

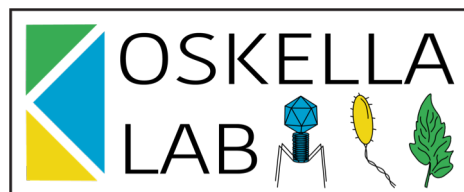
# The Multi-Faceted Impacts of Phages in the Plant Phyllosphere



Britt Koskella

@bkoskella 

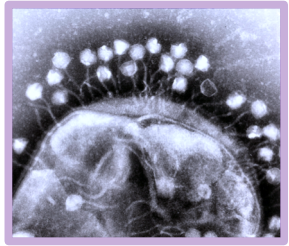
Assistant Professor, Integrative Biology  
UC Berkeley



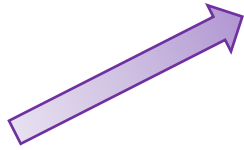
*Annual Review of Phytopathology*

# Multifaceted Impacts of Bacteriophages in the Plant Microbiome

Britt Koskella<sup>1</sup> and Tiffany B. Taylor<sup>2</sup>



Bacteriophages



Plant pathogen

Ecology  
Evolution

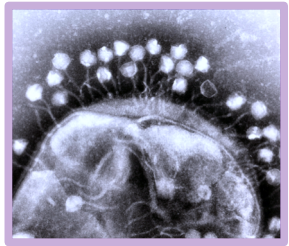
*Annual Review of Phytopathology*

# Multifaceted Impacts of Bacteriophages in the Plant Microbiome

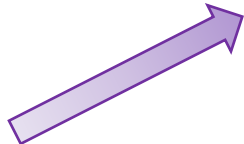


Britt Koskella<sup>1</sup> and Tiffany B. Taylor<sup>2</sup>

??



Bacteriophages



Plant pathogen

Bacterial trait	Phage-mediated selection	Impact on fitness within the plant
Growth rate	Lytic phages typically decrease population size; both lytic and temperate phages can increase growth rate	Positively associated
Exopolysaccharide production	Can provide protection against phage infection; also acts as phage receptors	Positively associated
Quorum-sensing ability	Linked with phage defense and life history	Positively associated
Type IV pili expression	Important for phage attachment	Associated with plant pathogen virulence
Density/function of lipopolysaccharide receptors	Common phage receptor	Important for growth in plant environment; also interacts with plant defenses
Increased motility	Can decrease phage attachment efficiency; also aids in cell surface access by phages	Positively associated
Pyocyanin and pyoverdinin production	Loss associated with phage resistance	Positively associated, known virulence factors
Phase variation (programmed genetic variation)	Allows persistence of genetically sensitive bacteria	Within-population heterogeneity can hinder growth; also allows evasion of plant defense
Biosurfactant production	Possible increase in phage dispersal	Positively associated
Formation of biofilms	Can protect bacteria from phage infection; phages can also degrade biofilm	Often associated with virulence

*Annual Review of Phytopathology*

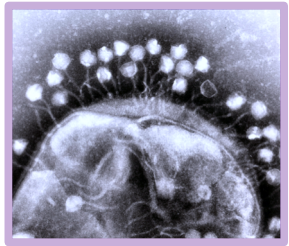
# Multifaceted Impacts of Bacteriophages in the Plant Microbiome



Britt Koskella<sup>1</sup> and Tiffany B. Taylor<sup>2</sup>

???????

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Bacteriophages



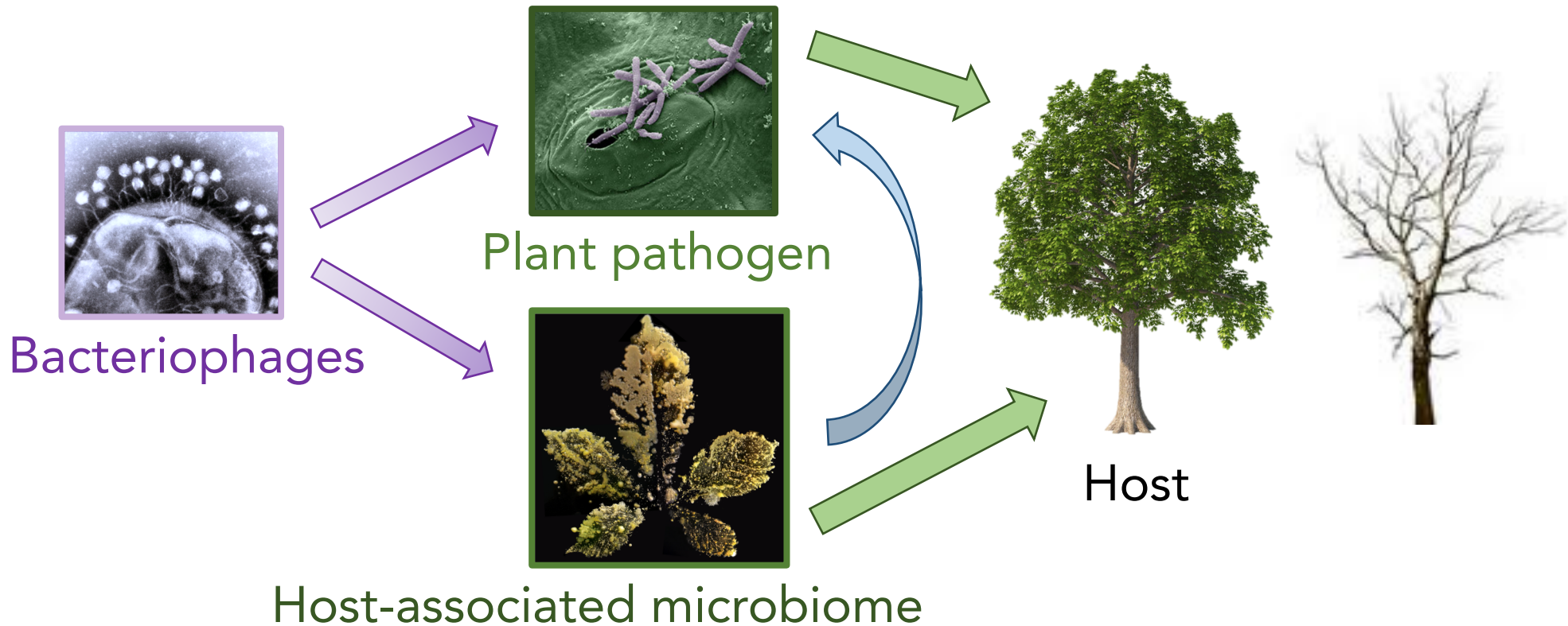
Plant pathogen



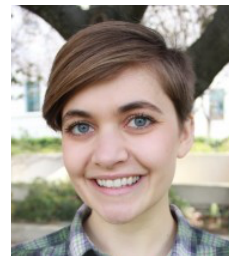
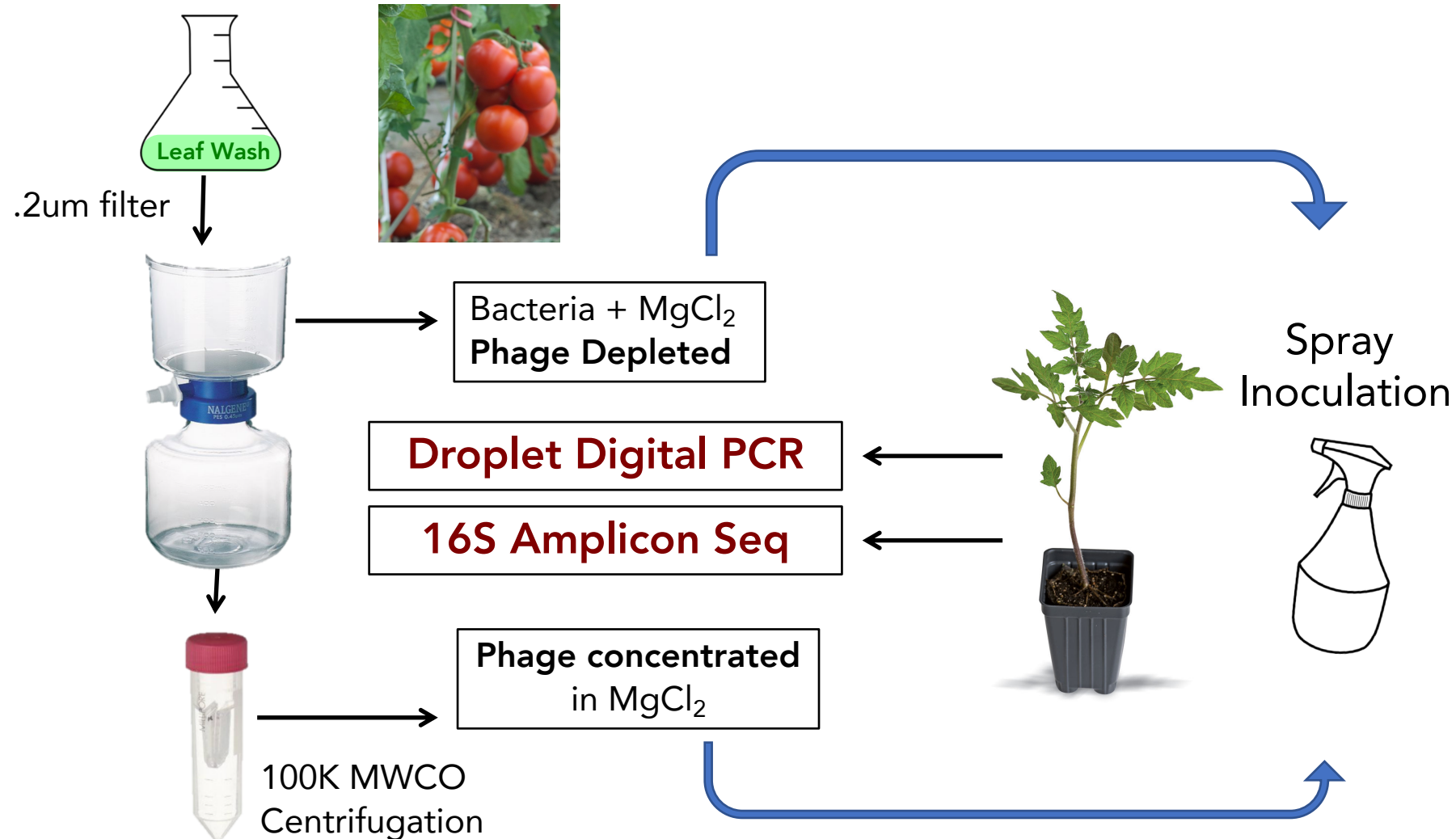
Host-associated microbiome

# Phages in the plant phyllosphere

## The phyllosphere as a model system



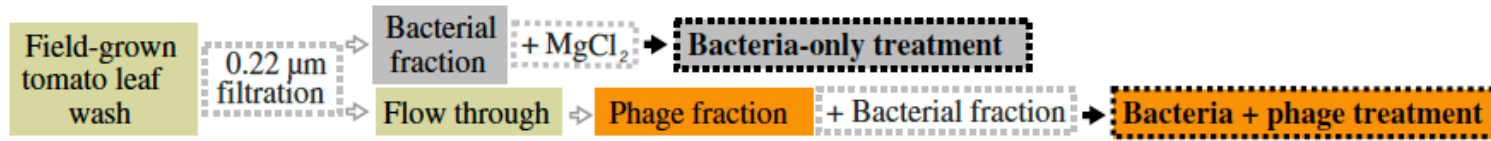
# Phages in the plant phyllosphere



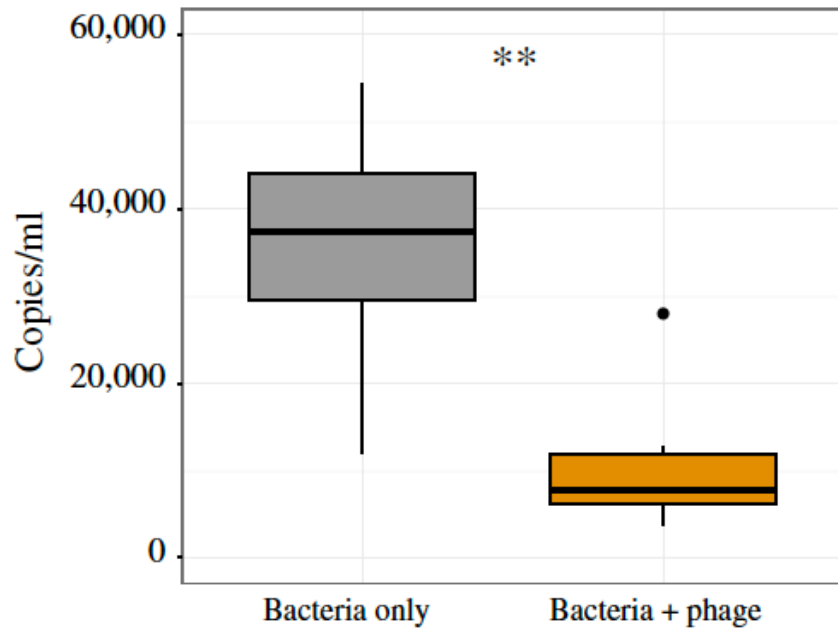
Norma Morella

# Phages in the plant phyllosphere

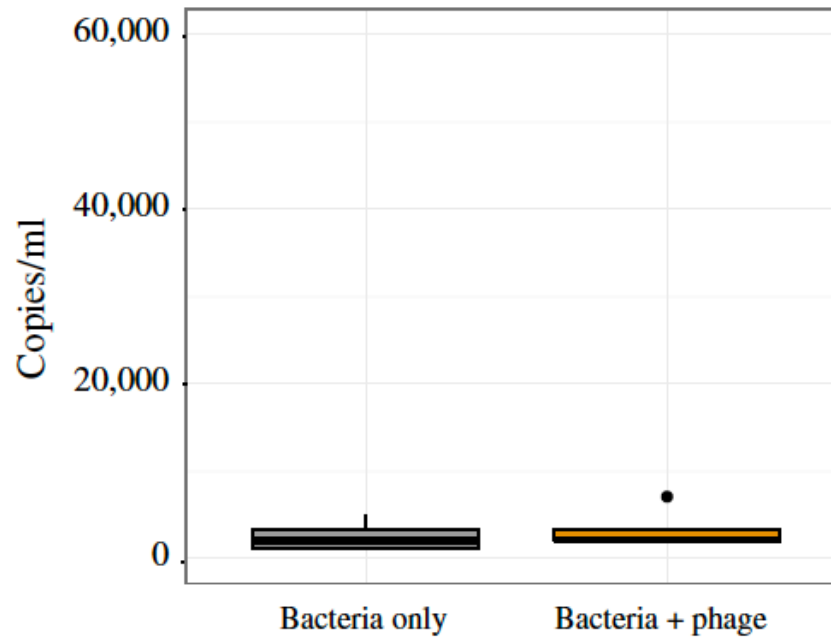
(a) Filtration steps used for each treatment



(b) Bacterial DNA across treatments at day 1



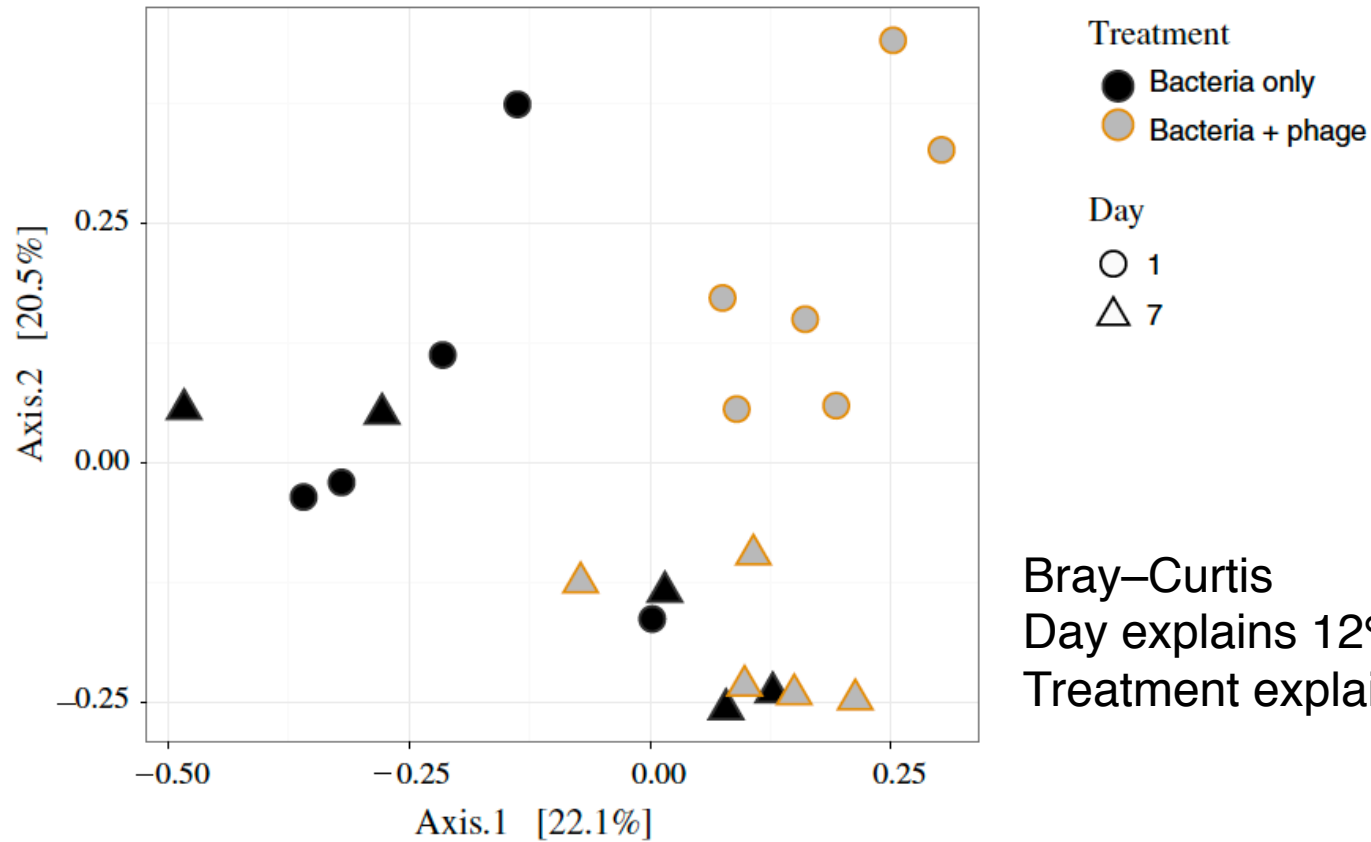
(c) Bacterial DNA across treatments at day 7



Norma Morella

# Phages in the plant phyllosphere

(a) Phyllosphere compositional dissimilarity across treatments and time



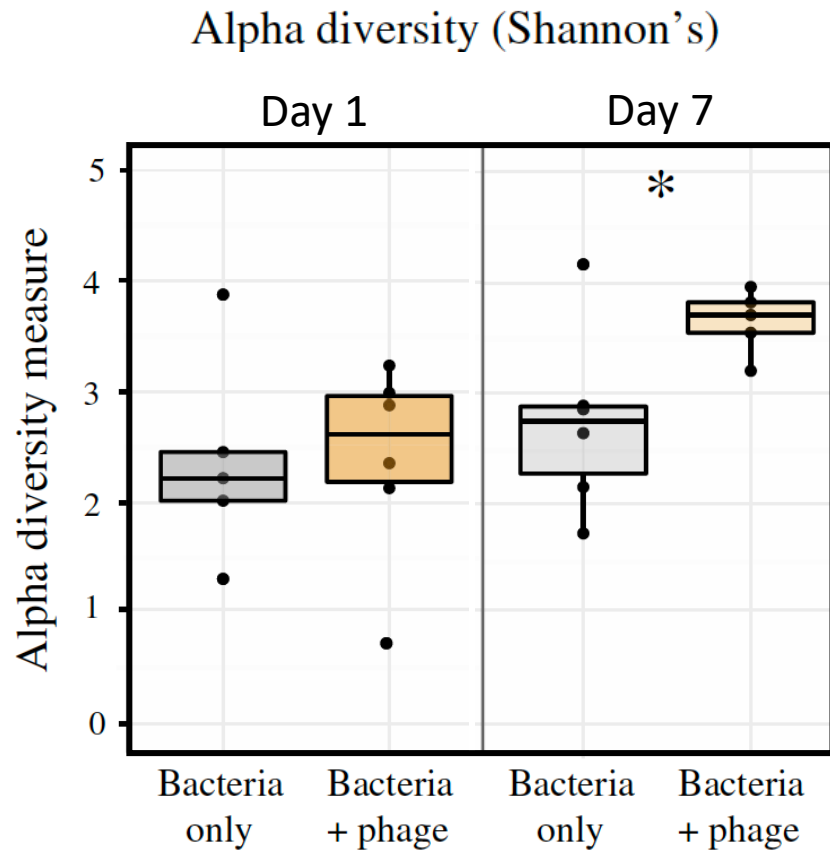
Bray-Curtis  
Day explains 12% of variation ( $p = .006$ )  
Treatment explains 13% ( $p = .002$ )



Norma Morella

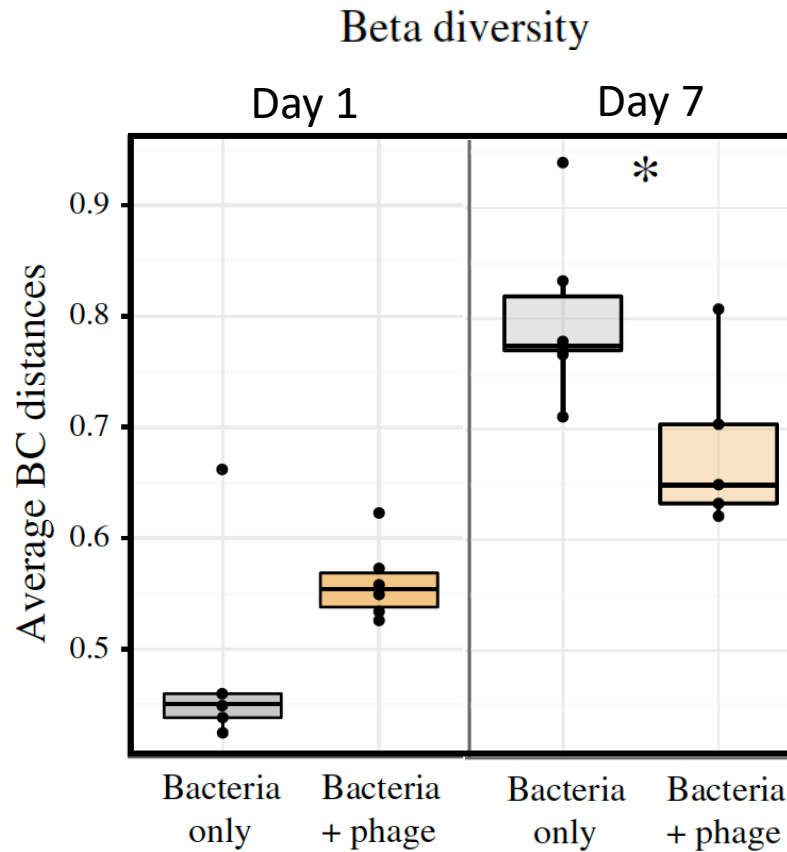
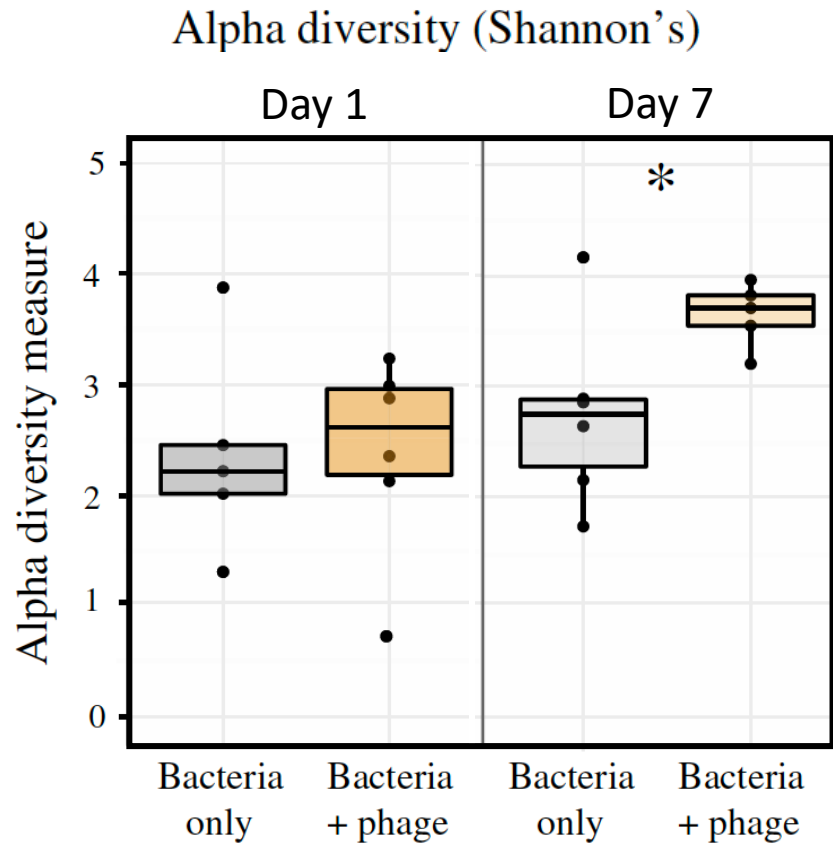


# Phages in the plant phyllosphere



Norma Morella

# Phages in the plant phyllosphere

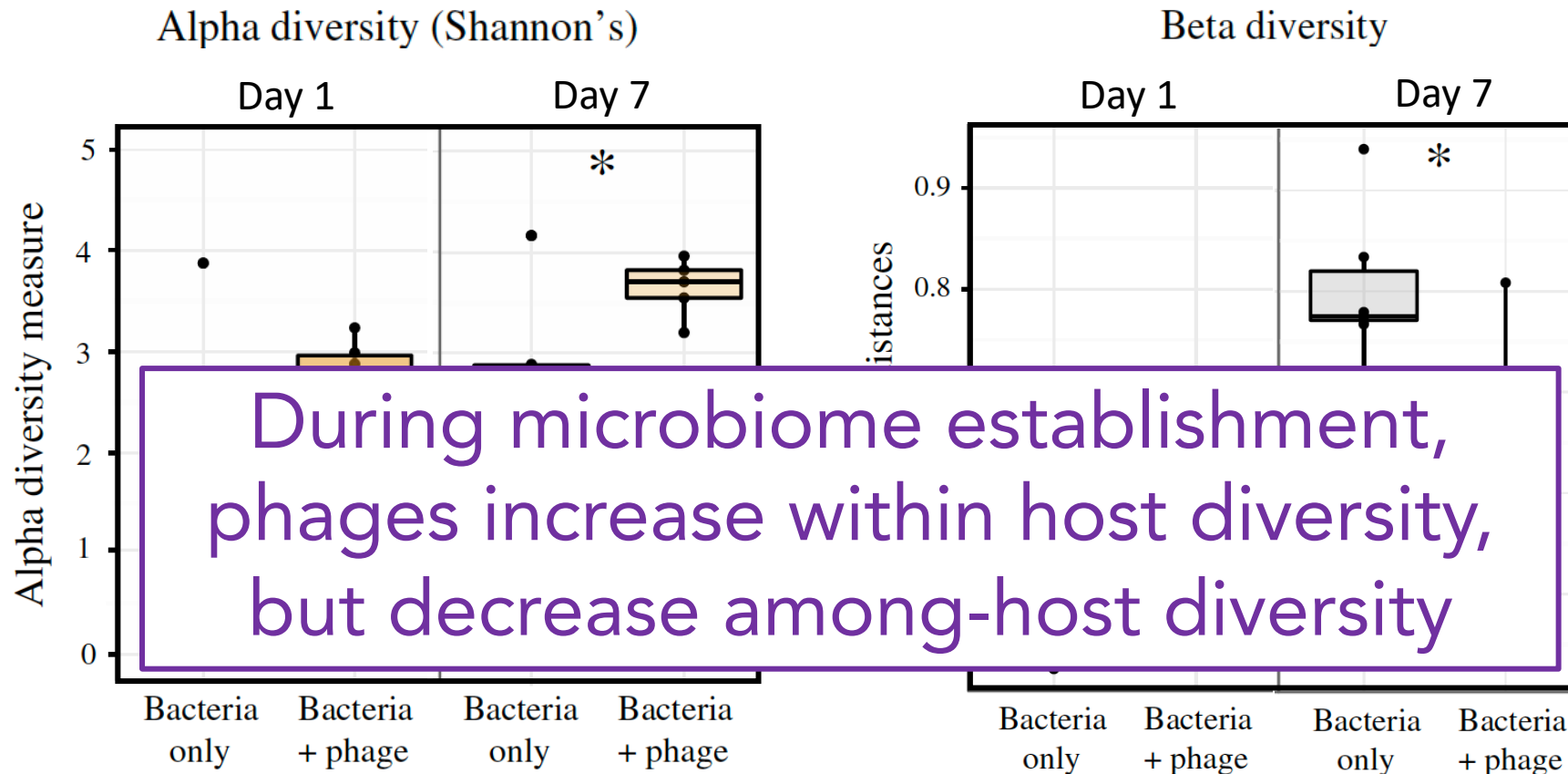


X 6

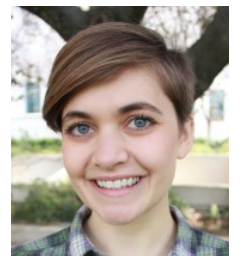


Norma Morella

# Phages in the plant phyllosphere

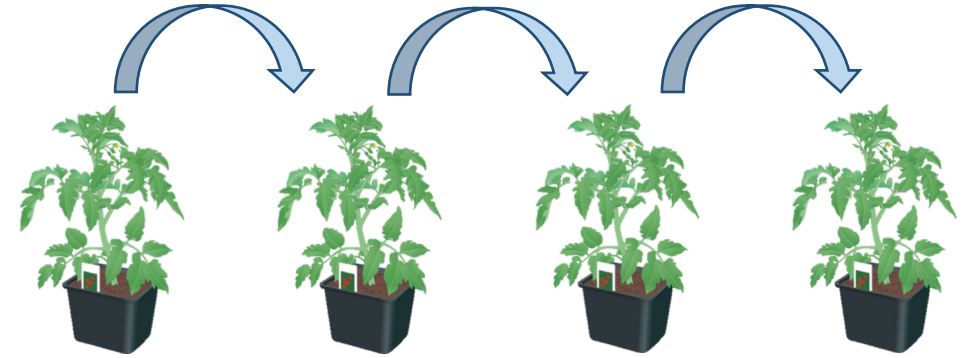


X 6



Norma Morella

# Phages in the plant phyllosphere



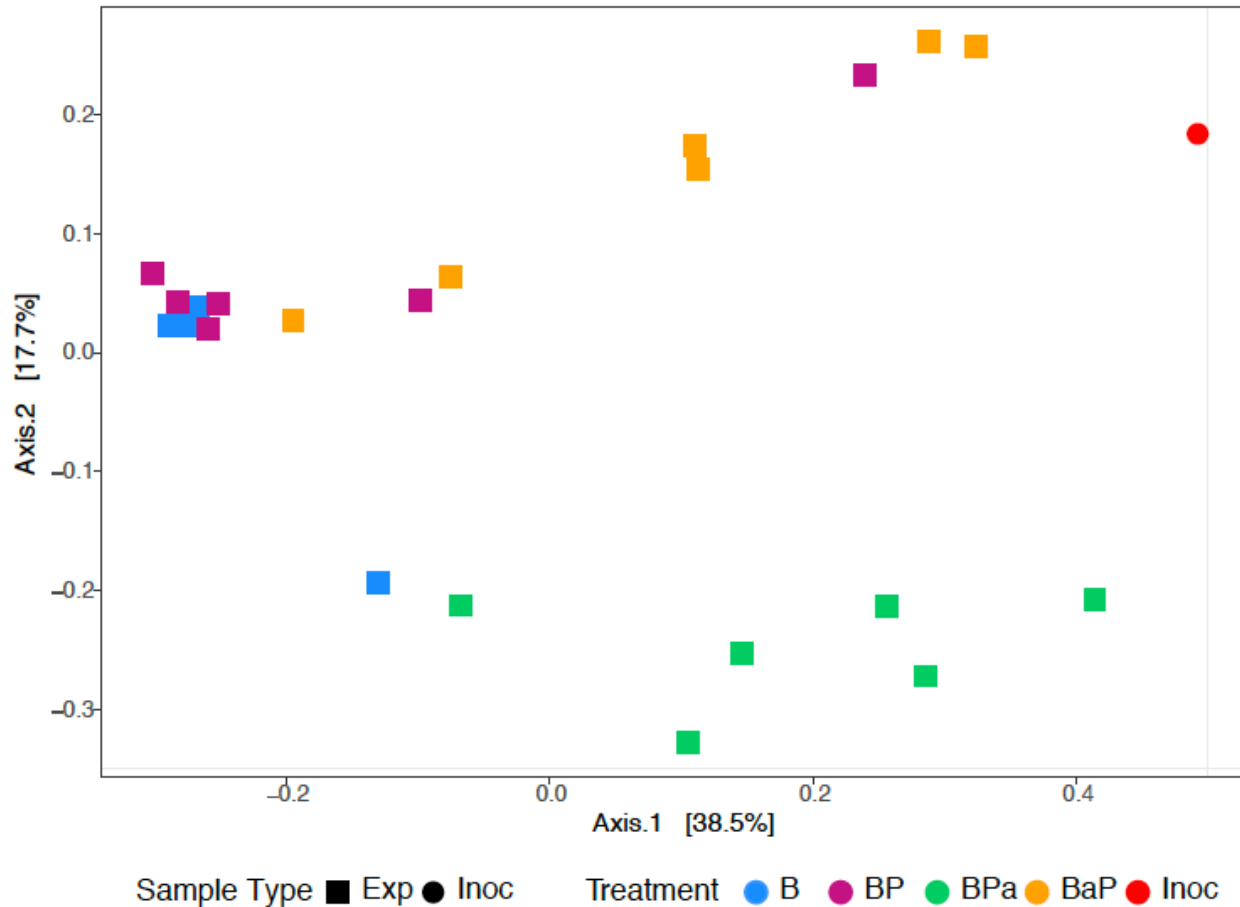
Treatments	Abbreviation
Passaged bacteria	B
Passaged bacteria and passaged phage	BP
Passaged bacteria; ancestral phage	BPa
Ancestral bacteria; passaged phage	BaP



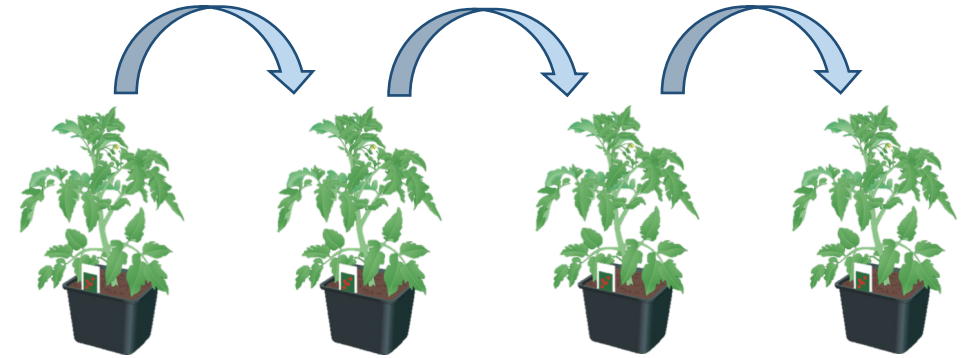
Norma Morella

- Morella & Koskella (unpublished)

# Phages in the plant phyllosphere



Treatment explains 42% of variation (ANOSIM;  $p=0.001$ )



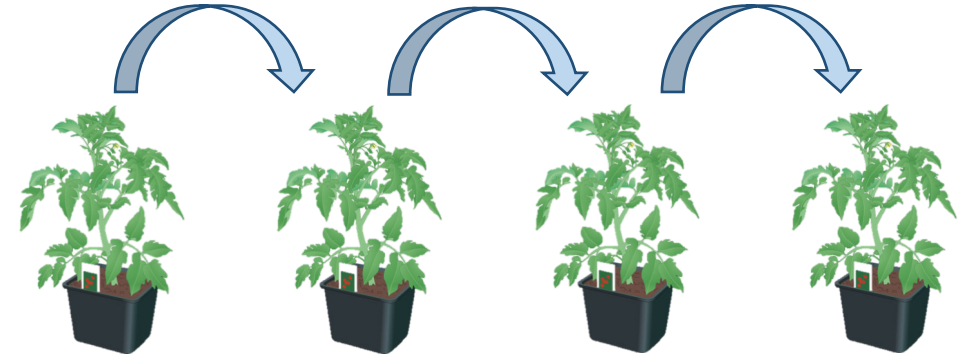
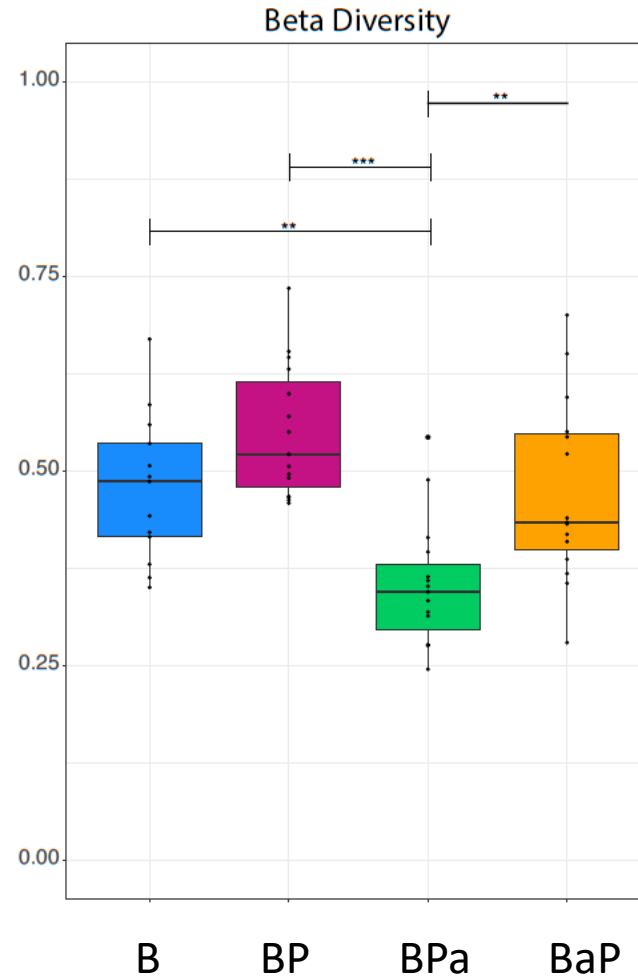
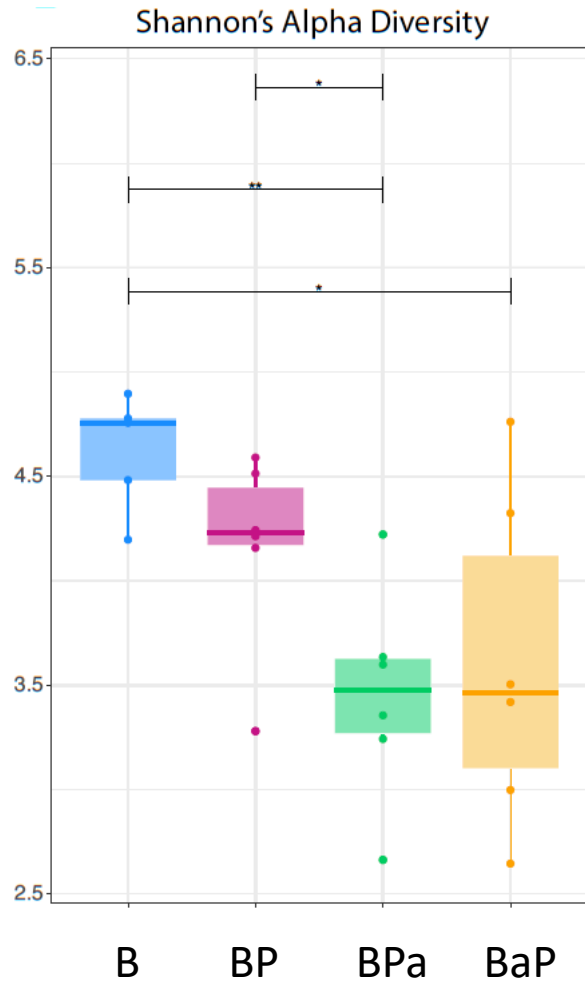
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Norma Morella

- Morella & Koskella (unpublished)

# Phages in the plant phyllosphere



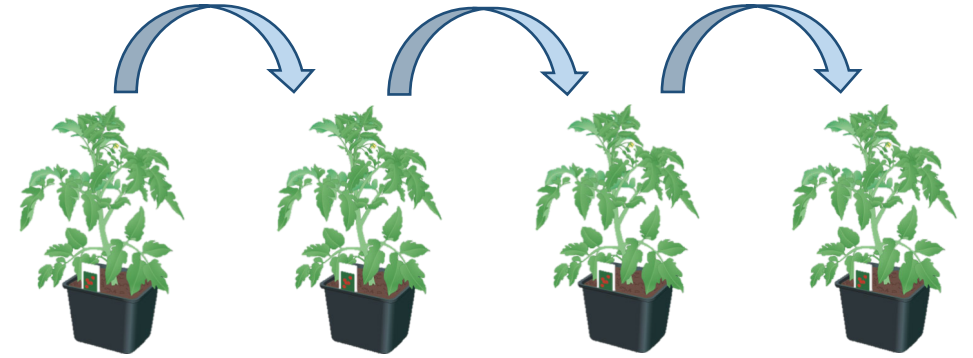
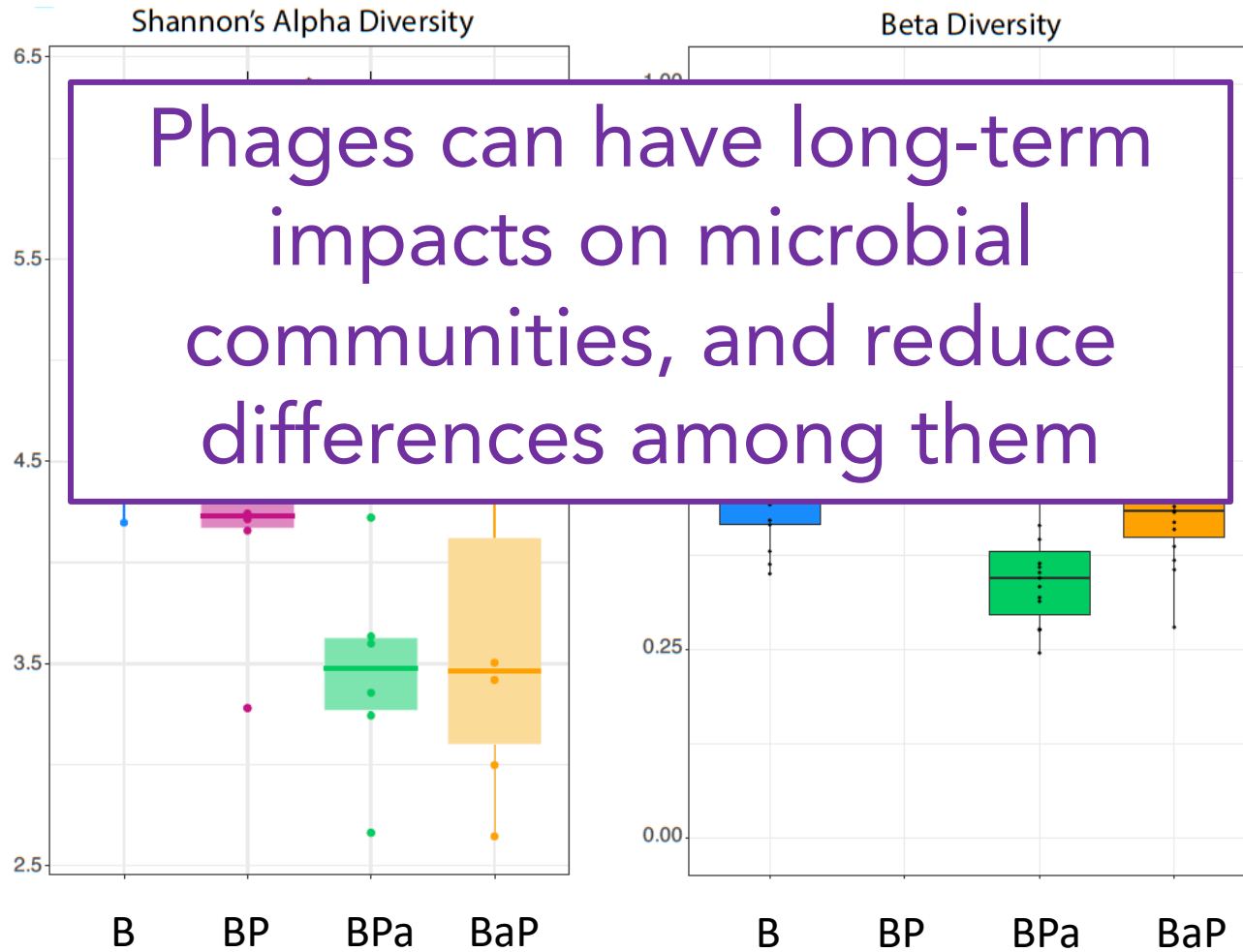
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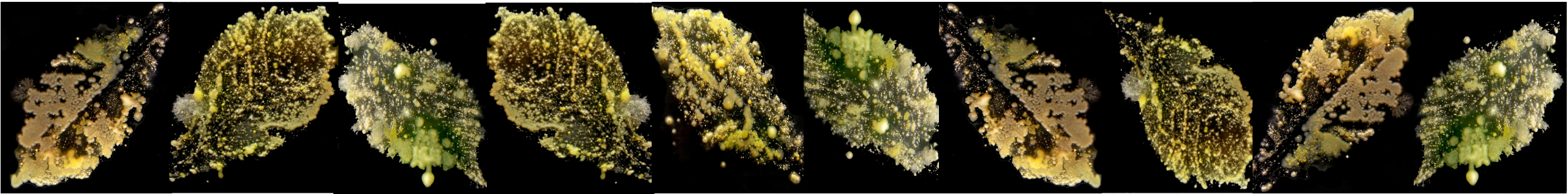
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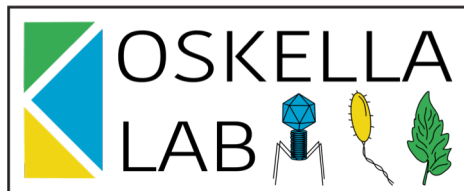
# What Can't We Learn from a Test Tube



Britt Koskella

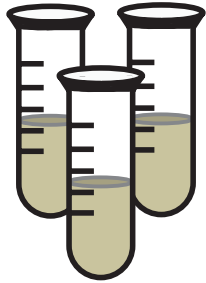
[@bkoskella](https://twitter.com/bkoskella) 

Assistant Professor, Integrative Biology  
UC Berkeley





# Phage-mediated selection



SCIENCE & INNOVATION | THE LOOM

## Eaters of bacteria: Is phage therapy ready for the big time?

BY CARL ZIMMER

1 MINUTE READ



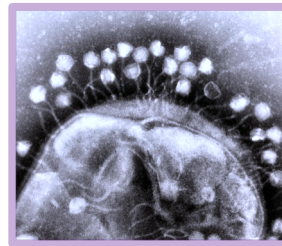
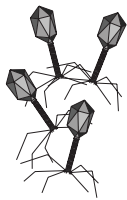
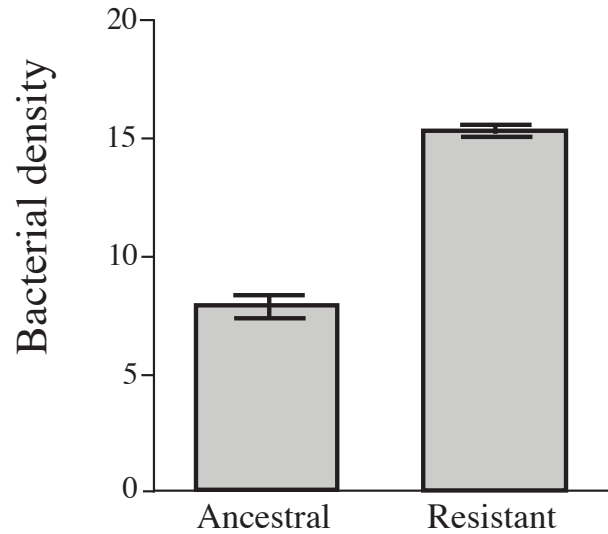
PUBLISHED MAY 20, 2011

Viruses that infect bacteria—known as bacteriophages—are the most abundant living things on Earth. (Yeah, that’s right. I called viruses living things. You gotta problem with that?) For nearly a century, doctors and scientists have dreamed of using them as medical weapons against the microbes that make us sick. Over at the University of Chicago Press’s blog, I discuss [the enduring dream of phage therapy](#) with MIT phage engineer Tim Lu, whom I [profiled](#) last year for *Technology Review*. This is my third UCP blog post to celebrate the publication of [A Planet of Viruses](#); the next and last will appear next Friday. ▣

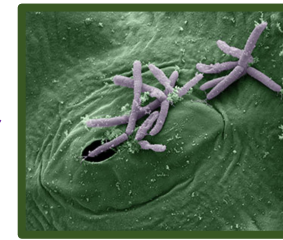


# Phage-mediated selection

(a) *In vitro*, with phage



Bacteriophages



*Pseudomonas syringae*



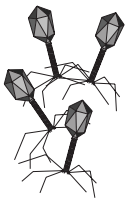
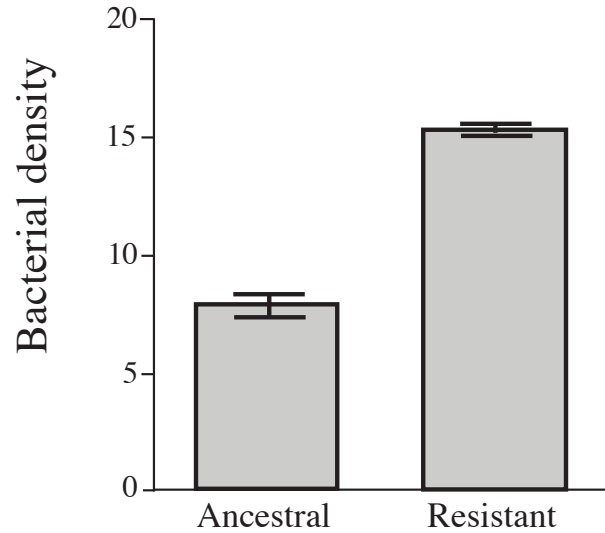
Tomato



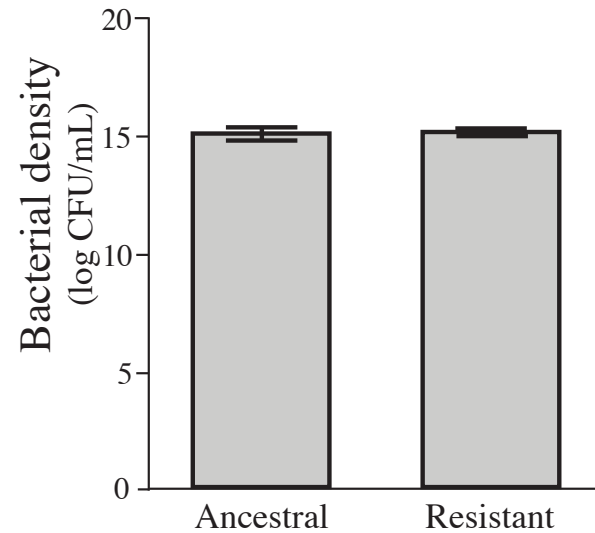
Sean Meaden

# Phage-mediated selection

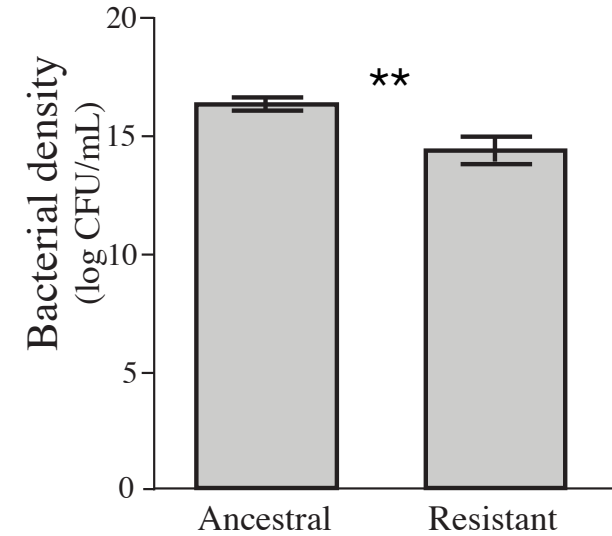
(a) *In vitro*, with phage



(b) *In vitro*, without phage



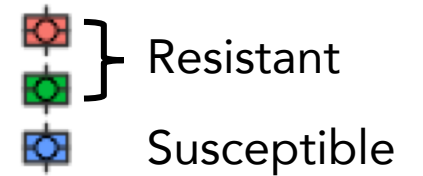
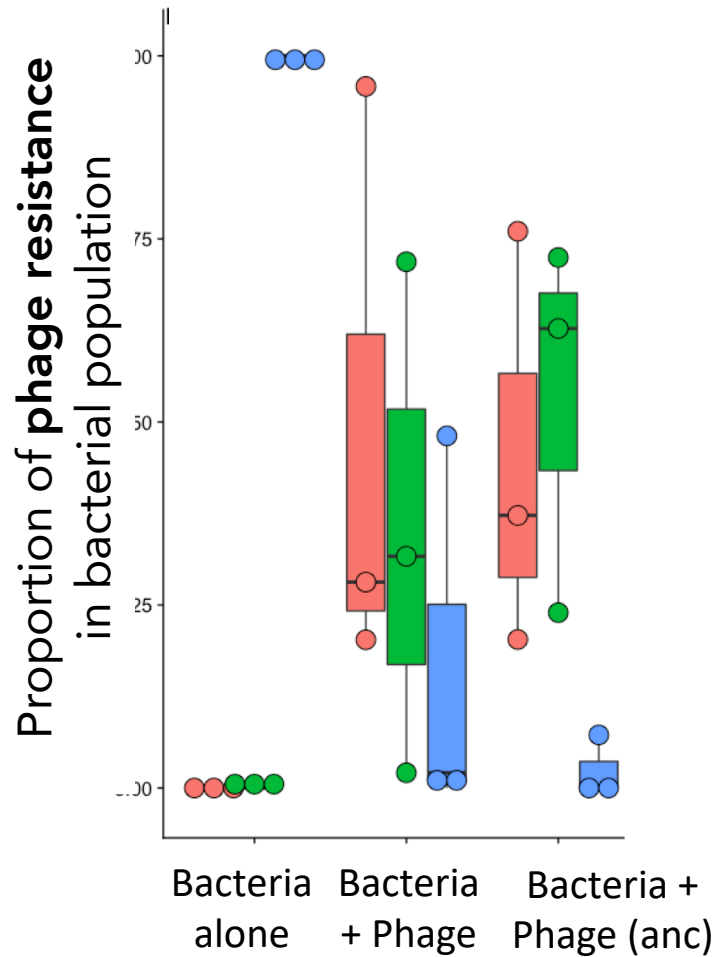
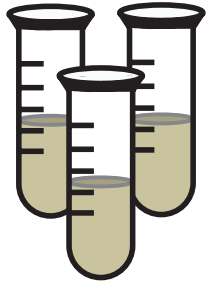
(c) *In planta*, without phage



Sean Meaden

Cost of bacterial resistance to phage is more pronounced in the plant environment

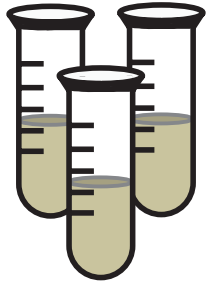
# Phage-mediated selection on plant pathogens



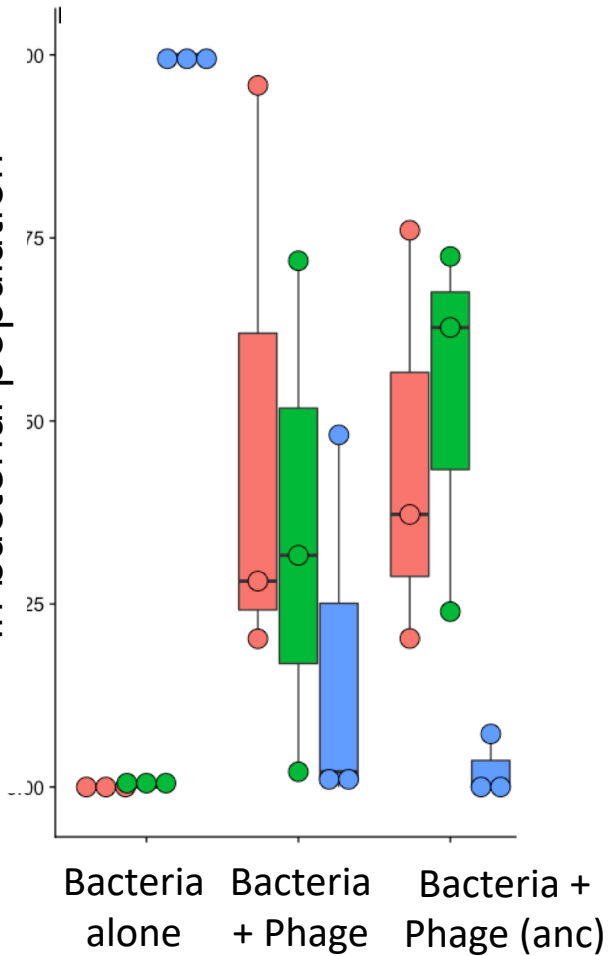
Cathy Hernandez

- Hernandez et al. (*Evolution* 2019)

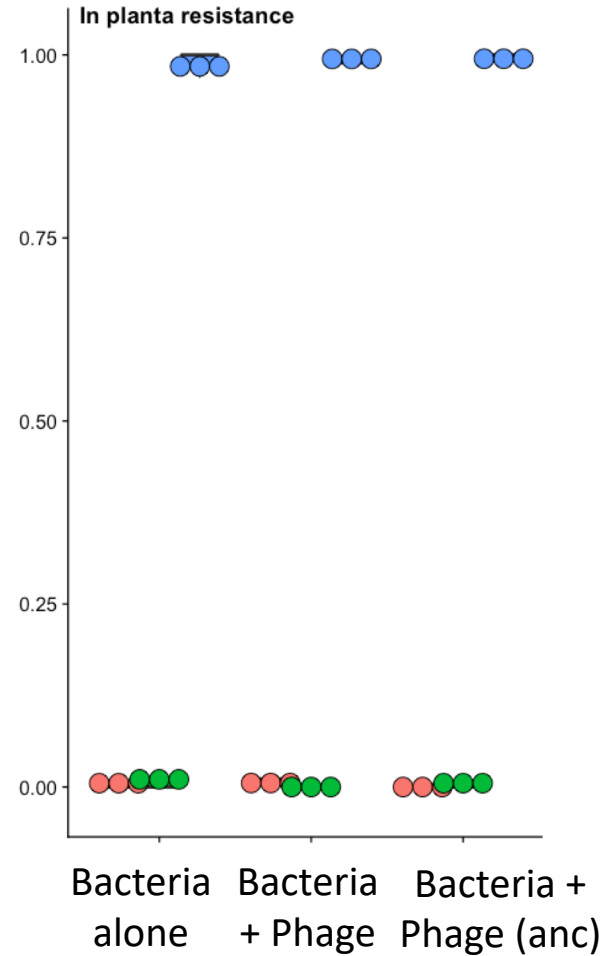
# Phage-mediated selection on plant pathogens



Proportion of phage resistance  
in bacterial population



Proportion of phage resistance  
in bacterial population



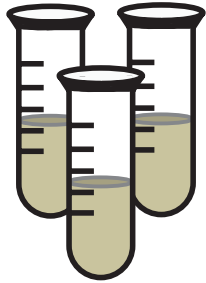
Resistant  
Susceptible



Cathy Hernandez

- Hernandez et al. (*Evolution* 2019)

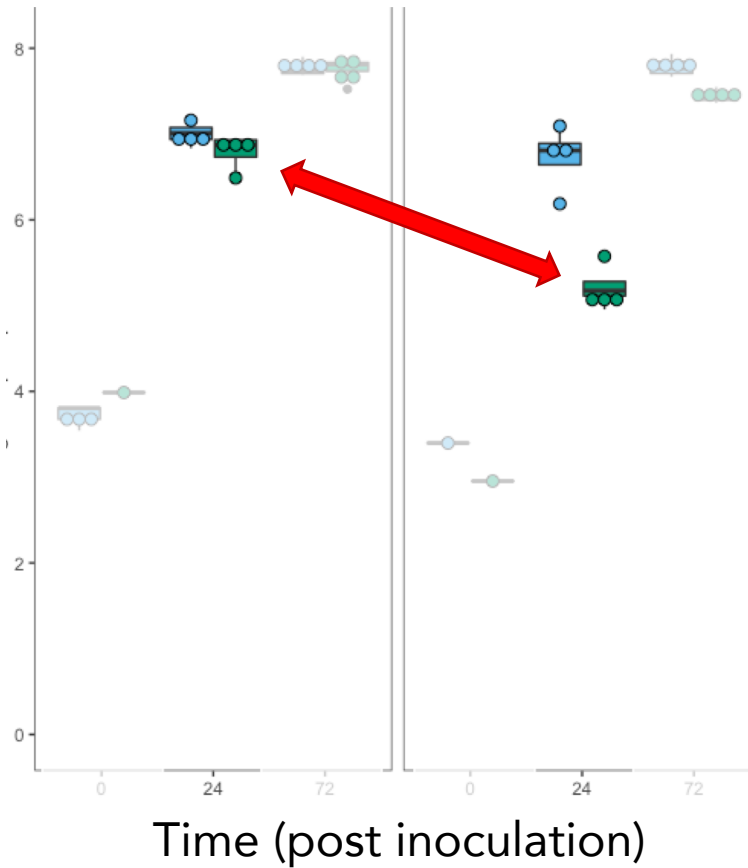
# Phage-mediated selection on plant pathogens



*P. syringae* copy number per mL (ddPCR)

Resistant mutants

Susceptible mutants

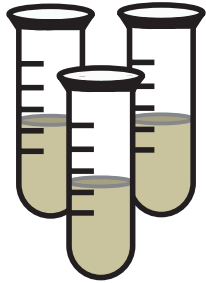


Phage



Cathy Hernandez

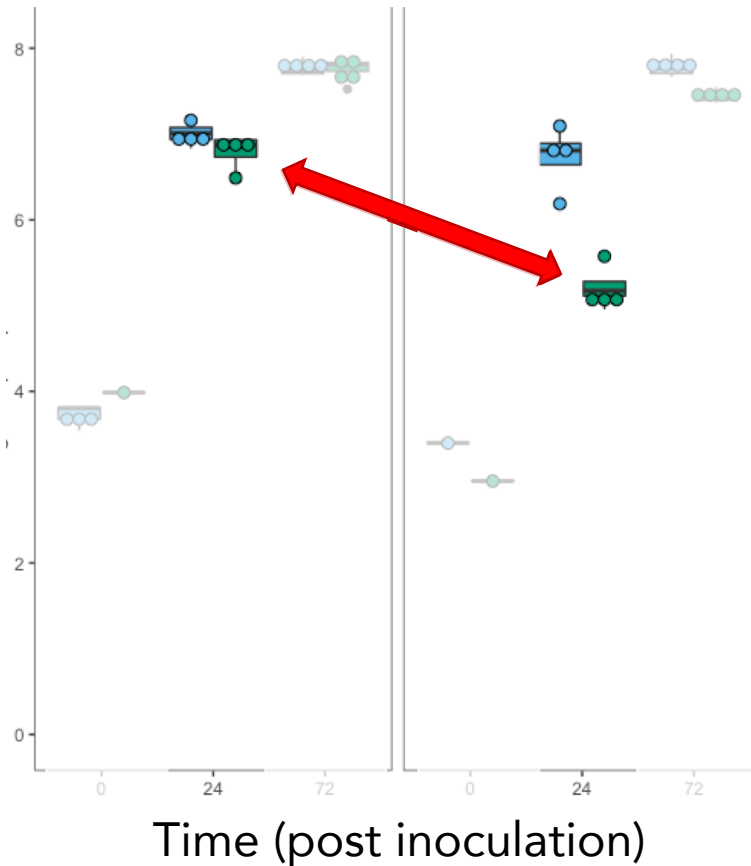
# Phage-mediated selection on plant pathogens



*P. syringae* copy number per mL (ddPCR)

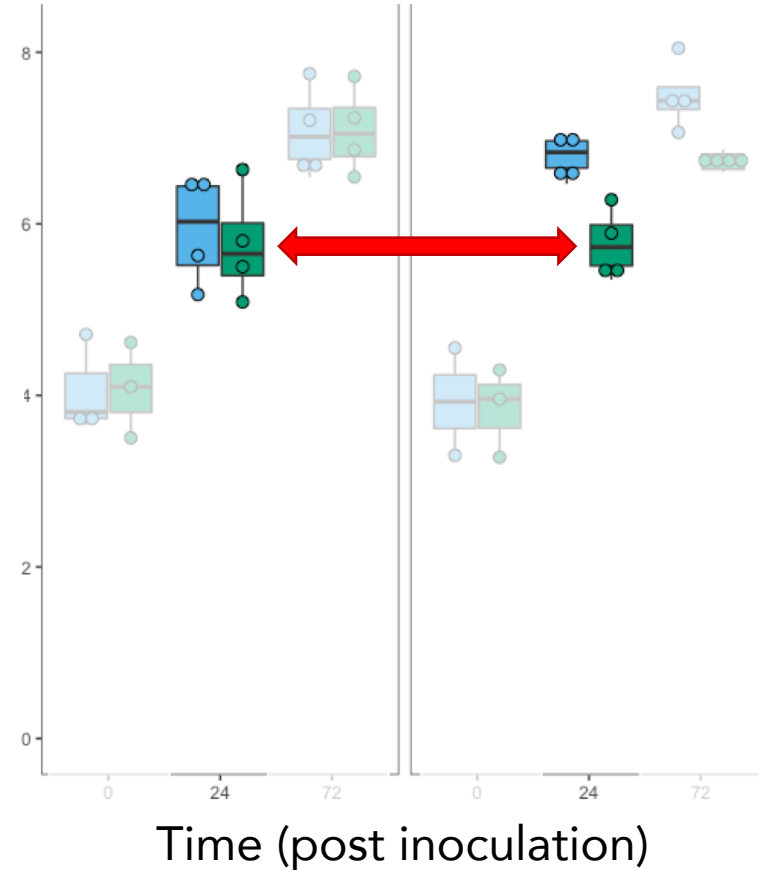
Resistant mutants

Susceptible mutants



Resistant mutants

Susceptible mutants



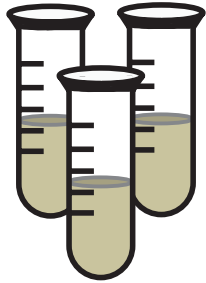
Phage  
No  
Yes



Cathy Hernandez

- Hernandez et al. (*Evolution* 2019)

# Phage-mediated selection on plant pathogens



*P. syringae* copy number per mL (ddPCR)

Resistant mutants

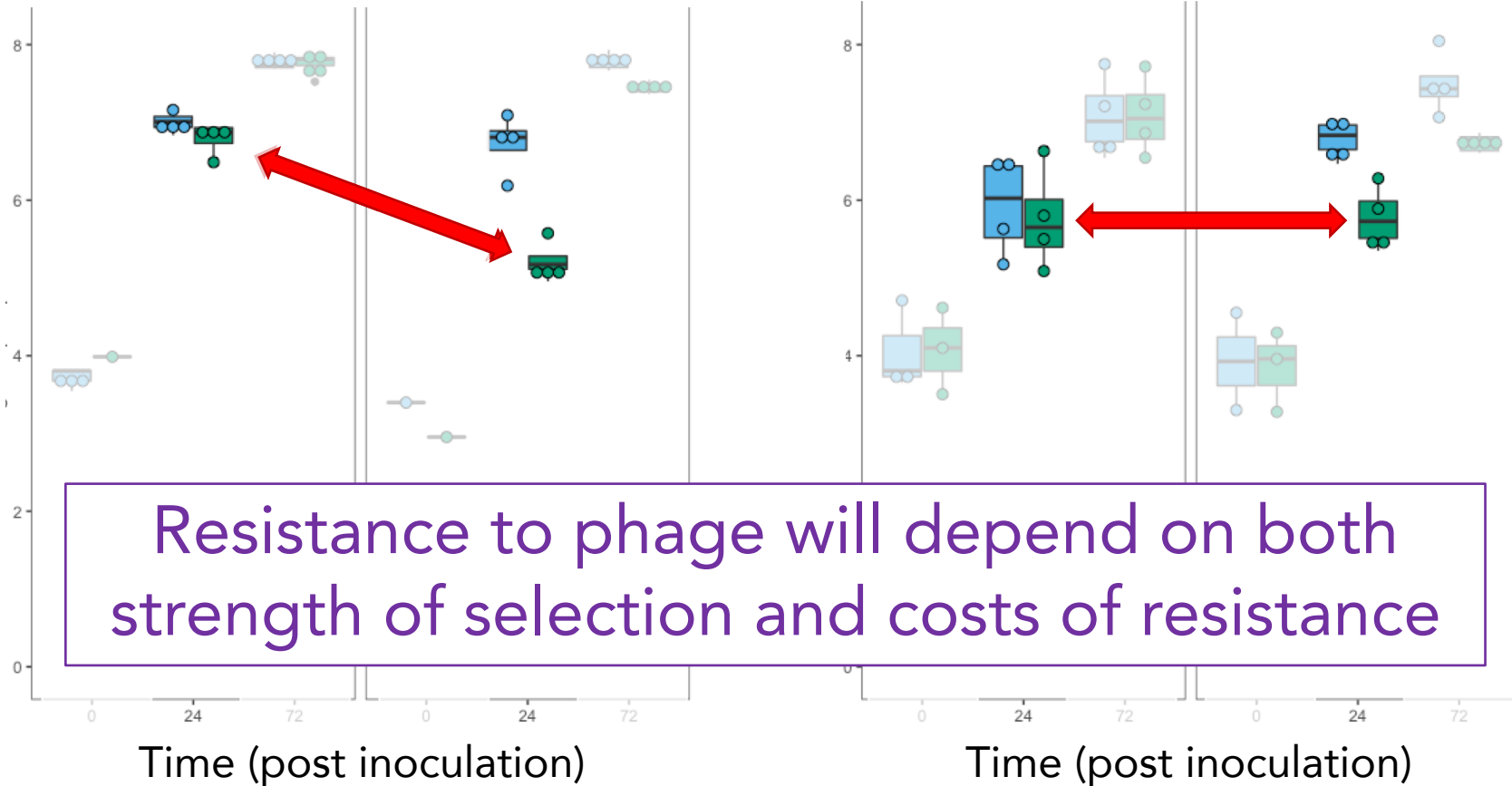
Susceptible mutants

Resistant mutants

Susceptible mutants



Phage  
No  
Yes



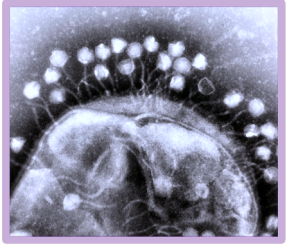
Resistance to phage will depend on both strength of selection and costs of resistance



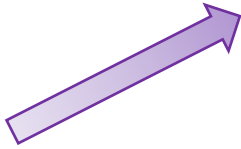
Cathy Hernandez



# Phage-mediated selection



Bacteriophages



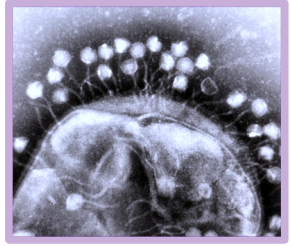
Plant pathogen



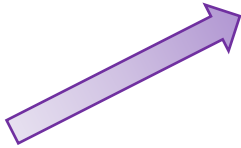
VS



# Bacteria-phage dynamics



Bacteriophages



Plant pathogen

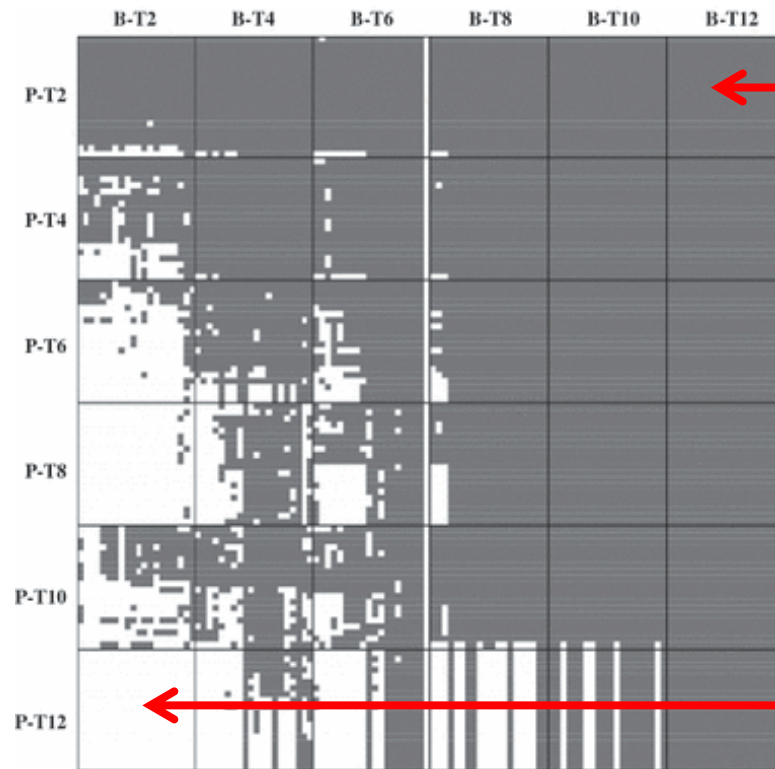


vs



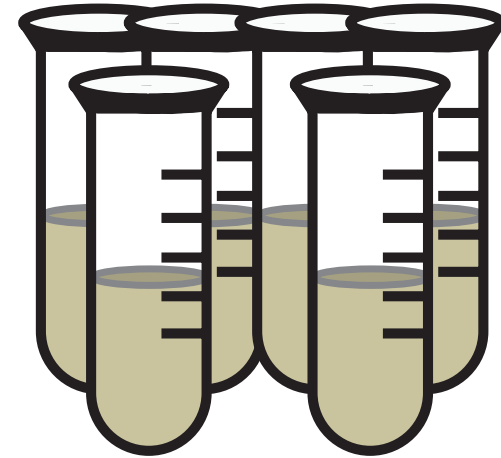
???????

# Bacteria-phage dynamics

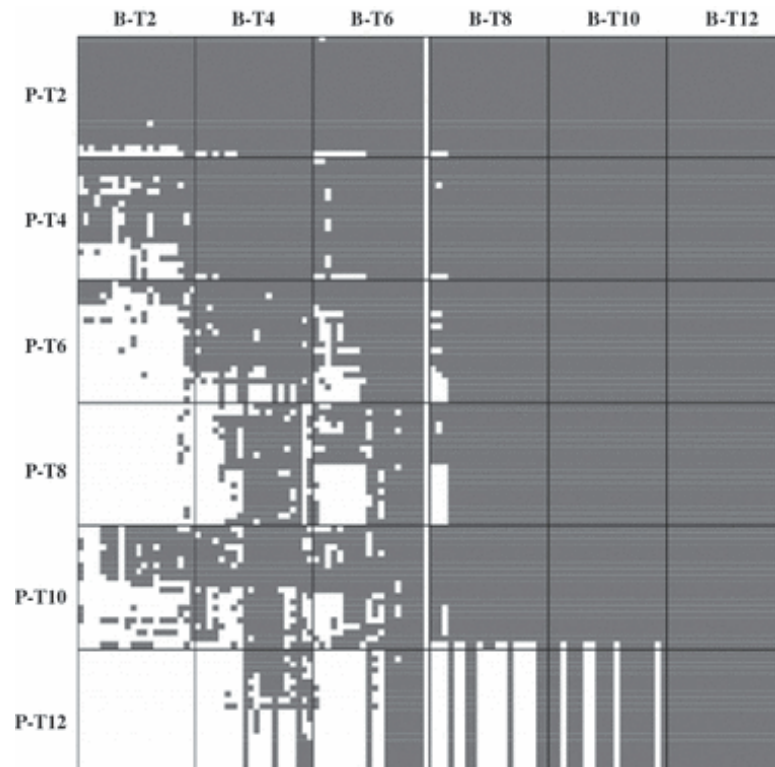


Bacteria increase  
resistance to phage

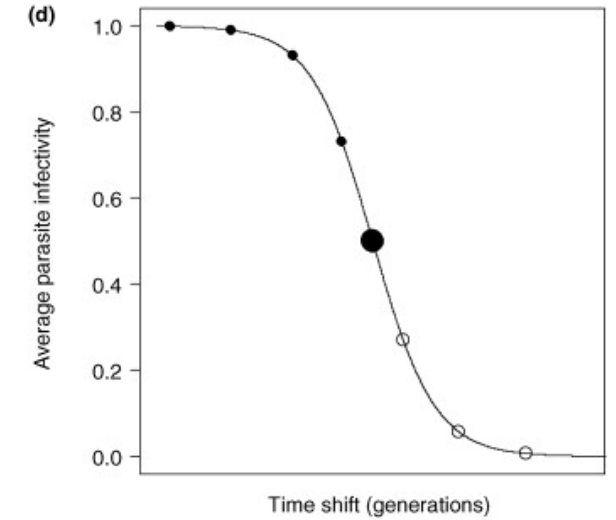
Phages increase  
infectivity to  
bacteria



# Bacteria-phage dynamics



Arms race  
dynamics

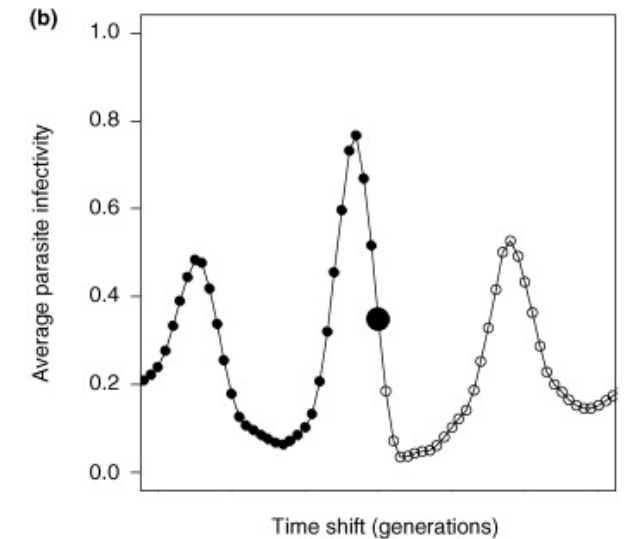
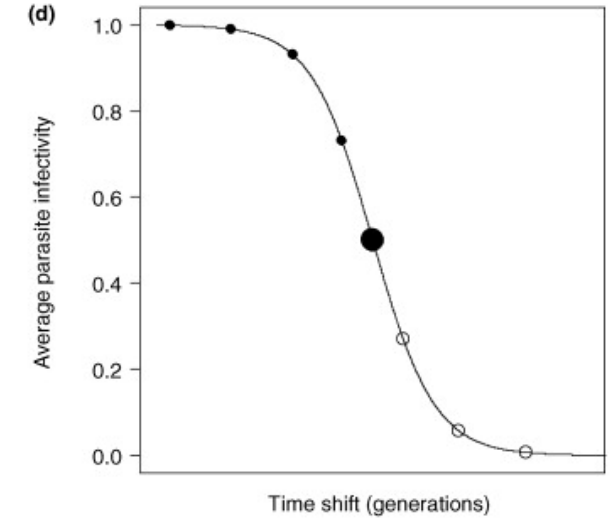


# Bacteria-phage dynamics



Arms race dynamics

Fluctuating selection dynamics



# Bacteria-phage dynamics

*Ecology Letters*, (2011) 14: 635–642

doi: 10.1111/j.1461-0248.2011.01624.x

LETTER

## Host–parasite coevolutionary arms races give way to fluctuating selection

Alex R. Hall,<sup>1\*†</sup> Pauline D. Scanlan,<sup>1†</sup> Andrew D. Morgan<sup>1,2</sup> and Angus Buckling<sup>1,3</sup>

PROCEEDINGS B

[rspb.royalsocietypublishing.org](http://rspb.royalsocietypublishing.org)

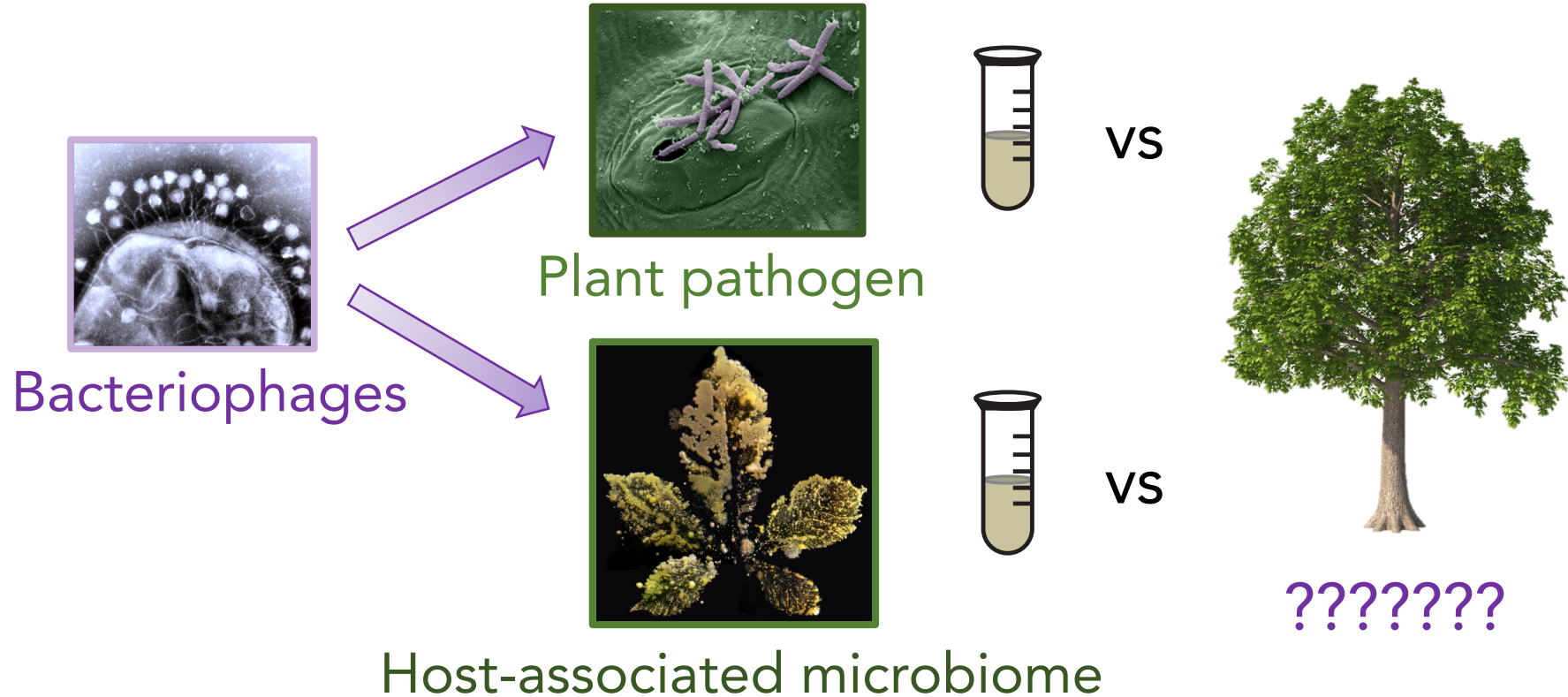
Population mixing promotes arms race host–parasite coevolution

Pedro Gómez<sup>1,†</sup>, Ben Ashby<sup>1,2</sup> and Angus Buckling<sup>1</sup>

-Hall et al. (2011) *Ecol Lett*

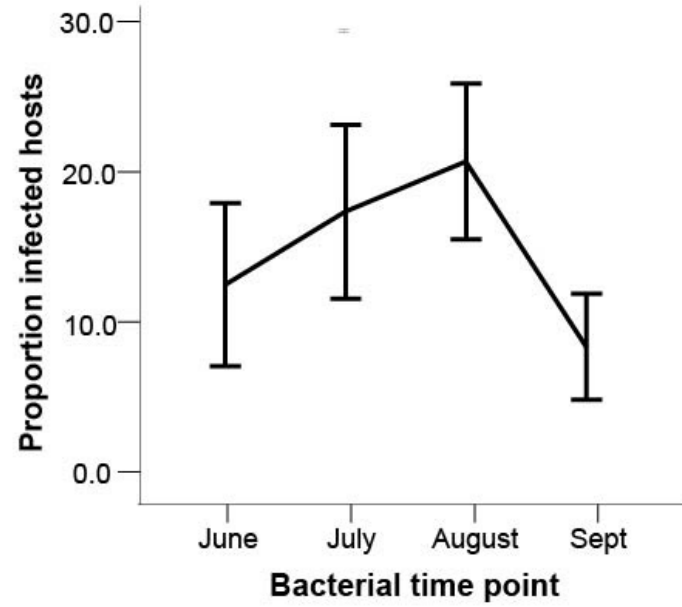
-Gomez et al. (2014) *Proc R Soc B*

# Microbiota-phage dynamics



# Microbiota-phage dynamics

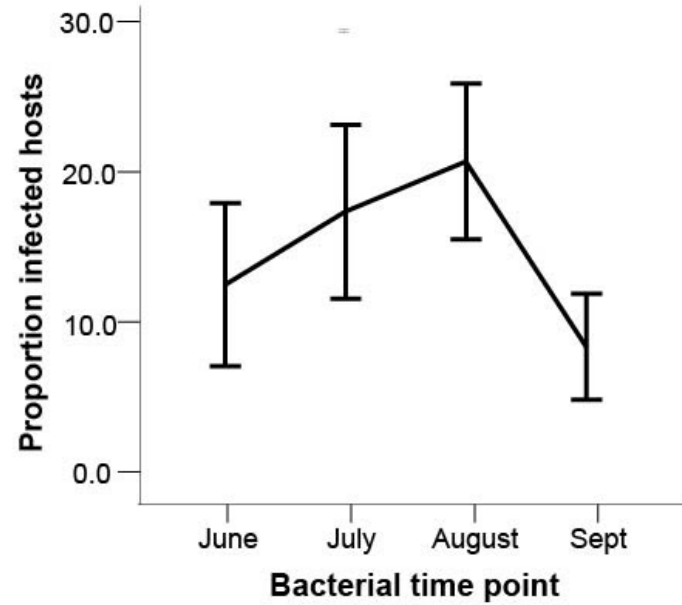
A) Infectivity of phage from September 2011 on time-shifted bacteria (Koskella 2014)



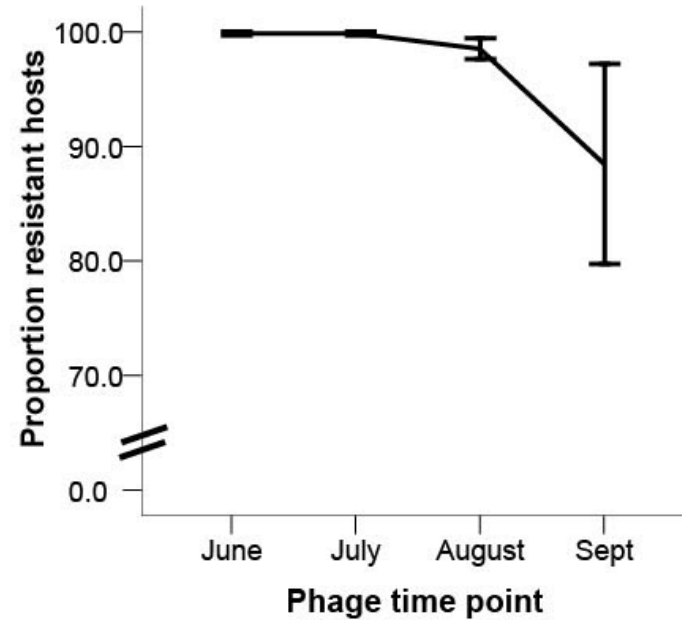


# Microbiota-phage dynamics

A) Infectivity of phage from September 2011 on time-shifted bacteria (Koskella 2014)

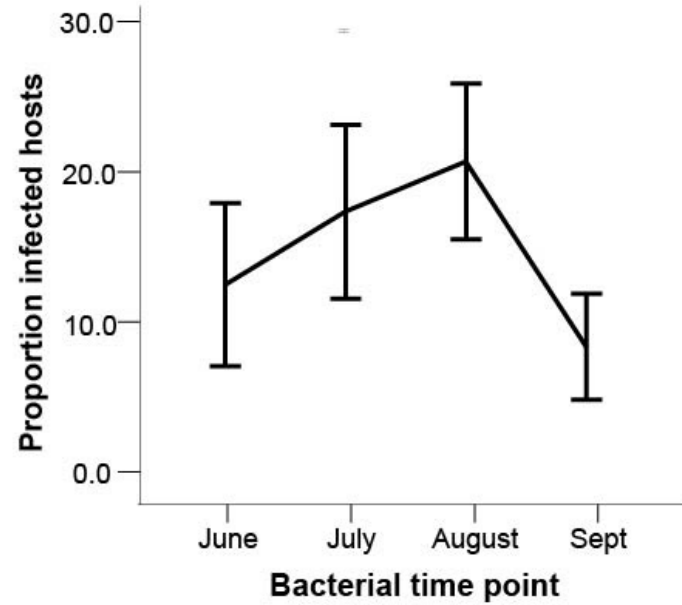


B) Resistance of bacteria from September 2011 to time-shifted phage (Koskella & Parr 2015)

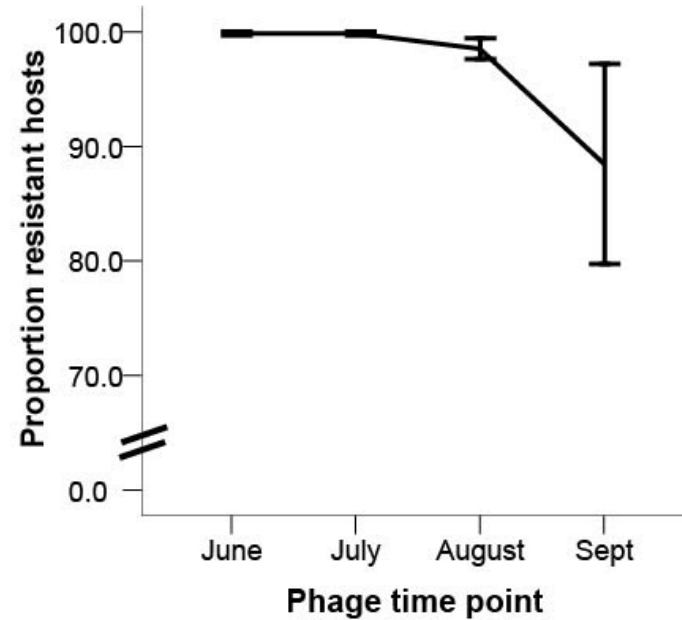


# Microbiota-phage dynamics

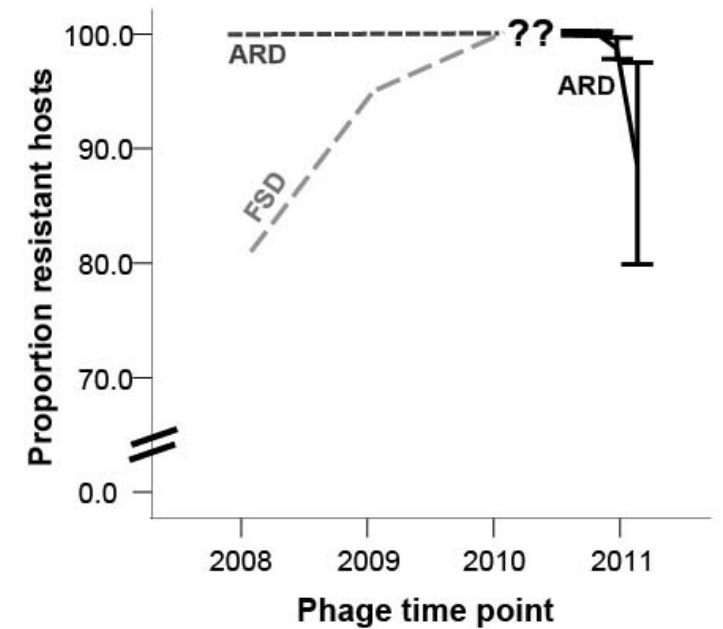
A) Infectivity of phage from September 2011 on time-shifted bacteria (Koskella 2014)



B) Resistance of bacteria from September 2011 to time-shifted phage (Koskella & Parr 2015)

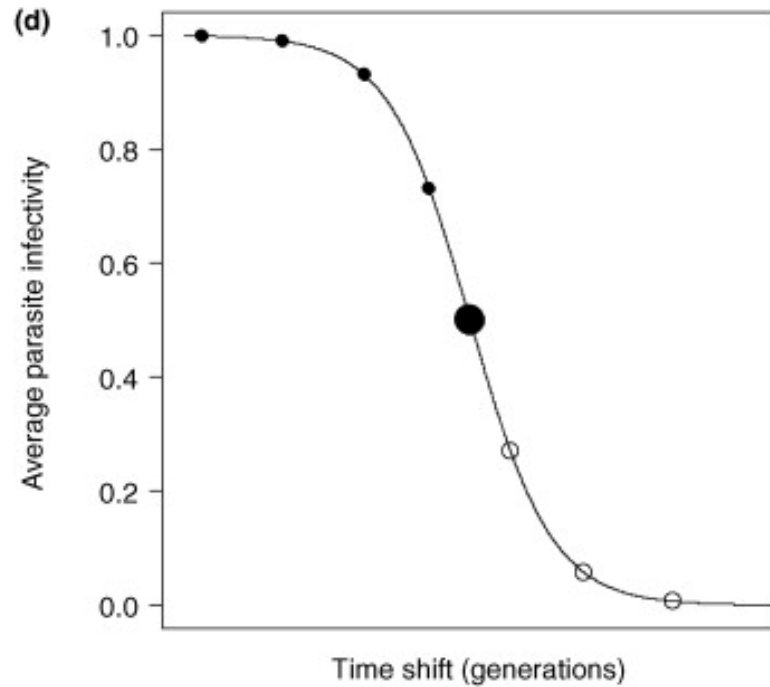


C) Illustration of the importance of timescale in interpretation of time-shift experiments

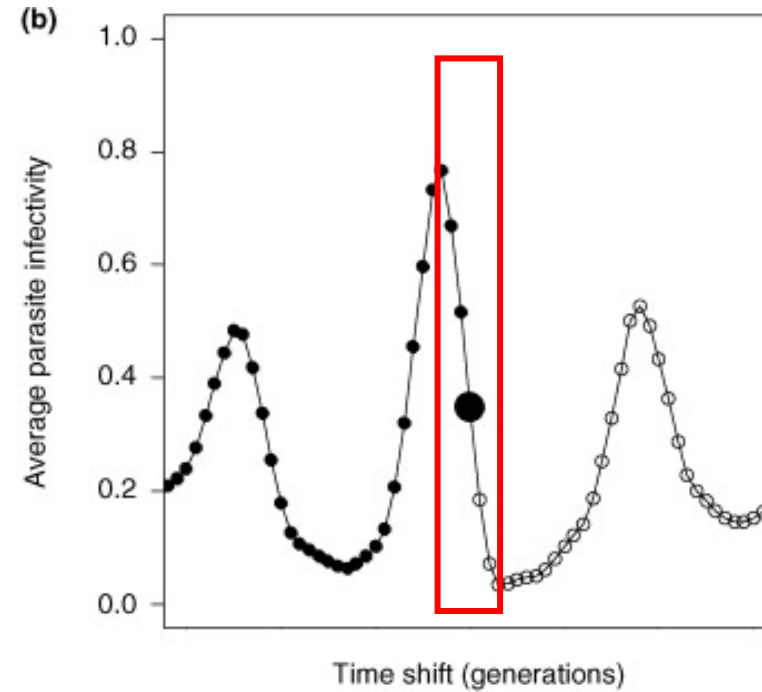


# Microbiota-phage dynamics

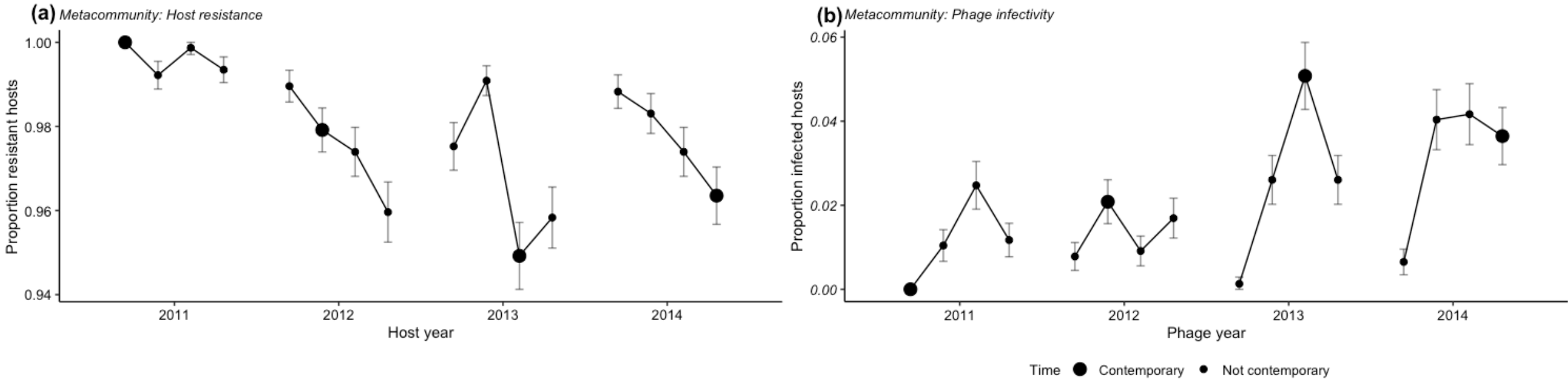
## Arms race dynamics



## Fluctuating selection



# Microbiota-phage dynamics



Nicole Parr

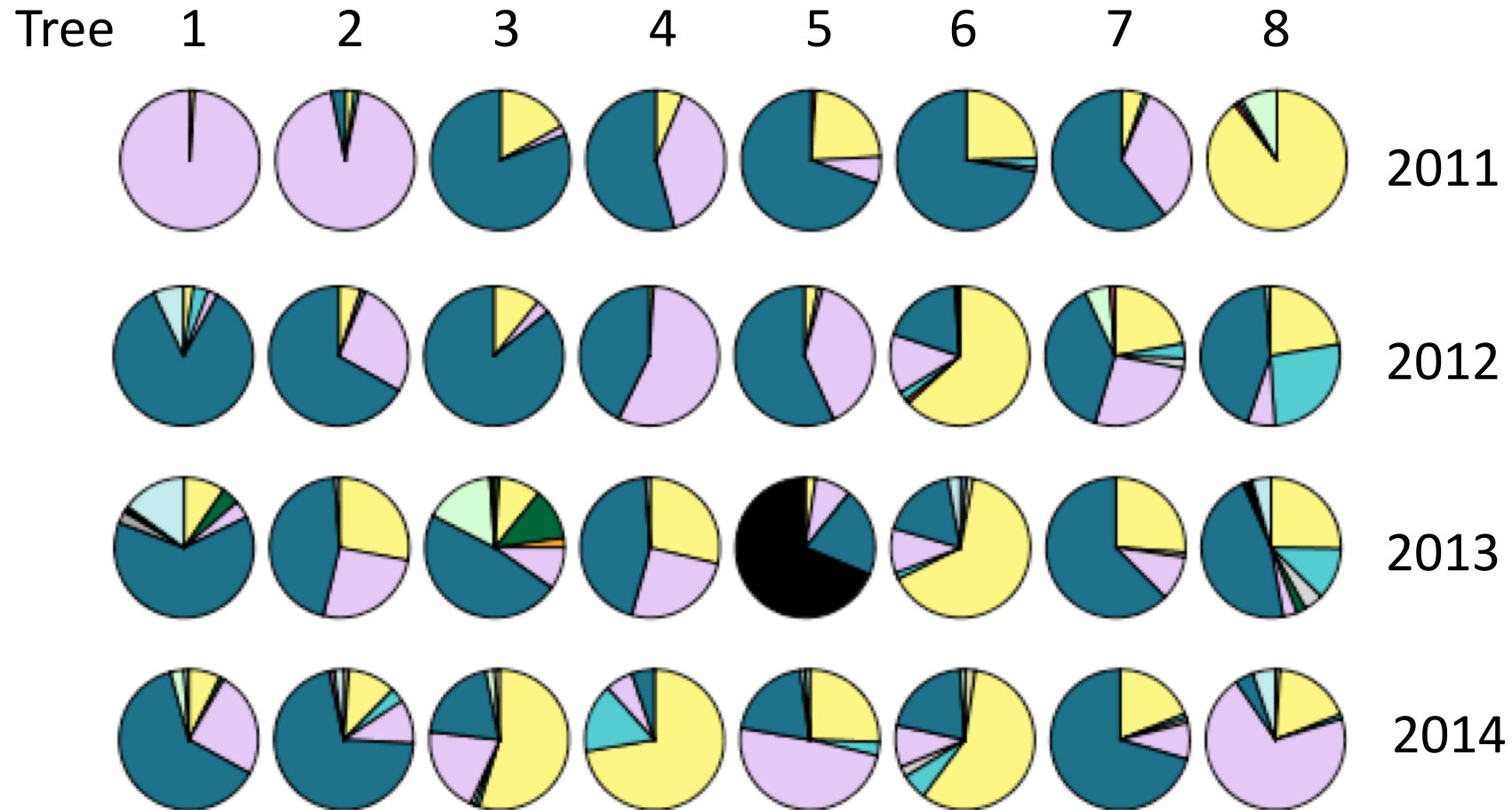


Emily Dewald-Wang

Phage infectivity seems more specific and short-lived than bacterial resistance

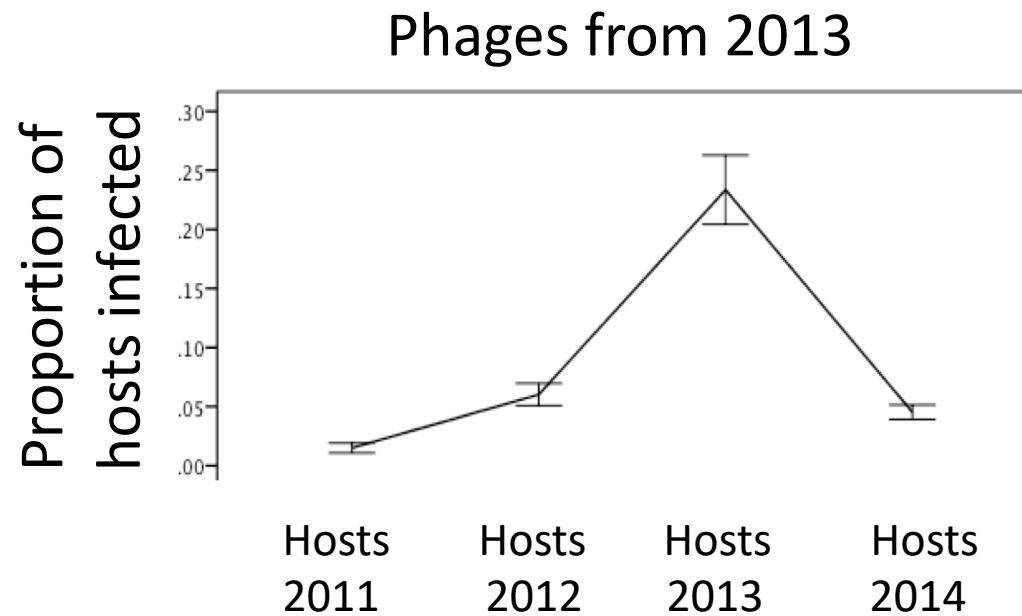
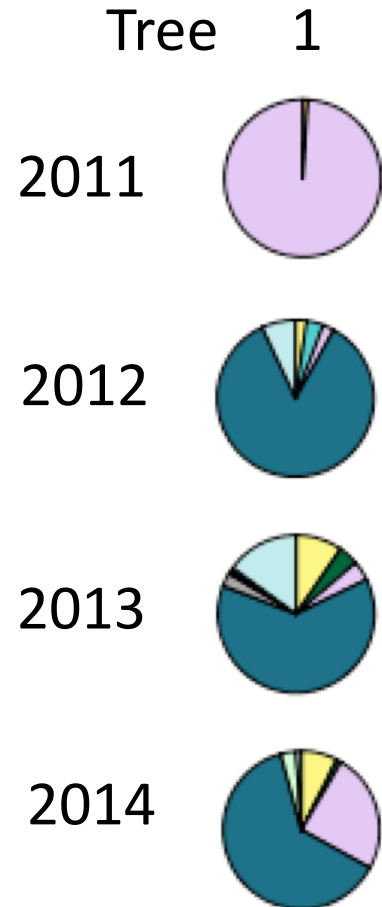
- Dewald-Wang et al. *In prep*

# Microbiota-phage dynamics

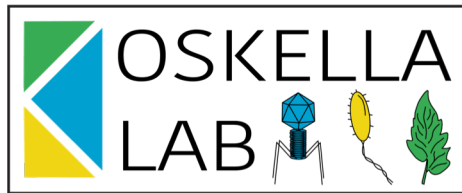


Yellow = *Erwinia*, Pink = *Pantoea*, Blue/Green = *Pseudomonas*, Black = *Stenotrophomonas*

# Microbiota-phage dynamics



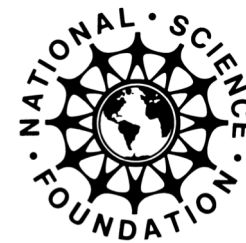
Yellow = *Erwinia*, Pink = *Pantoea*, Blue/Green = *Pseudomonas*, Black = *Stenotrophomonas*



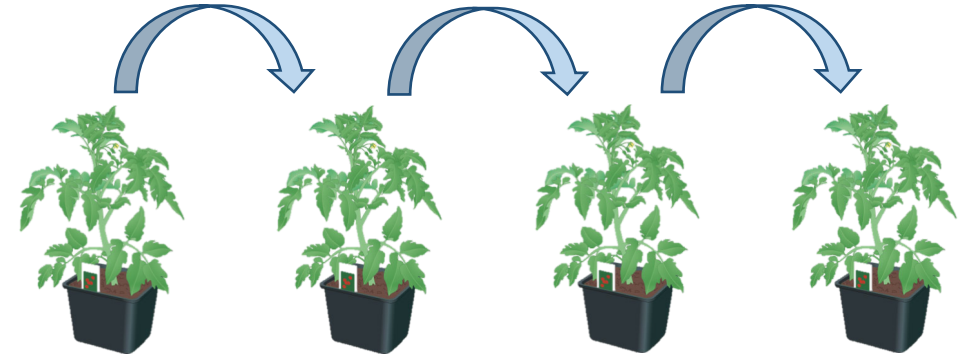
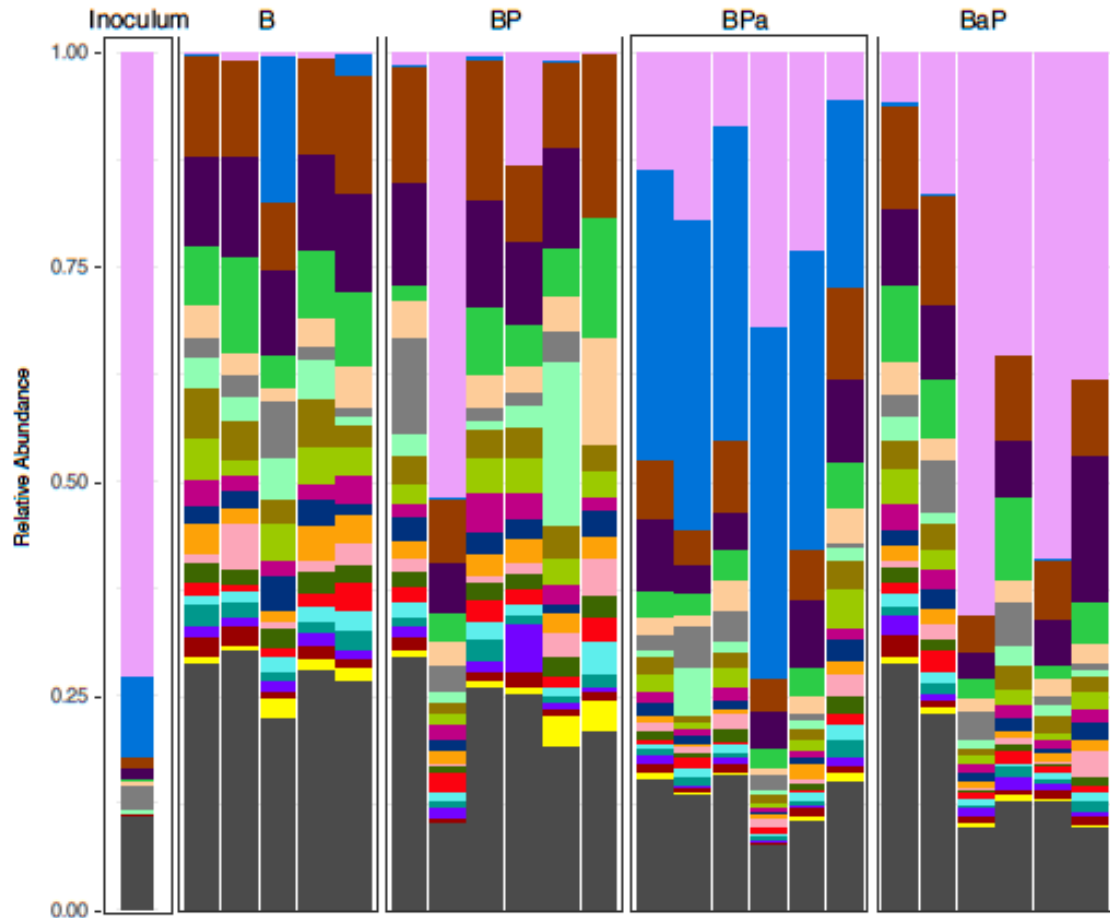
Britt Koskella

@bkoskella 

Assistant Professor, Integrative Biology  
UC Berkeley



# Phages in the plant phyllosphere



Treatments	Abbreviation
Passaged bacteria	B
Passaged bacteria and passaged phage	BP
Passaged bacteria; ancestral phage	BPa
Ancestral bacteria; passaged phage	BaP

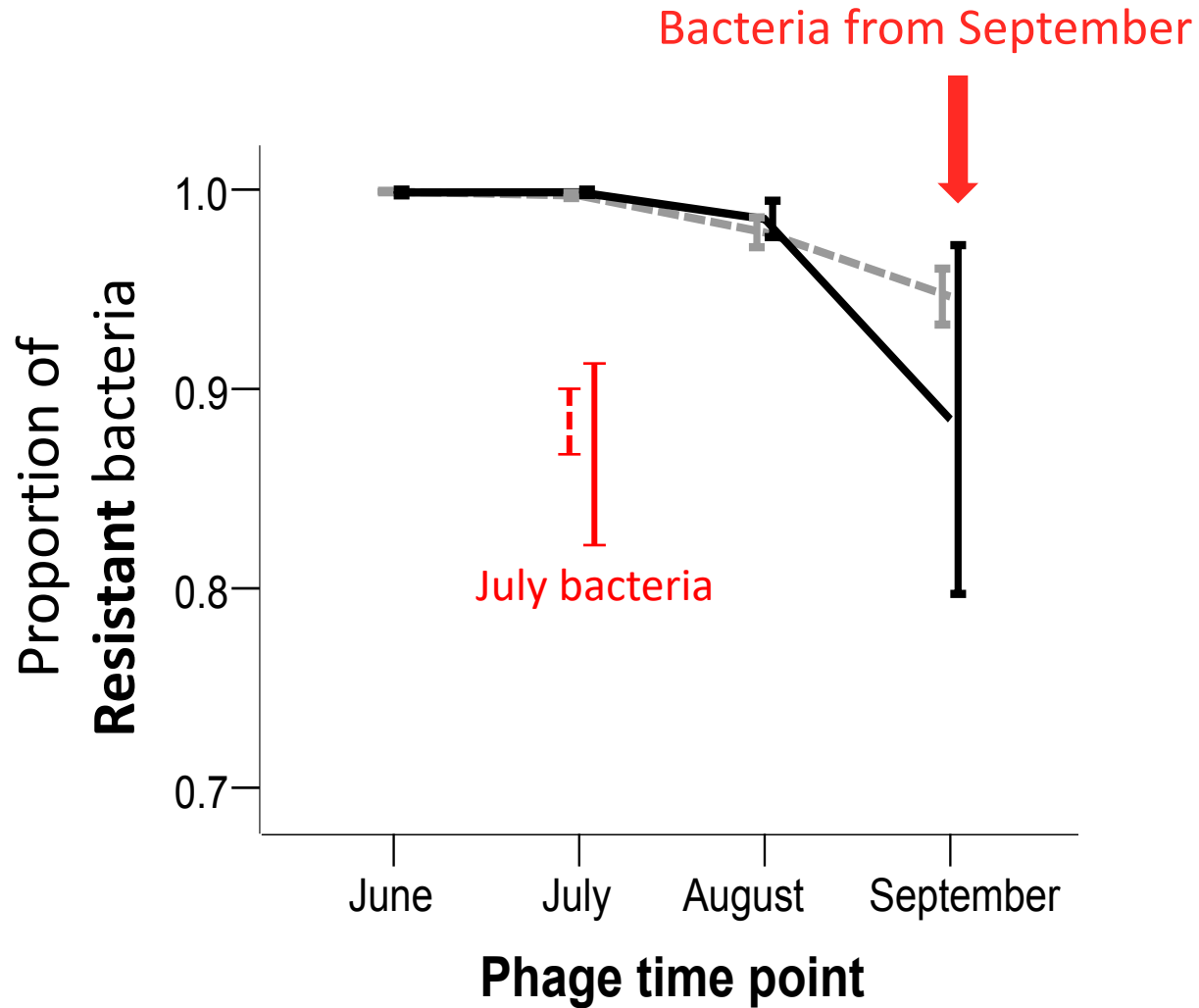


Norma Morella

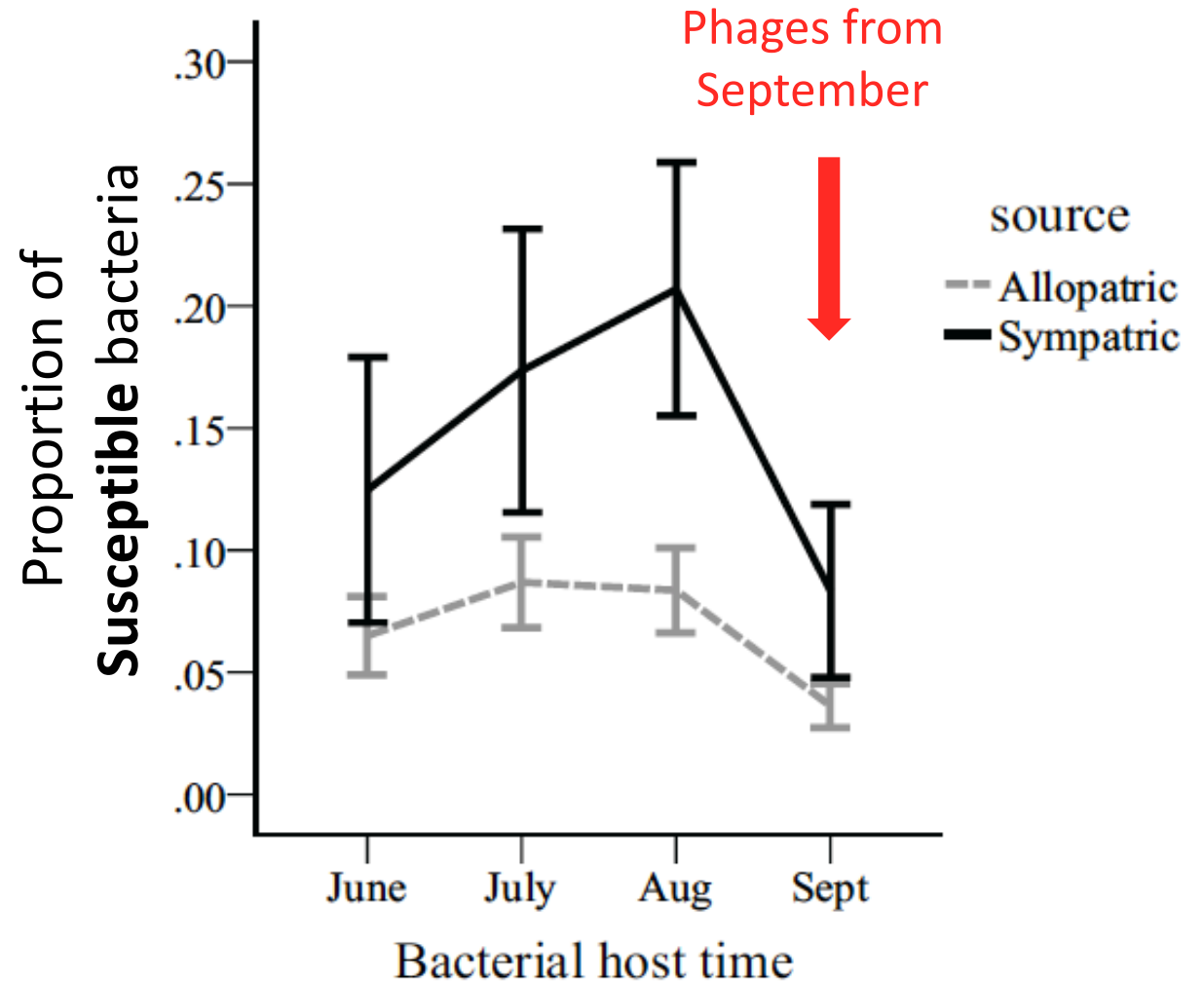
- Morella & Koskella (unpublished)



# Bacteria-phage interactions in the phyllosphere



- Koskella & Parr, Phil Trans B (2015)



- Koskella, American Naturalist (2014)