landscape 2	Highly aggregated	55%	10 +
Landscape 3	Highly fragmented	45%	2
Landscape 3	Balanced	55%	3
Landscape 3	Highly aggregated	55%	10 +
Landscape 4	Highly fragmented	45%	1
Landscape 4	Balanced	50%	2
Landscape 4	Highly aggregated	50%	1
Landscape 5	Highly fragmented	45%	5
Landscape 5	Balanced	55%	2
Landscape 5	Highly aggregated	50%	10 +

Debriefing

Round #1

Optimising landscape organisation

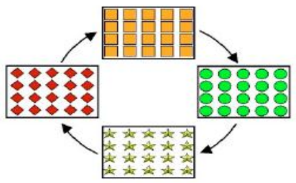
- What is the effect of landscape boundaries?

No detectable effect of landscape boundaries

- What is the effect of spatial aggregation?

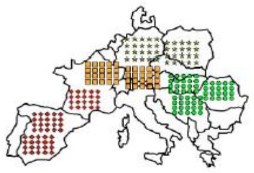
The proportion of diseased susceptible hosts is generally minimize for highly fragmented landscape, while the number of years before resistance breakdown is generally maximize for highly aggregated landscapes

General assembly of
Beauce, the place to wheat

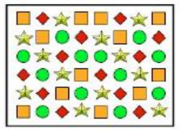


Rotations in time

Pyramids



Mosaics



Cultivar mixtures

Round #2

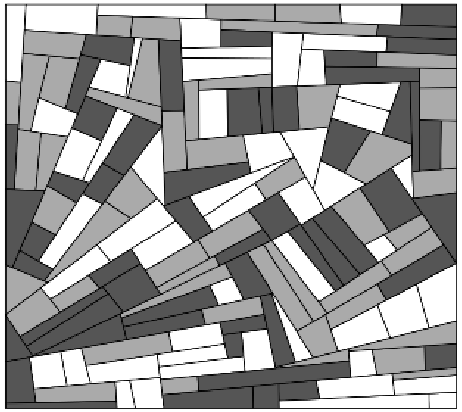
Growers: Optimising deployment strategies

You have heard that 2 completely efficient major resistance genes have just been developed by breeders. You want to use them during 10 years (120 days/year) in a system composed of a susceptible (33%, weak aggregation) and 1 or 2 resistant cultivars (with the same proportion).

Among mosaics, mixtures, rotations and pyramiding:

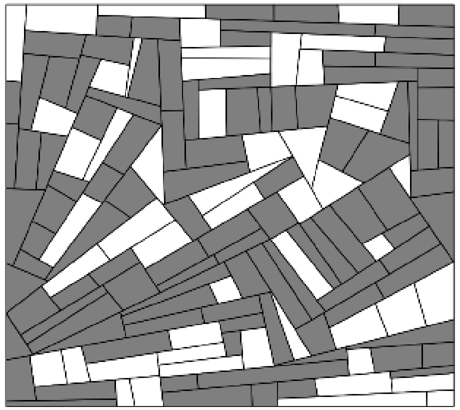
- What is the most efficient strategy in the short term?
- What is the most durable strategy in the long term?

Mosaics



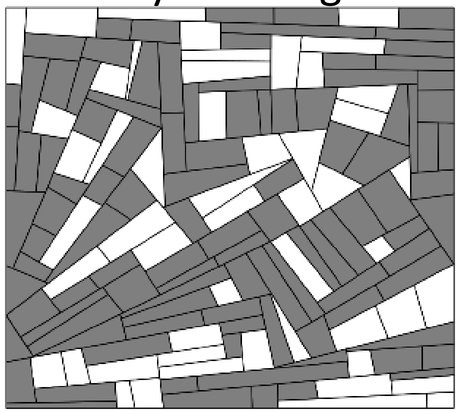
Susceptible crop
Resistant crop 1
Resistant crop 2

Mixtures



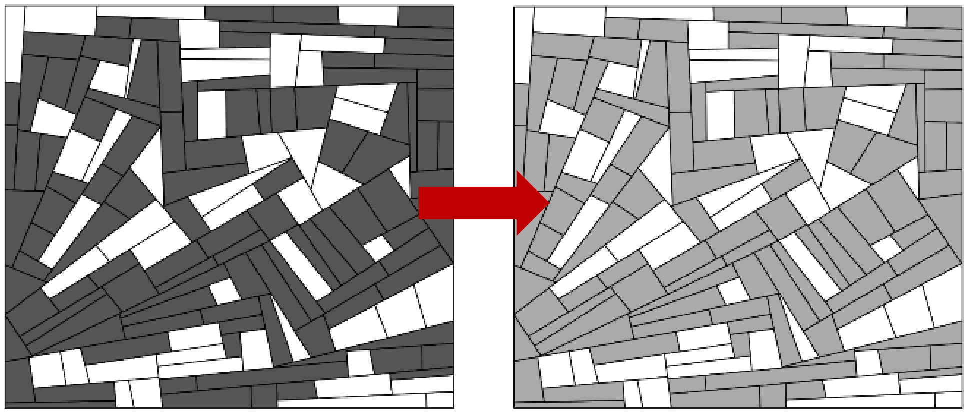
Susceptible crop
Mixture (RC1 + RC2)

Pyramiding



Susceptible crop
Pyramiding

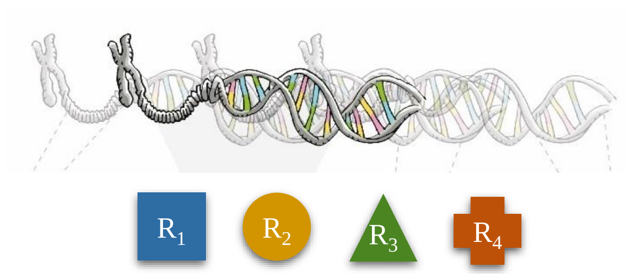
Rotations

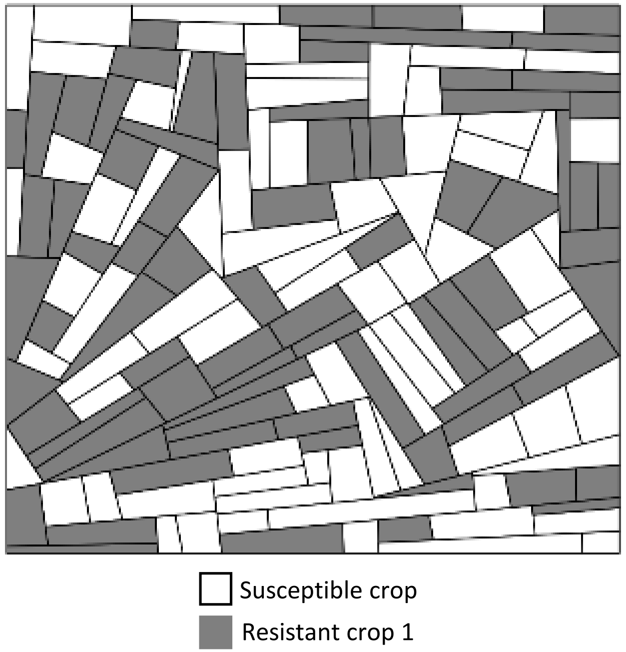


Susceptible crop
Resistant crop 1

Susceptible crop
Resistant crop 2

General assembly of
Beauce, the place to wheat





<u>Round #2</u>

<u>Breeders</u>: Optimising resistance sources

The scientific literature mentions several possible resistance sources, but they differ in efficiency and adaptation cost for the pathogen. You would like to know their potential in simple mosaics of S + R (50%-50%, weak aggregation) grown for 10 years (120 days/year).

what is the effect of :

- Efficiency of the resistance gene
- Fitness cost of pathogen adaptation
- Note : <u>relative advantage = 0</u>

on resistance efficiency and durability?

percentage of reduction of pathogen targeted aggressiveness component, the infection rate here

fitness penalty paid by a pathogen genotype fully adapted to the resistance gene on any host

Cereal growers

		Short term	Long term
Landscape structure	**Resistant deployment strategy**	**Proportion of diseased susceptible hosts**	**Years before resistance breakdown**
Landscape 1	Mosaic		
Landscape 1	Mixture		
Landscape 1	Pyramiding		
Landscape 1	Rotation		
Landscape 2	Mosaic		
Landscape 2	Mixture		
Landscape 2	Pyramiding		
Landscape 2	Rotation		
Landscape 3	Mosaic		
Landscape 3	Mixture		
Landscape 3	Pyramiding		
Landscape 3	Rotation		
Landscape 4	Mosaic		
Landscape 4	Mixture		
Landscape 4	Pyramiding		
Landscape 4	Rotation		
Landscape 5	Mosaic		
Landscape 5	Mixture		
Landscape 5	Pyramiding		
Landscape 5	Rotation		

Running the *landsepi* simulator
to get the results for all the
landscape structure X strategy combinations
(balanced aggregation)

Cereal growers

		Short term	Long term
Landscape structure	Resistant deployment strategy	Proportion of diseased susceptible hosts	Years before resistance breakdown
Landscape 1	Mosaic	52%	6
Landscape 1	Mixture	52%	10+
Landscape 1	Pyramiding	50%	7
Landscape 1	Rotation	32%	7
Landscape 2	Mosaic	46%	2
Landscape 2	Mixture	55%	10+
Landscape 2	Pyramiding	46%	9
Landscape 2	Rotation	55%	5
Landscape 3	Mosaic	48%	3
Landscape 3	Mixture	43%	3
Landscape 3	Pyramiding	45%	10+
Landscape 3	Rotation	50%	10+
Landscape 4	Mosaic	41%	2
Landscape 4	Mixture	45%	10+
Landscape 4	Pyramiding	48%	10+
Landscape 4	Rotation	43%	10+
Landscape 5	Mosaic	49%	8
Landscape 5	Mixture	52%	10+
Landscape 5	Pyramiding	53%	10+
Landscape 5	Rotation	46%	10+

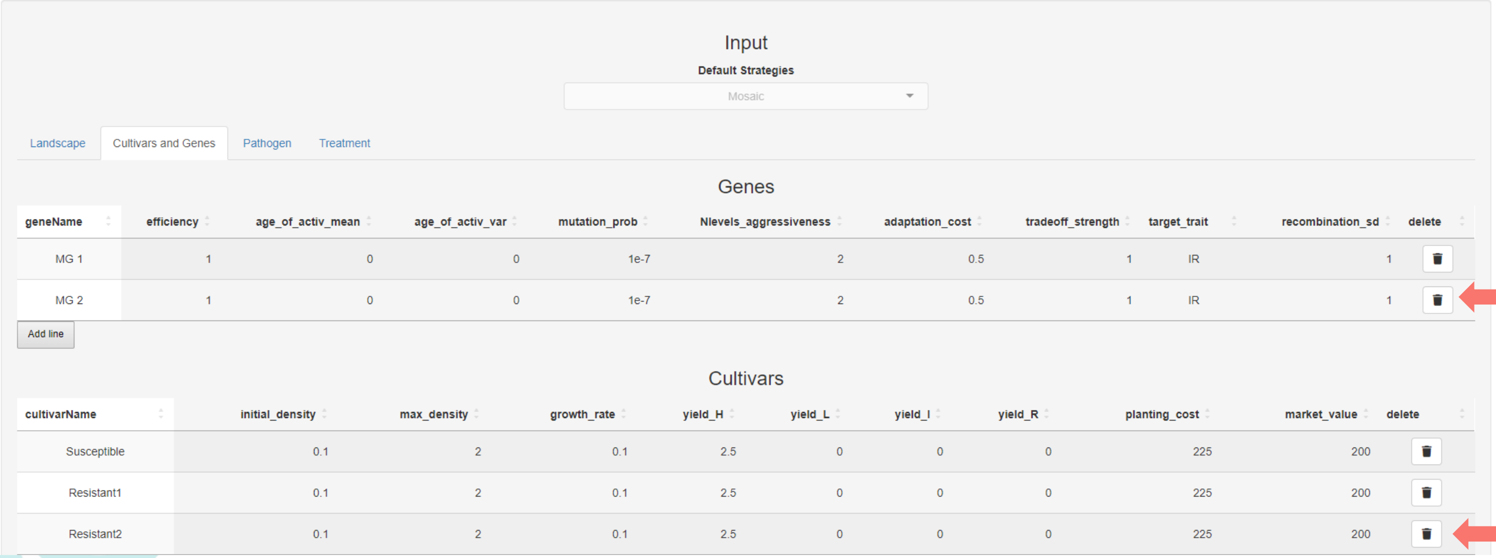
Cereal breeders

Gene	Efficiency	Adaptation cost	Proportion of diseased hosts in the whole landscape	Years before resistance breakdown
Lr12	88%	25%	55%	1
Lr13	100%	25%		
Lr16	10%	75%		
Lr22	88%	50%		
Lr34	75%	25%		
Lr35	88%	0%		
Lr37	50%	50%		
Lr46	10%	25%		

Running the *landsepi* simulator to get the results for all the genes (highly fragmented aggregation)

Landsepi : Landscape Epidemiology and Evolution

About | Advanced Mode On/Off ← Switch on the ``Advanced mode''



geneName	efficiency	age_of_activ_mean	age_of_activ_var	mutation_prob	Nlevels_aggressiveness	adaptation_cost	tradeoff_strength	target_trait	recombination_sd	delete
MG 1	1	0	0	1e-7	2	0.5	1	IR	1	
MG 2	1	0	0	1e-7	2	0.5	1	IR	1	

cultivarName	initial_density	max_density	growth_rate	yield_H	yield_L	yield_I	yield_R	planting_cost	market_value	delete
Susceptible	0.1	2	0.1	2.5	0	0	0	225	200	
Resistant1	0.1	2	0.1	2.5	0	0	0	225	200	
Resistant2	0.1	2	0.1	2.5	0	0	0	225	200	

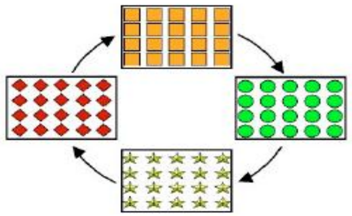
Keep only one resistance gene

Keep only one resistant cultivar

Cereal breeders

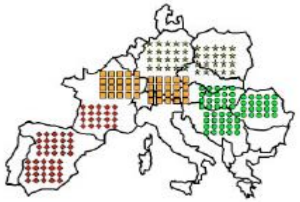
Gene	Efficiency	Adaptation cost	Proportion of diseased hosts in the whole landscape	Years before resistance breakdown
Lr12	88%	25%	25%	1
Lr13	100%	25%	25%	10 +
Lr16	10%	75%	55%	1
Lr22	88%	50%	30%	1
Lr34	75%	25%	40%	1
Lr35	88%	0%	30%	1
Lr37	50%	50%	30%	1
Lr46	10%	25%	55%	1

Debriefing

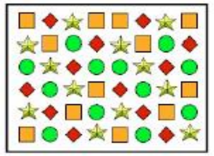


Rotations in time

Pyramids



Mosaics



Cultivar mixtures

Round #2

Growers: Optimising deployment strategies

Among mosaics, mixtures, rotations and pyramiding of 2 major resistance genes:

- What is the most efficient strategy in the short term?

Rotation

- What is the most durable strategy in the long term?

Pyramiding

Breeders: Optimising resistance sources

Given that several resistance genes are available, what is the effect of :

- gene efficiency
- fitness cost of pathogen adaptation

on resistance efficiency and durability?

Only a gene efficiency = 100% assured a durability 10 +,
A high gene efficiency and adaptation cost assured a better resistant efficiency (better control of the disease)

Selected reviews for a good start on R durability

Annu. Rev. Phytopathol. 2002. 40:349–79
doi: 10.1146/annurev.phyto.40.120501.101443

PATHOGEN POPULATION GENETICS, EVOLUTIONARY POTENTIAL, AND DURABLE RESISTANCE

Bruce A. McDonald and Celeste Linde

Infection, Genetics and Evolution xxx (2014) xxx–xxx
Contents lists available at ScienceDirect
Infection, Genetics and Evolution
journal homepage: www.elsevier.com/locate/meegid
ELSEVIER

Review

Durable resistance: A key to sustainable management of pathogens and pests

Christopher C. Mundt *

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Playing on a Pathogen's Weakness: Using Evolution to Guide Sustainable Plant Disease Control Strategies

Jiasui Zhan,[1,2,*] Peter H. Thrall,[3] Julien Papaïx,[4,5] Lianhui Xie,[2] and Jeremy J. Burdon[3]

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[4]INRA, Santé des Plantes et Environnement, UR 1290 BIOGER-CPP, 78850 Thiverval-Grignon, France; email: jpapaix@jouy.inra.fr
[5]INRA, Mathématiques et Informatiques Appliquées, UR 341 MIAJ, 78352 Jouy-en-Josas, France

Annu. Rev. Phytopathol. 2015. 53:19–43
First published online as a Review in Advance on May 4, 2105
The *Annual Review of Phytopathology* is online at phyto.annualreviews.org

Keywords
ecological disease management, spatiotemporal resistance gene deployment, trade-offs, evolutionary plant pathology, multilayer disease forecasting

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Plant-Parasite Coevolution: Bridging the Gap between Genetics and Ecology

James K. M. Brown[1] and Aurélien Tellier[2]

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[2]Section of Evolutionary Biology, Biocenter, University of Munich, 82152 Planegg-Martinsried, Germany; email: tellier@bio.lmu.de

Annu. Rev. Phytopathol. 2011. 49:345–67
The *Annual Review of Phytopathology* is online at phyto.annualreviews.org

Keywords
resistance, avirulence, effector, frequency-dependent selection, polymorphism, boom-and-bust cycle

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Annual Review of Phytopathology

Models of Plant Resistance Deployment

Loup Rimbaud,[1,2] Frédéric Fabre,[3] Julien Papaïx,[4] Benoît Moury,[1] Christian Lannou,[5] Luke G. Barrett,[2] and Peter H. Thrall[2]

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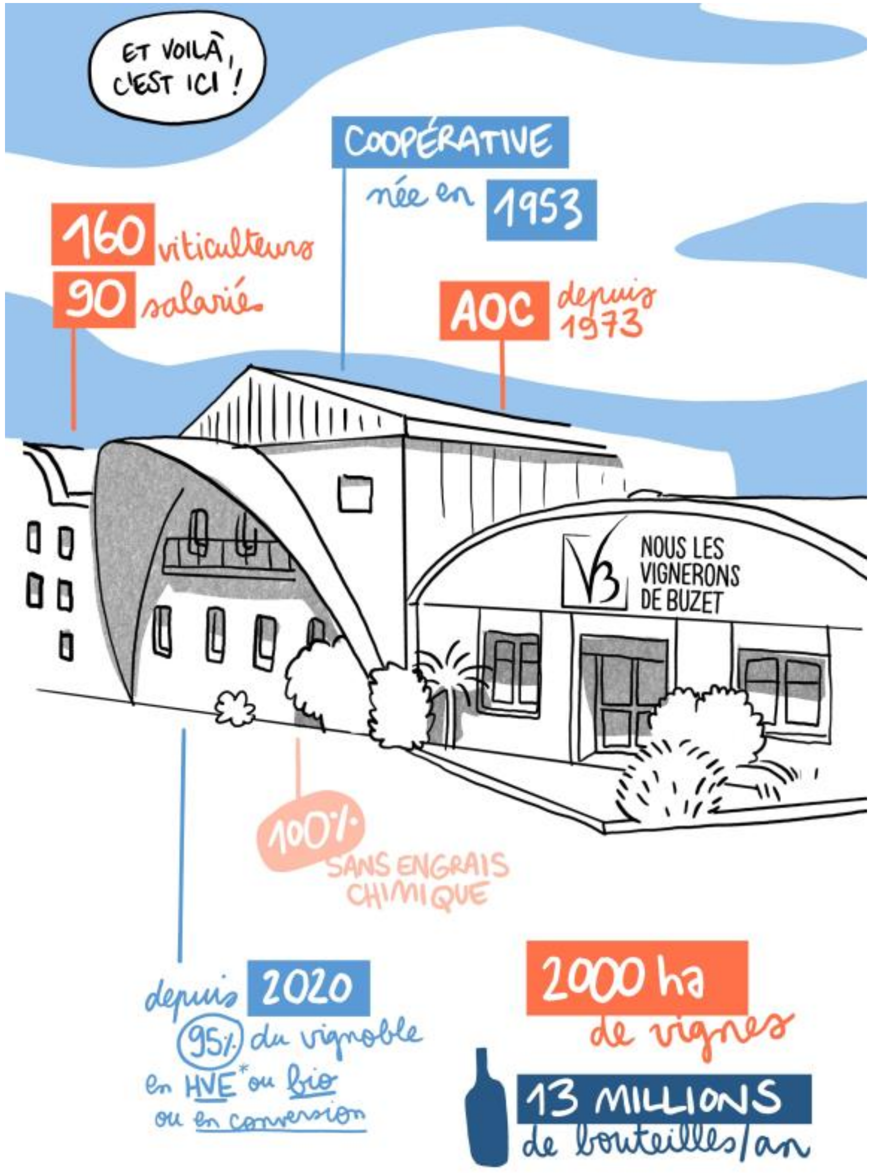
[5]INRAE, BIOGER, 78850 Thiverval-Grignon, France; email: christian.lannou@inrae.fr

Annu. Rev. Phytopathol. 2021. 59:125–52
First published as a Review in Advance on April 30, 2021

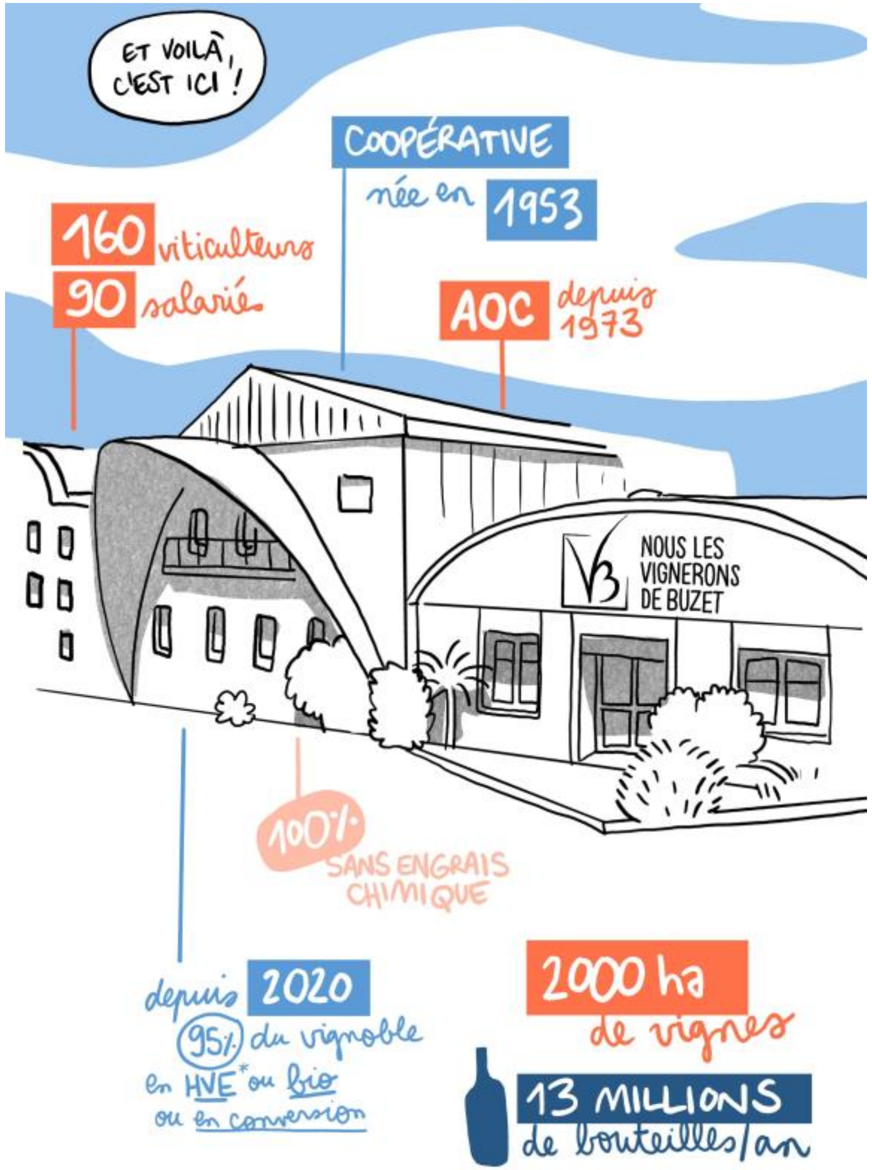
Keywords
adaptation, durability, evolution, host–microbe interaction, immunity, simulation

Beyond « square fields in a square landscape »



- Cooperative listened by its members
- A player capable of driving forward actions on a regional scale
- The user association promoted by Elinor Ostrom

Beyond square fields in a square landscape



What does winegrowers think about R cultivars? How researchers can dialogue with winegrowers for deploying R cultivars?

- Four ateliers with the cooperative cellar growing *''Les vignerons des Buzet''*

01
Understanding the issues and sharing objectives

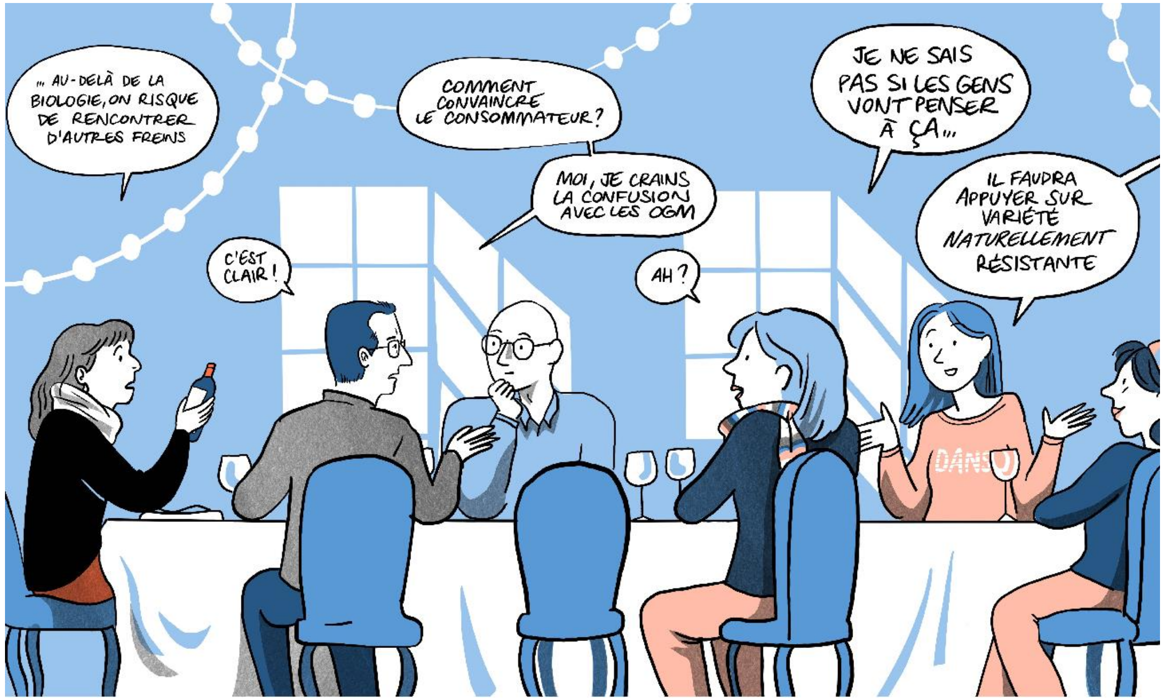
02
Design of deployment strategies for VDB

Think+
THE ECO-INNOVATIVE AGENCY

What does winegrowers think about R cultivars? How researchers can dialogue with winegrowers for deploying R cultivars?

- Four ateliers with the cooperative cellar growing *"Les vignerons des Buzet"*

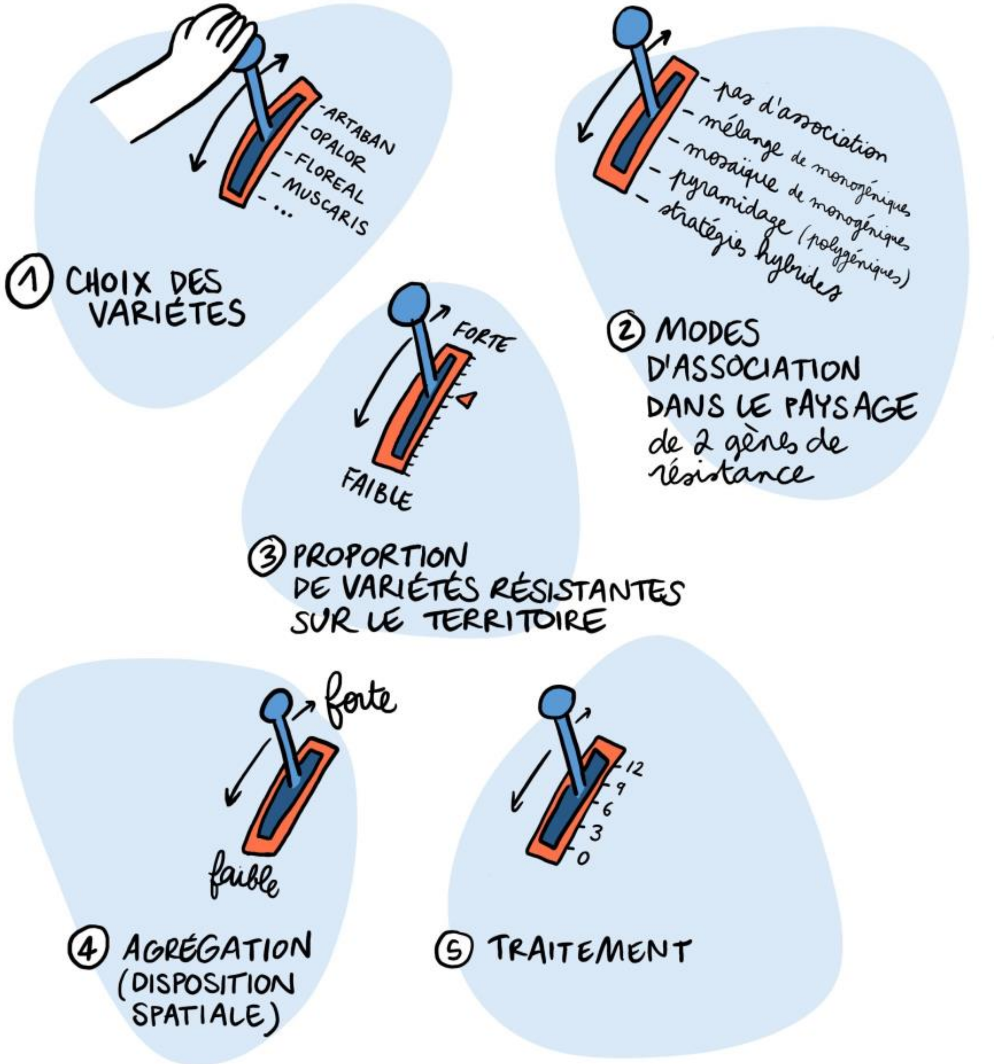
01	02		
Understanding the issues and sharing objectives	Design of deployment strategies for VDB	Results of the deployment strategies for VDB	Summary and conclusion



Design of strategies

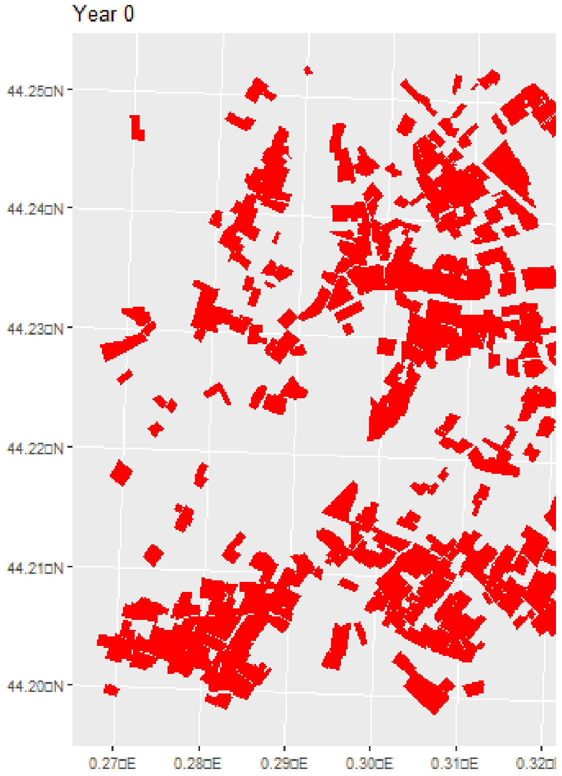
Facteur	Valeur	
Resistant cultivar	Polygenic (PY)	cultivar ResDur 1 (Rpv1-Rpv3.1)
Choice of fields planted with R cultivars	Age > 30 years	no limit
		max 5% / farmer
		max 20% / farmer
	Age > 40 years	no limit
		max 5% / farmer
		max 20% / farmer
	3%/year of the oldest	
	ZNT aquatic	treatment > 0
		treatment = 0
	ZNT neighbouring	treatment > 0
		treatment = 0

Design of strategies…and Marta doing all the hard work !

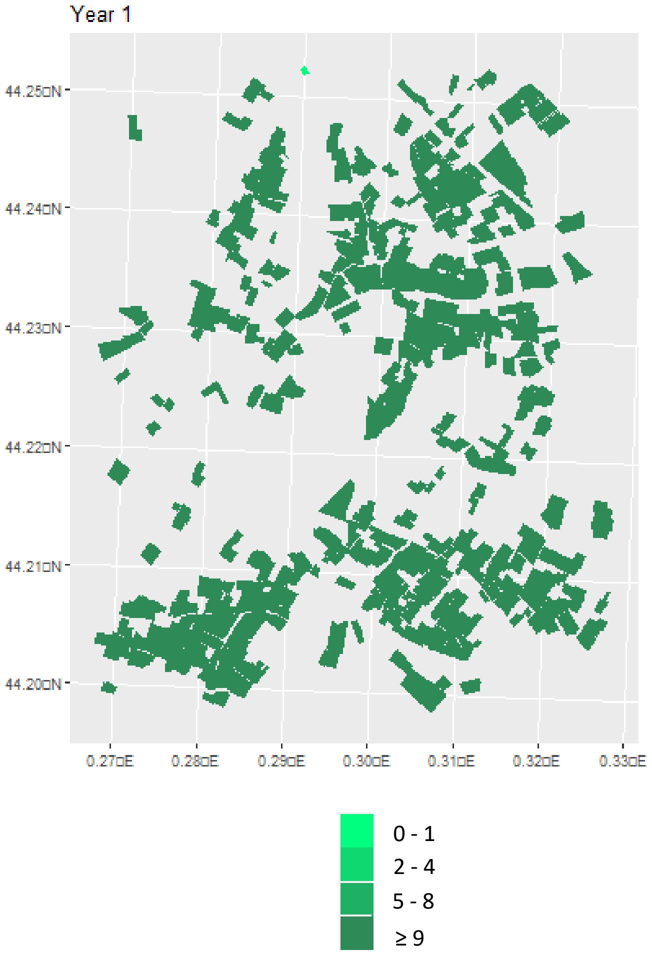


Scenario 5: 3% of the oldest fields each year

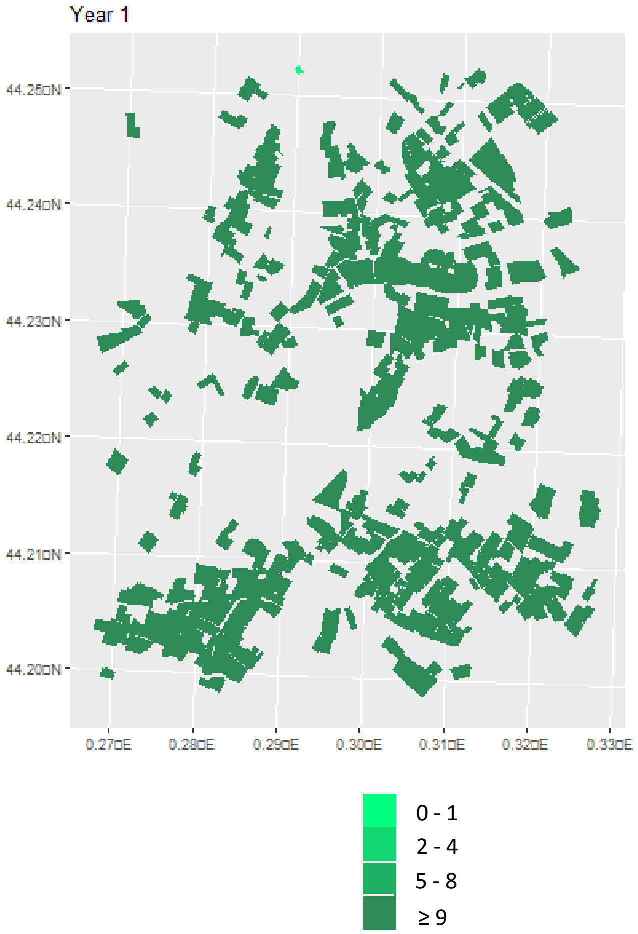
91% of fields planted with CR during 30 years



A simulation with a breakdown



No breakdown



- *Soon a popular science comic strip on the subject*

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