Setting the agenda in research

Comment

Clouds of dust caused by a fungus engulf a crop field.

Address the growing urgency of fungal disease in crops

Eva Stukenbrock & Sarah Gurr

More political and public awareness of the plight of the world's crops when it comes to fungal disease is crucial to stave off a major threat to global food security.

In October 2022, the World Health Organization (WHO) published its first list of fungal pathogens that infect humans, and warned that certain increasingly abundant disease-causing fungal strains have acquired resistance to known antifungals[1]. Even though more than 1.5 million people die each year from fungal diseases, the WHO's list is the first global effort to systematically prioritize surveillance, research and development, and public-health interventions for fungal pathogens.

Yet fungi pose another major threat to human health – one that has received even less attention than infections in people.

Hundreds of fungal diseases affect the 168 crops listed as important in human nutrition by the Food and Agricultural Organization (FAO) of the United Nations. Despite widespread spraying of fungicides and the planting of cultivars bred to be more disease resilient, growers worldwide lose between 10% and 23% of their crops to fungal disease every year, and another 10–20% post-harvest[2]. In fact, the five most important calorie crops – rice, wheat, maize (corn), soya beans and potatoes – can be affected by rice blast fungus, wheat stem rust, corn smut, soybean rust and potato late blight disease (caused by a water mould oomycete), respectively. And losses from these fungi equate to enough food to provide some 600 million to 4,000 million people with 2,000

Stukenbrock and Gurr (2023) *Nature*

A grainy future? The impact of fungal disease and climate change on wheat

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21st WGIN

Norwich 2024

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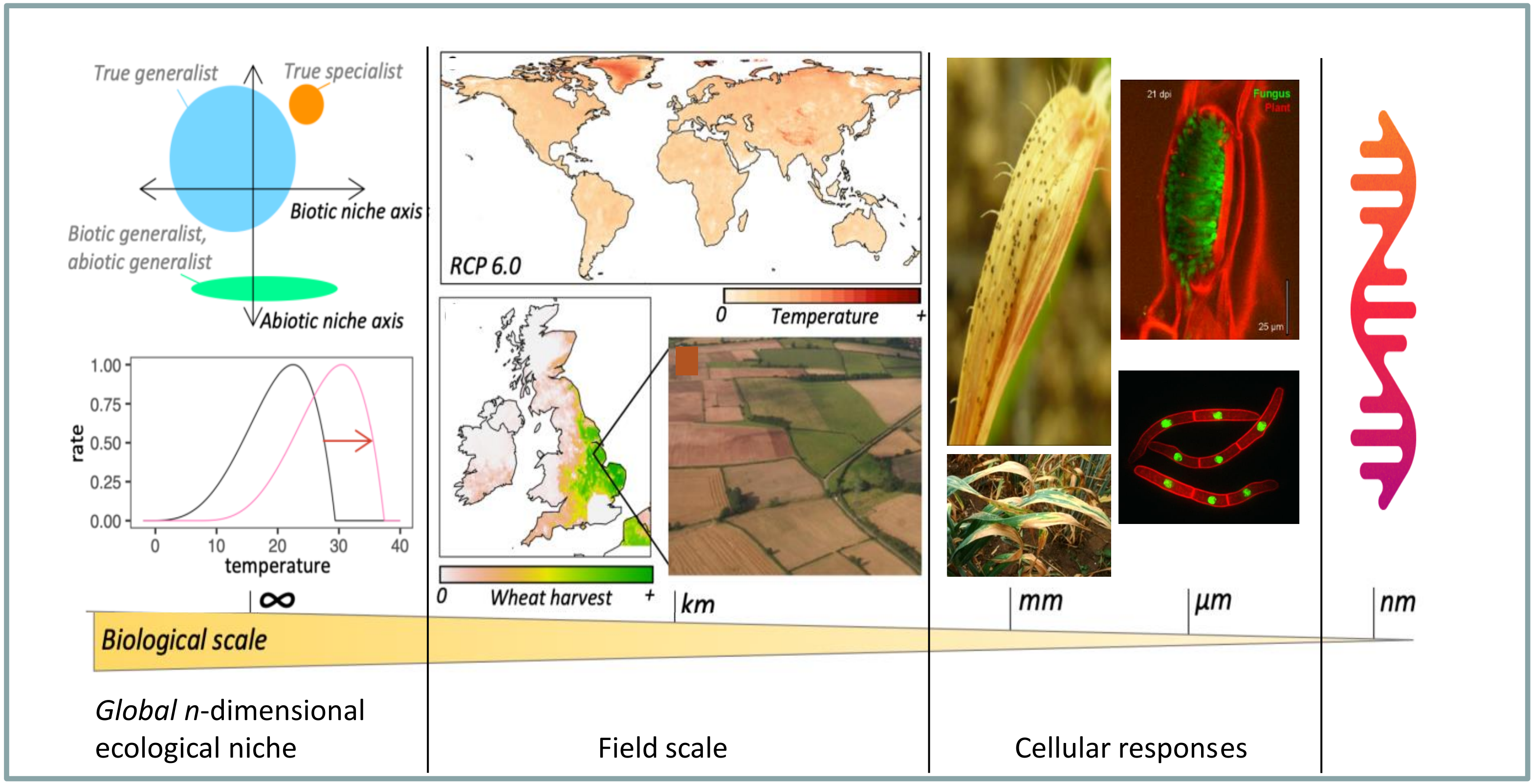
Crop Pests and Pathogens (CPPs) act across Biological Scales



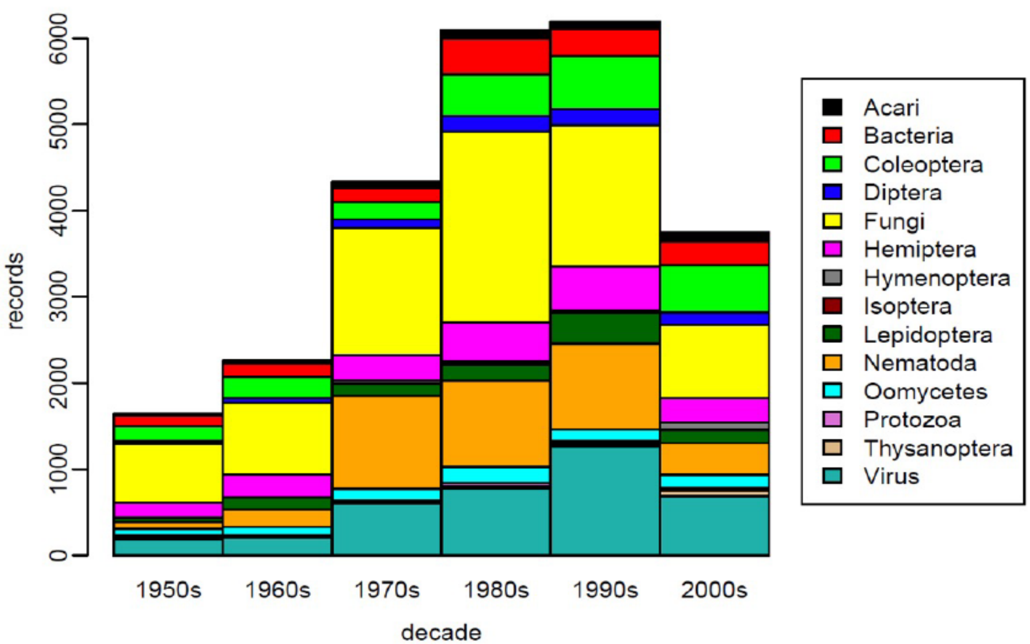
Chaloner *et al* (2020)
Nature Comm

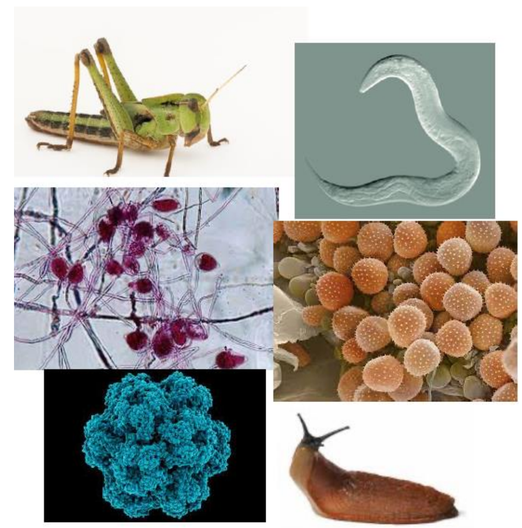
Chaloner *et al* (2021)
Nature Climate Change

Chaloner *et al* (2019)
Phil Trans Royal Soc B

Fones *et al* (2020) *Nature Food*
Stukenbrock and Gurr (2023) *Nature*

Crop Pests and Pathogens (CPPs)





Fisher *et al* (2012) *Nature*
Bebber *et al* (2013*) Nature Climate Change*

Fungi & Oomycetes - Major threats to global food security

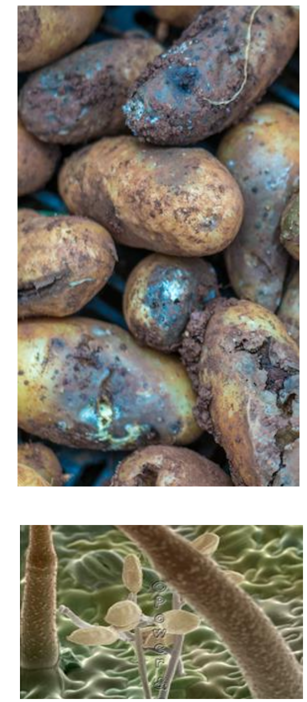
Wheat Stem Rust

Rice Blast

Corn Smut

Soybean Rust

Potato Late Blight



Annual losses sufficient to feed ~ 600 – 4,000 million people
2000 kCal per day for a year

Fisher *et al* (2012) *Nature*
Fones *et al* (2020) *Nature Food*

Septoria tritici blotch (STB) challenges temperate grown wheat in UK

Wheat Stem Rust

Zymoseptoria tritici

Annual wheat yield worth £2.4 billion (2023)
losses to STB 5-10%

Fones and Gurr (2015) *Fungal Genetics & Biology (FGB)*
Fones *et al* (2017) *Fungal Genetics and Biology*

What do we know about crop pests and pathogens (CPP)?

- Where are they?
- Are they on the move: in concert with climate change?
- What are the greatest threats?
- When and where will they occur?

- Can we run predictive distribution models?
- Can we tailor our models across the scales of sizes (global, field, crop and pathogen?)

- *What can we do to prevent disease?*

Bebber and Gurr (2015) *Fungal Genetics and Biology*
Steinberg and Gurr (2020) *Fungal Genetics and Biology*
Steinberg *et al* (2020) *Nature Comms*

Our work: - Two approaches to model crop pests and pathogens

Statistical

- Correlative
- Large Scale
- Static
- Minimal Assumptions

Mechanistic

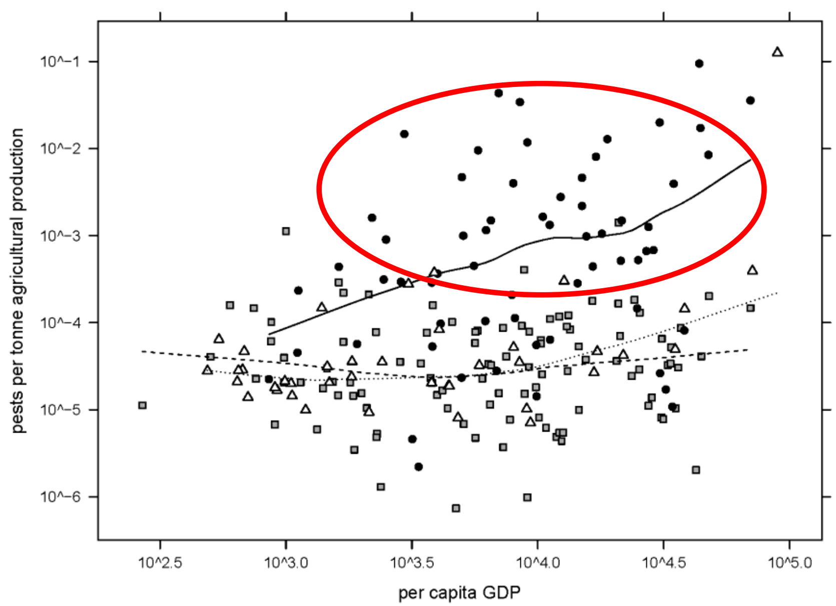
- Process-based
- Small Scale
- Dynamic
- "Forward" Modelling
- Extrapolation

Dormann *et al* (2012) *J of Biogeography* "Correlation & process in species distribution modelling"

Global distribution & movement of crop pests and pathogens …

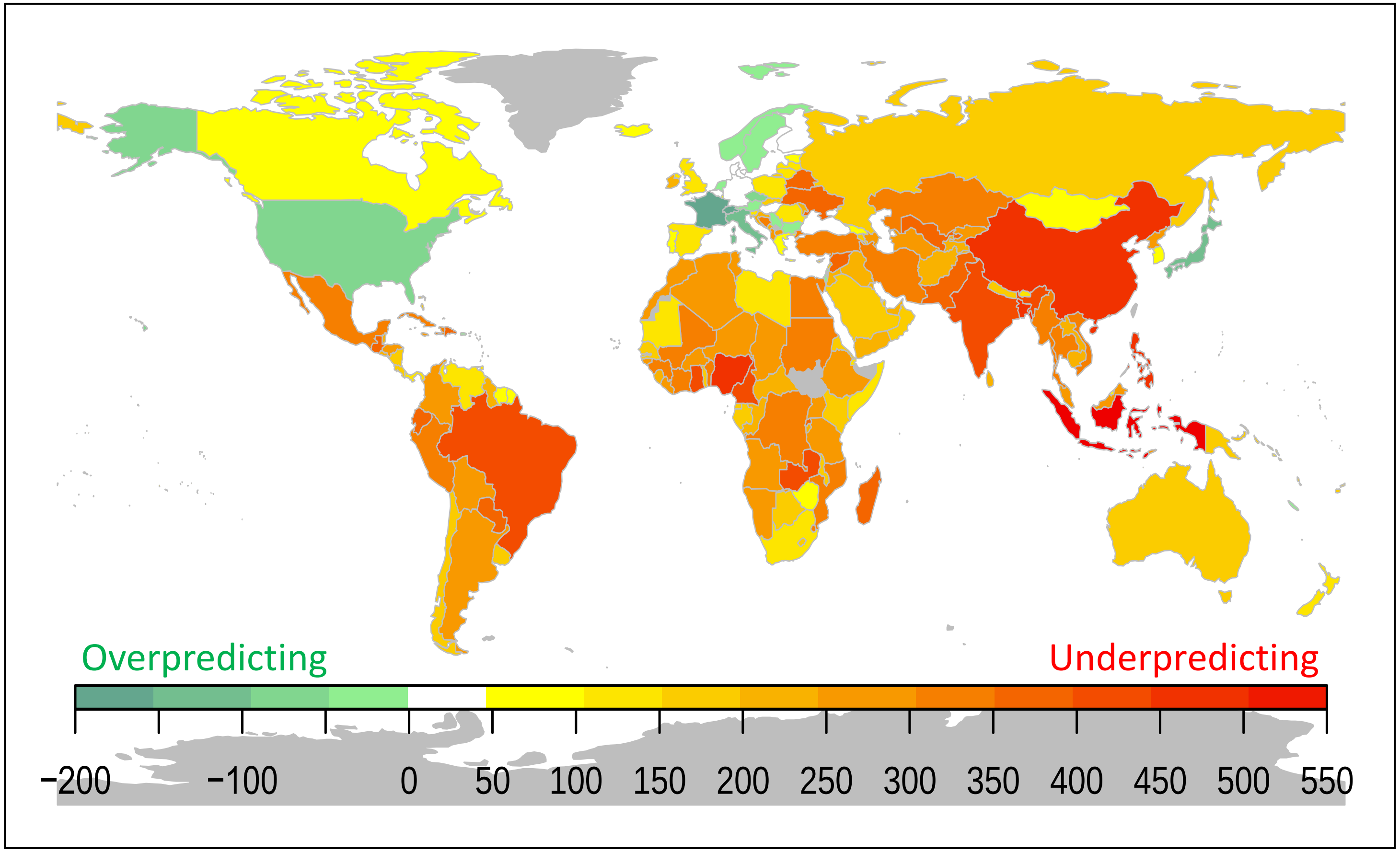
What is the global distribution of pests and pathogens?

Outcome: More pests on islands than in land-locked nations….



Each point is a country
Islands ●
Land-locked △
Coastal □

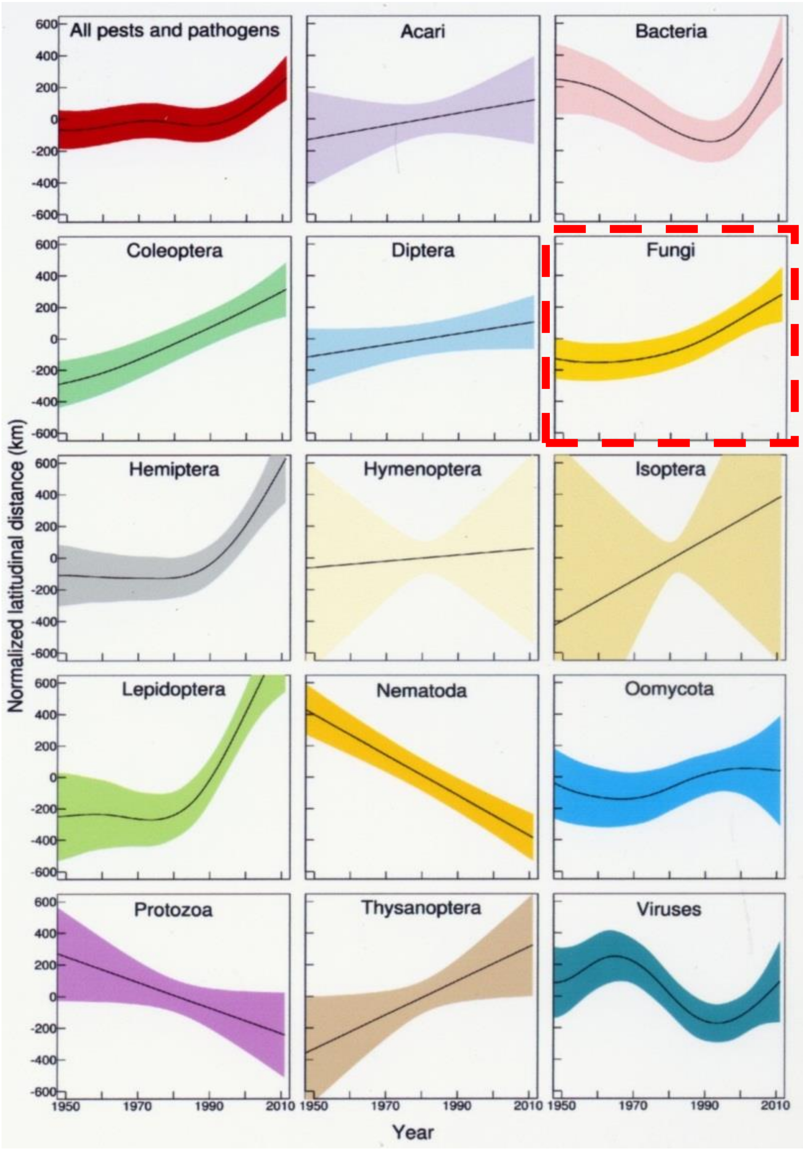
Outcome: Estimation of the accuracy of global pathogen burden predictions

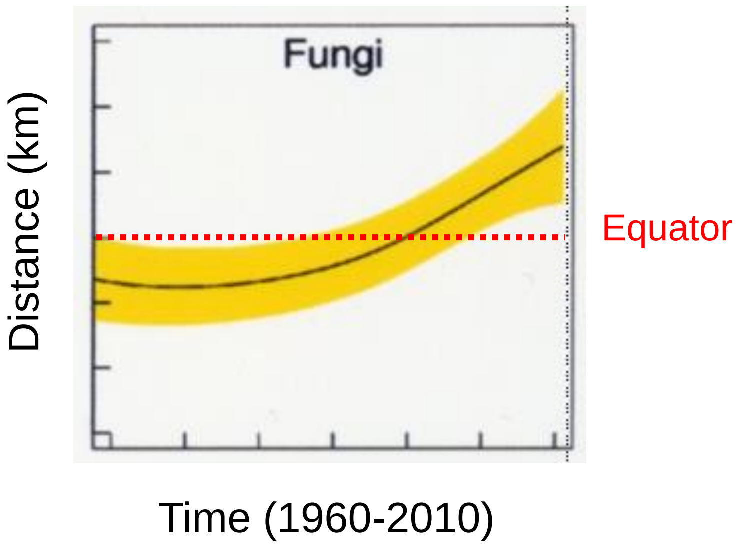


Myanmar reports 371 pests but, when compared to USA should report 671

Bebber, Holmes, Smith and Gurr (2014) *New Phytologist*

Are CPP on the move?





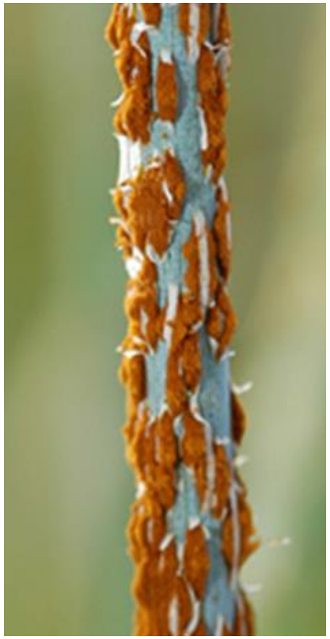
Fungi "marching" at 7.6 km per year; and are accelerating...

Bebber, Gurr (2013) *Nature Climate Change*

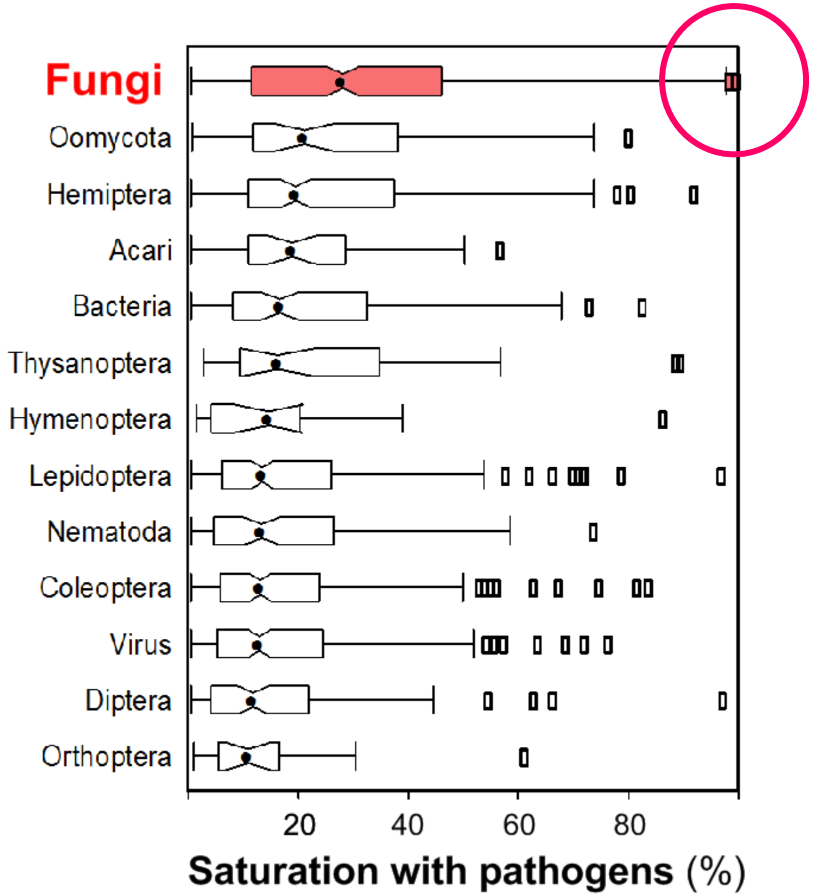
Can we predict the greatest threats, when and where?

Mildew

Rust



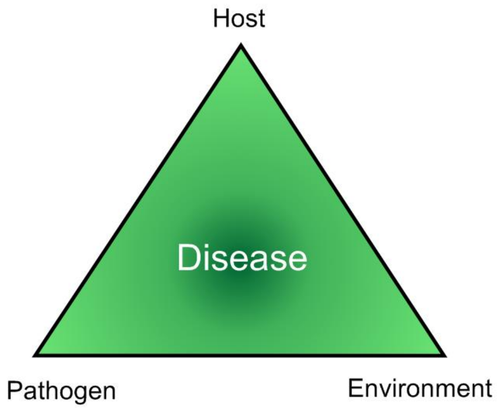
....specialist fungi!



Bebber *et al* (2014) *Global Ecology & Biogeography*

Bebber and Gurr (2015) *Fungal Genetics and Biology*

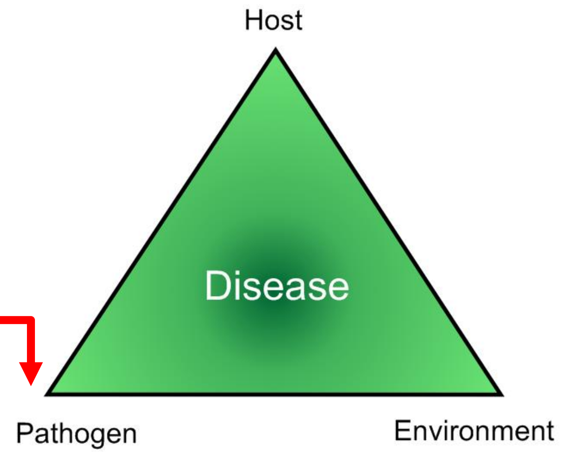
Mechanistic Models



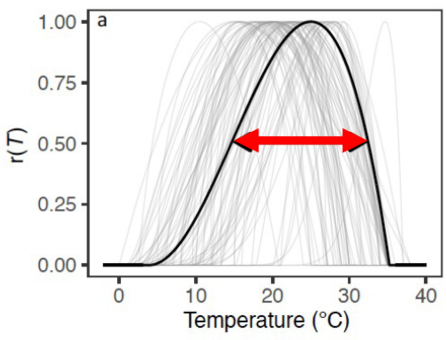
Fones *et al* (2020) *Nature Food*

Building a model to predict global pathogen burden in the future..

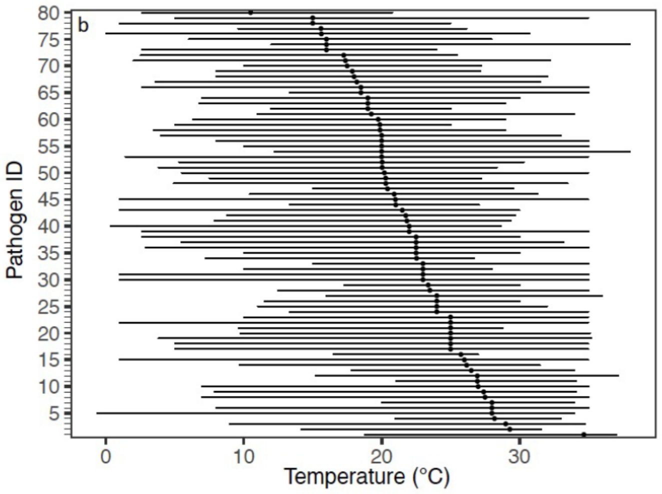
Pathogen data



Cardinal temperatures (CT) to define thermal limits of various biological processes in fungi and oomycetes - need temperature response data…



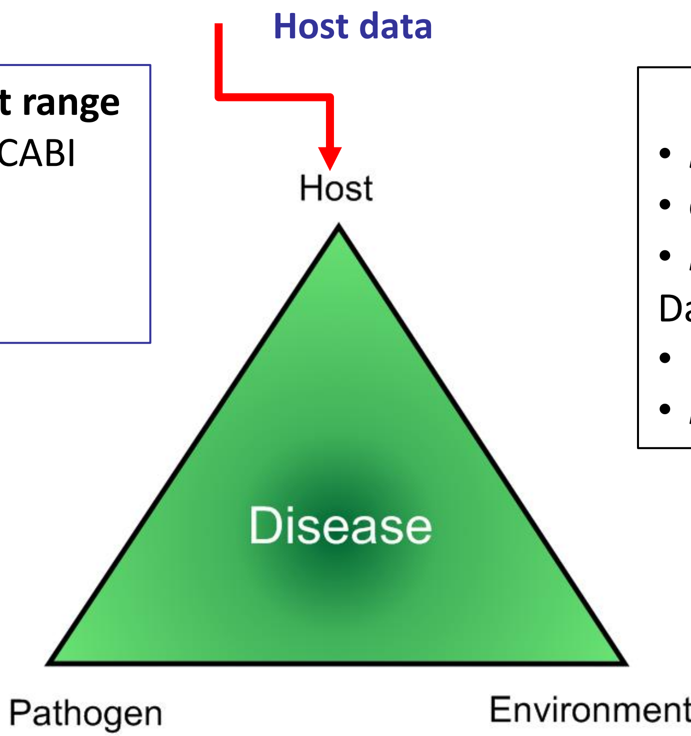
Relative infection rate >0.5 means "significant impact"



Chaloner *et al* (2020) *Nature Comms*

Building a model to predict global pathogen burden in the future..

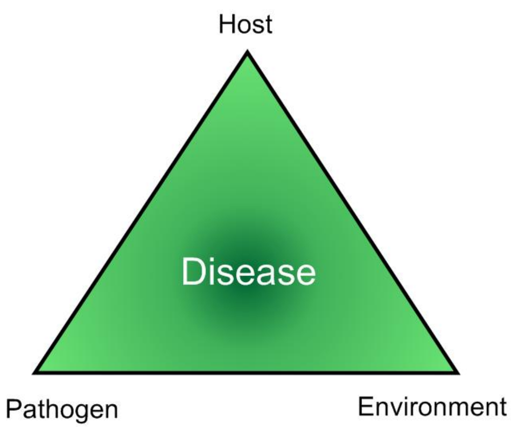
Match to host range
- PlantWise /CABI
- FAOSTAT
- EarthStat
- MIRCA2000

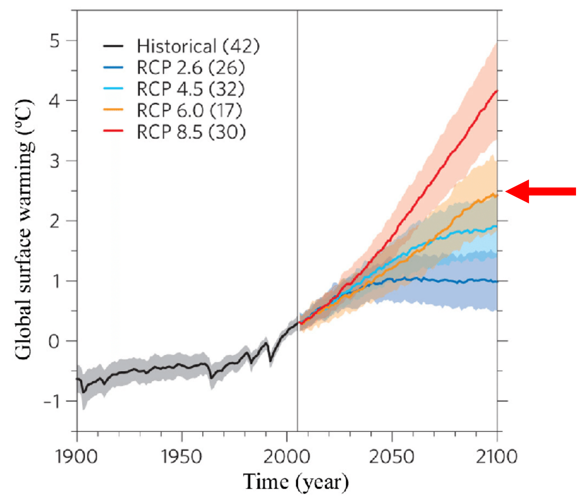


3 crop yield models
- *LPJmL*
- *GEPIC*
- *PEPIC*

Data / plant response - *eg*
- *Temperature*
- *Humidity*

Building a model to predict global pathogen burden in the future..





Environment data

4 climate models RCP
- 2.6
- 4.5
- **6.0**
- 8.5

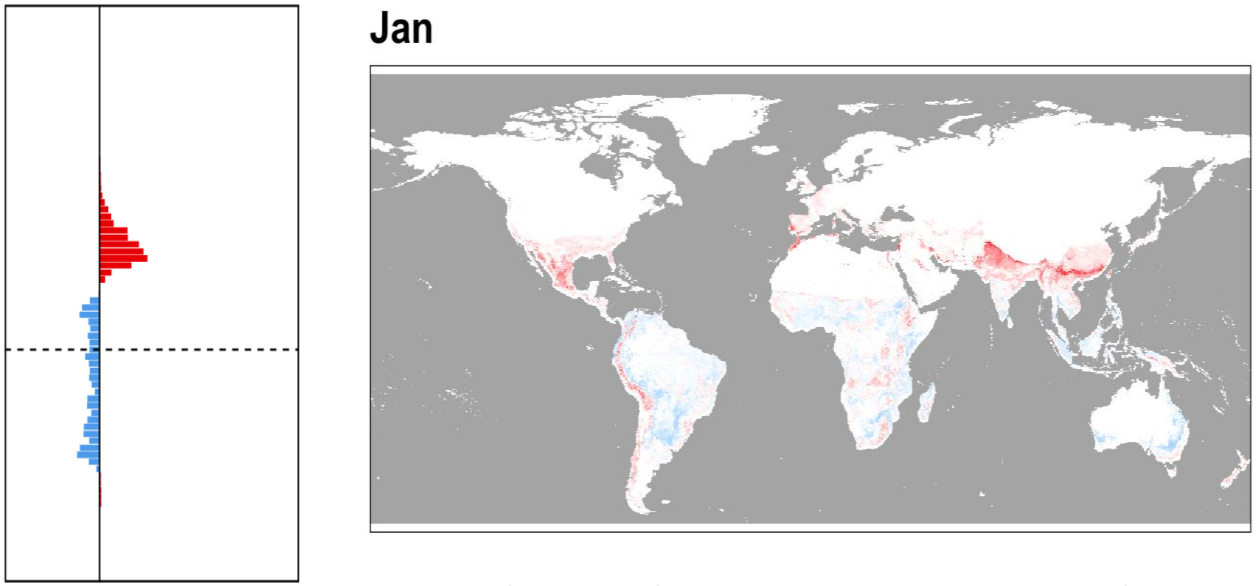
Temp and RH

Chaloner *et al* (2021) *Nature Climate Change*

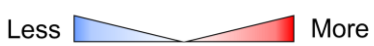
How do you validate the model?

- Compare outputs with observed pathogen presence (CABI PlantWise database)
- Regional scale
- GDP and research output equilibrated
- *Then*, forwards projections …. to 2070..

Changes in global pathogen burden:
Presence of pathogens in 2070 as compared with "now"



Pathogen burden compared with today



Chaloner, Gurr, Bebber (2021) *Nature Climate Change*

Double Jeopardy: The emergence of new fungal diseases

- Global changes (eg climate change) & trade and transport create new disease challenges
- Modern agriculture forces new variants of extant pathogens

Largest wheat field in world is 14,160 hectares
- A pathogen's feeding and breeding paradise!

UK Wheat

	2018	2023
Hectares planted - million	1.9	1.7
Yield – tonnes per hectare	7.8	8.1
Harvest total - million tonnes	14	12.8
Value per tonne - £	198	185
Value to UK economy - £	£2.7 billion	£2.4 billion

Data from: AnalystAgritel; Agri.eu/wheat-market; Farming-statistics@defra; Federal ministry of food and agriculture; International grain council wheat index; Agrimoney

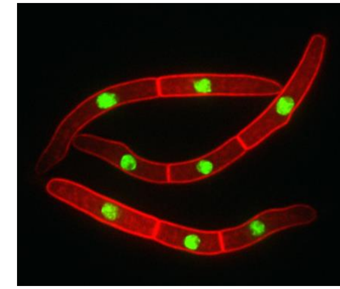
Value of losses to STB and usage and value of fungicide spraying

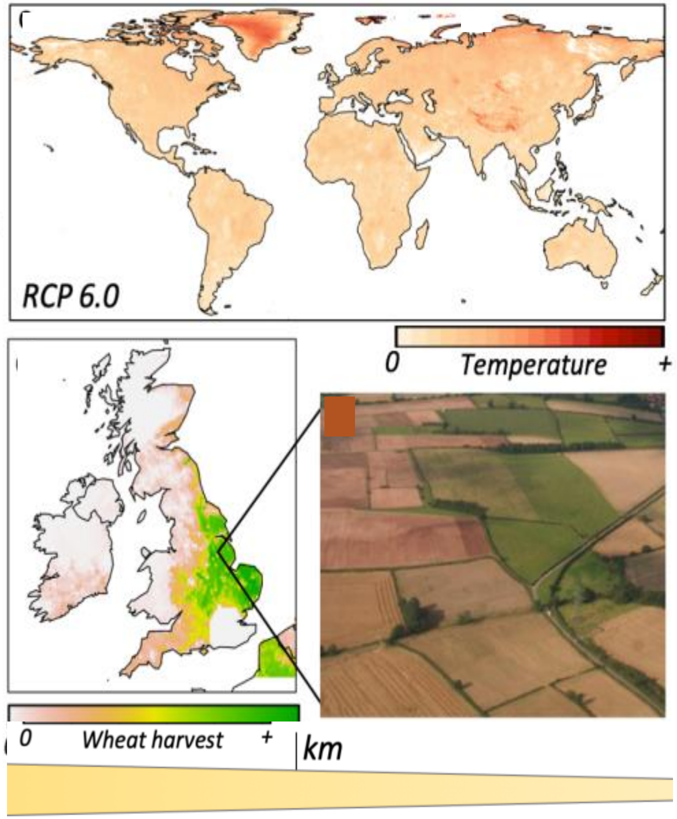
Losses to STB	UK
Value of 5-10% harvest losses due to STB	£120-240 million
Spraying costs, at £100 per hectare[1]	£163 million
Added value: boost in crop yield of 2.5 tonnes per hectare, post spraying[2]	£800 million

. [1]The spraying costs equate with 3 fungicide sprays per season (see Torriani et al 2025 STB special edition FGB (2014).

[2] Yield enhancement following fungicide sprays

A Mechanistic Model to Estimate Pathogen Burden in STB





Field scale

Data: (invoked Disease Triangle)

- ***Pathogen***: T^0C response function for germination growth and death (humidity)
- ***Host***: spatial resolution of UK wheat
- ***Environment***: high resolution climate data sets; defined field infection period by T^0C, humidity

Outcomes:

- Validated predictive model with observed STB in UK organic farms

Impact:

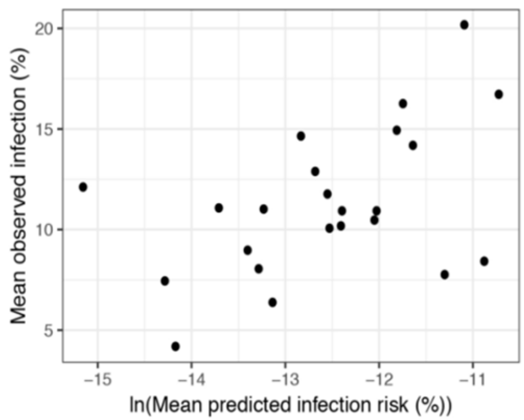
- First predictive mechanistic plant disease model parametrised by Disease Triangle data
- Model limitations…

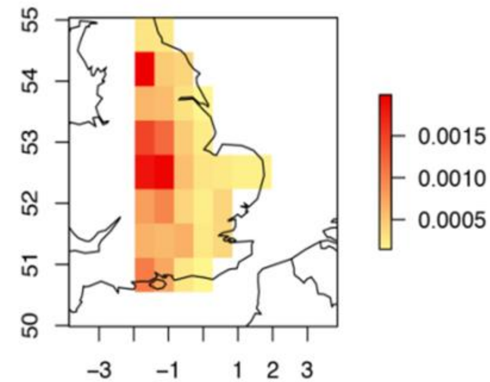
Chaloner *et al* (2019) *Philosophical Trans Royal Soc B*

A new mechanistic model for STB disease risk

Model A
(our model)

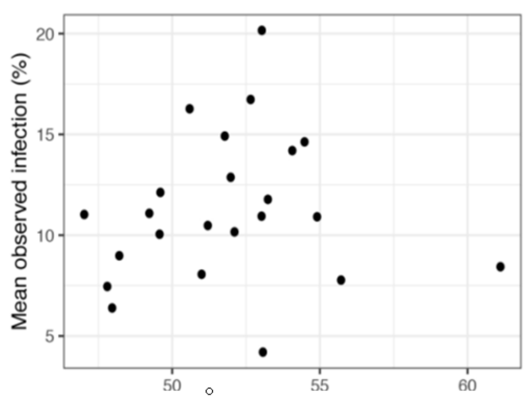
corr = 0.61

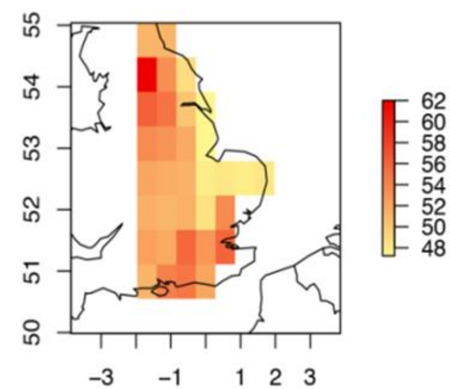




Model B
Bernard *et al.*, (2013)
New Phytologist

corr = 0.2





Model A predicts 61% of infections, whereas Model B predicts 20%

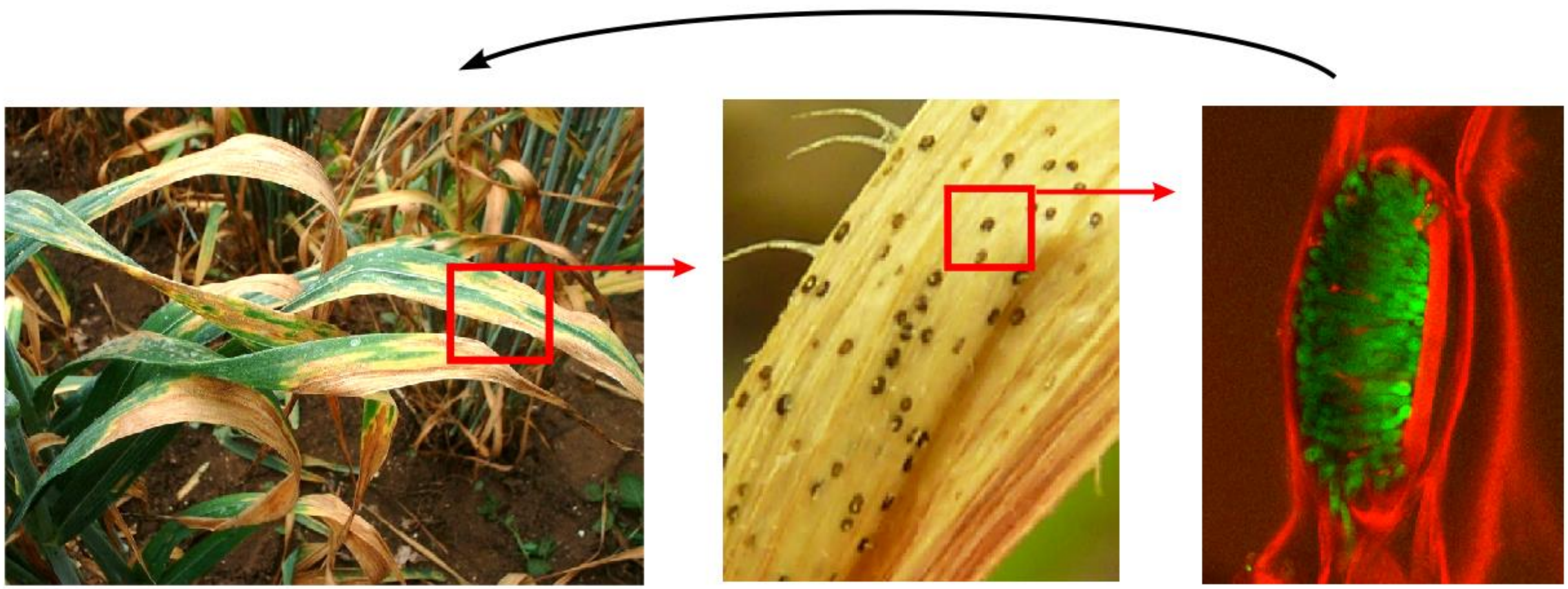
Chaloner *et al* (2019) *Philosophical Trans Royal Soc B*

Double jeopardy: Have we “forced” pathogen emergence with modern agricultural practices?

Host:
Vast “feeding fields”
Genetically uniform
Poorly-guarded crops

Pathogen:
Fast reproduction (cycles)
Vast numbers of spores
Plastic genomes

Outcome:
Fungicide resistant
and highly
virulent strains



STB - *Zymoseptoria tritici*

Fones and Gurr (2015) *Fungal Genetics & Biology*
Fones *et al* (2017) *Fungal Genetics and Biology*
Fones *et al* Gurr *(2020) Nature Food*

Fungi: a growing threat to wheat production in a changing climate

STB/ Zt
- Genomic plasticity
- Fast asexual life-cycle generating spore load per hectare

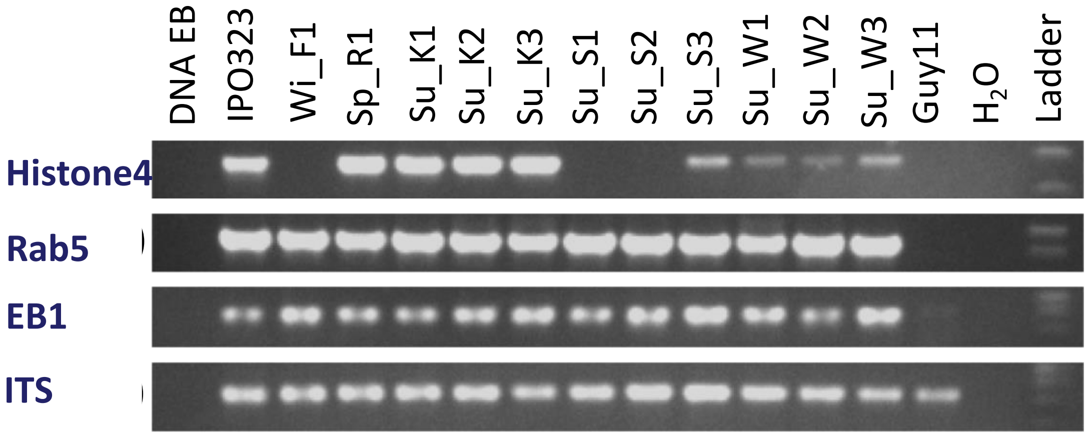
Fungi
- Fungicide resistance emergence under cc*?
- Overcoming plant disease resistance genes?
- Mycotoxin profiles changes**..
- Host hopping?

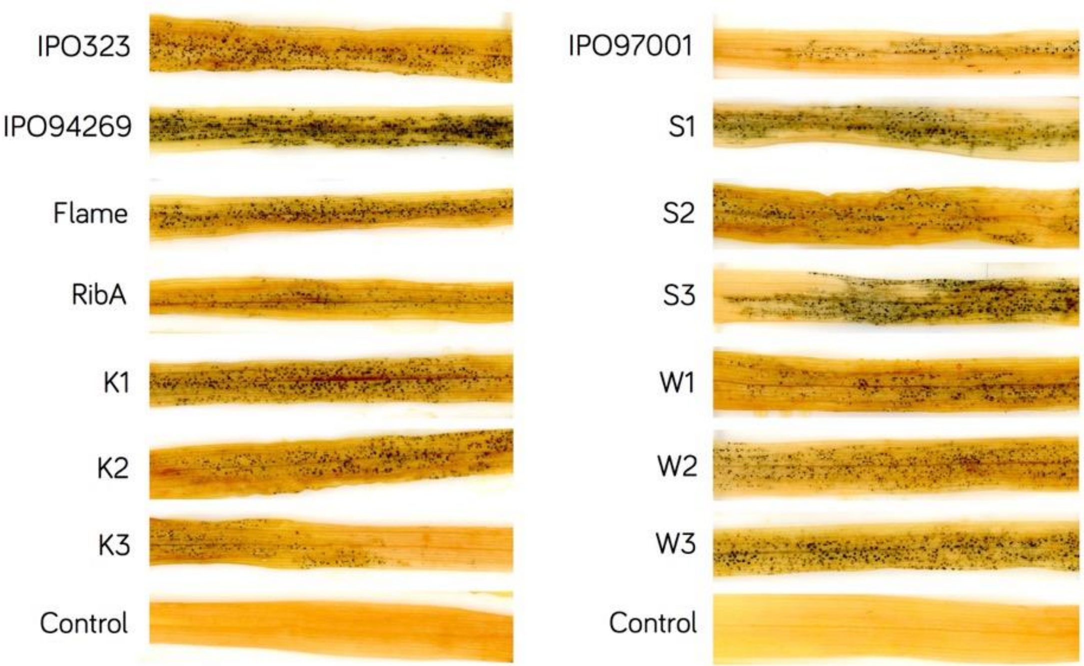
- **Climate change? Temperature - Adaptation and acclimation work (*unpublished*)**

Fones and Gurr (2015) *FGB*
Johns *et al (2022) Nature Food***
Fisher *et al (2028) Science**
Fisher *et al (2023) Nature Microbiology**

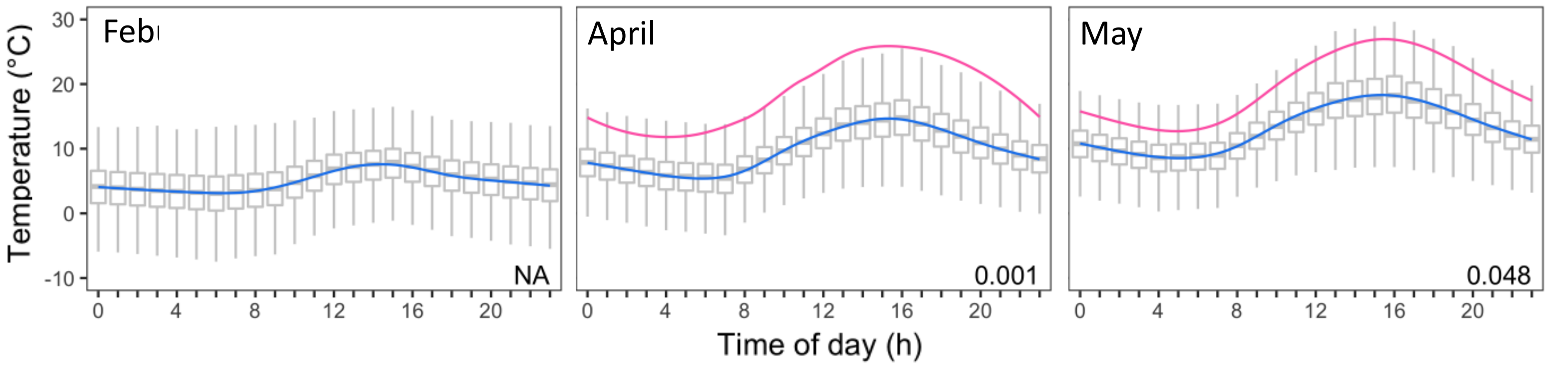
Zt Adaptation and acclimation

1. Field isolates / strains / verification





2. High / extreme and heat shock temperatures in UK wheat fields



Hourly air temperatures in wheat growing regions of UK - Feb, April, May (1990 – 2016). Raw 3-hourly data extracted from JRA-55 (https://rda.ucar.edu/datasets/ds628.0/)

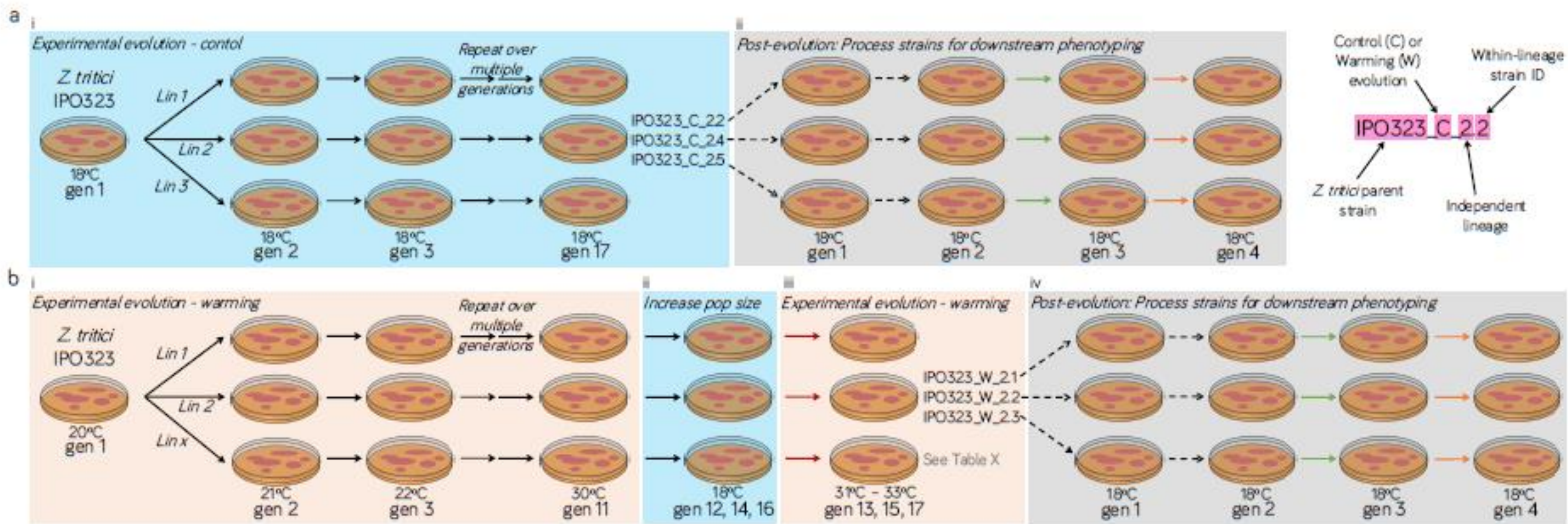
Pink lines are GAMs data-fitted for days where T_{max} ≥ 26.0 ^{o}C for April / May

Outcome:

- 26 and 29^{0}C represent realistic UK spring / summer heatwave temperatures
- 36 and 40^{0}C are extreme but occur

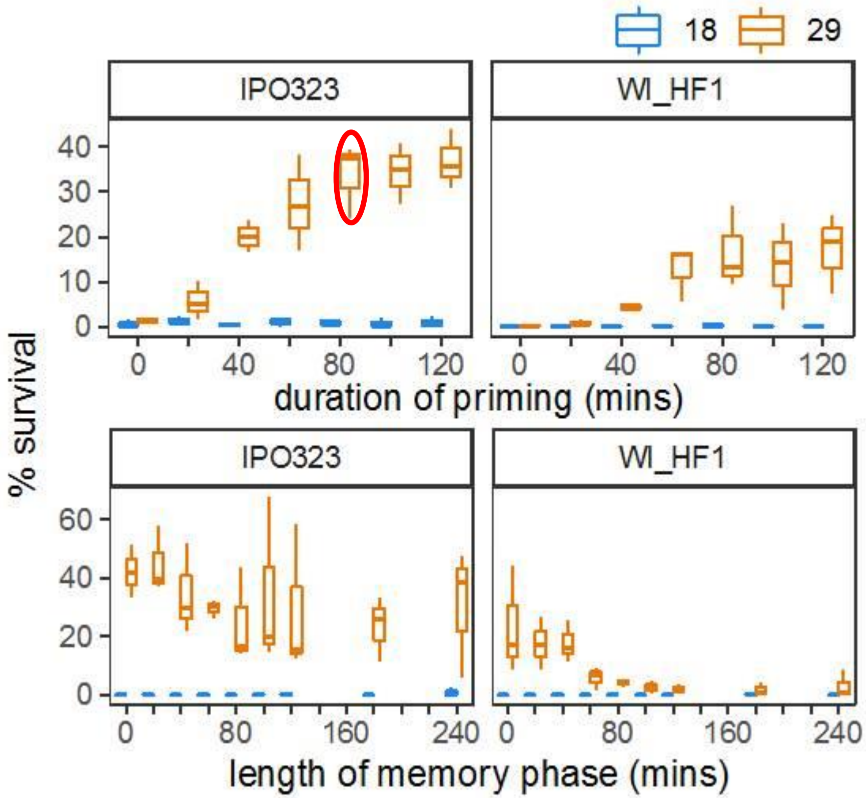
***Zt* grows in lab at 18^{0}C – what is impact of a) gradual temp rise or**
b) heat shock on *Zt*?

a. Evolution of thermal tolerance in *Z. tritici*



In vitro evolution of i) warming evolution (18-34^{0}C ii) control (plate to plate at 18^{0}C)

b. Thermal *cis*-priming & duration of memory in *Zt* model and field isolate

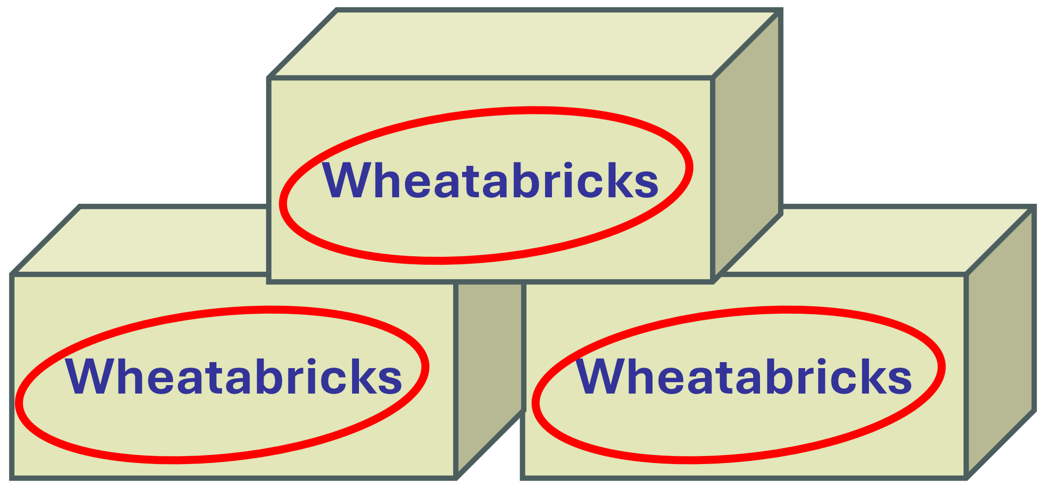


Priming - cells at 18^{0}C placed at 29^{0}C for 1-120 mins. Primed (orange) and control cells (blue) exposed to lethal temp – 40^{0}C for 60 mins.

Memory – cells primed at 29^{0}C for 80 mins and incubated at 18^{0}C for 1-240 mins, prior to triggering at 40^{0}C (60 mins), to assess "memory"

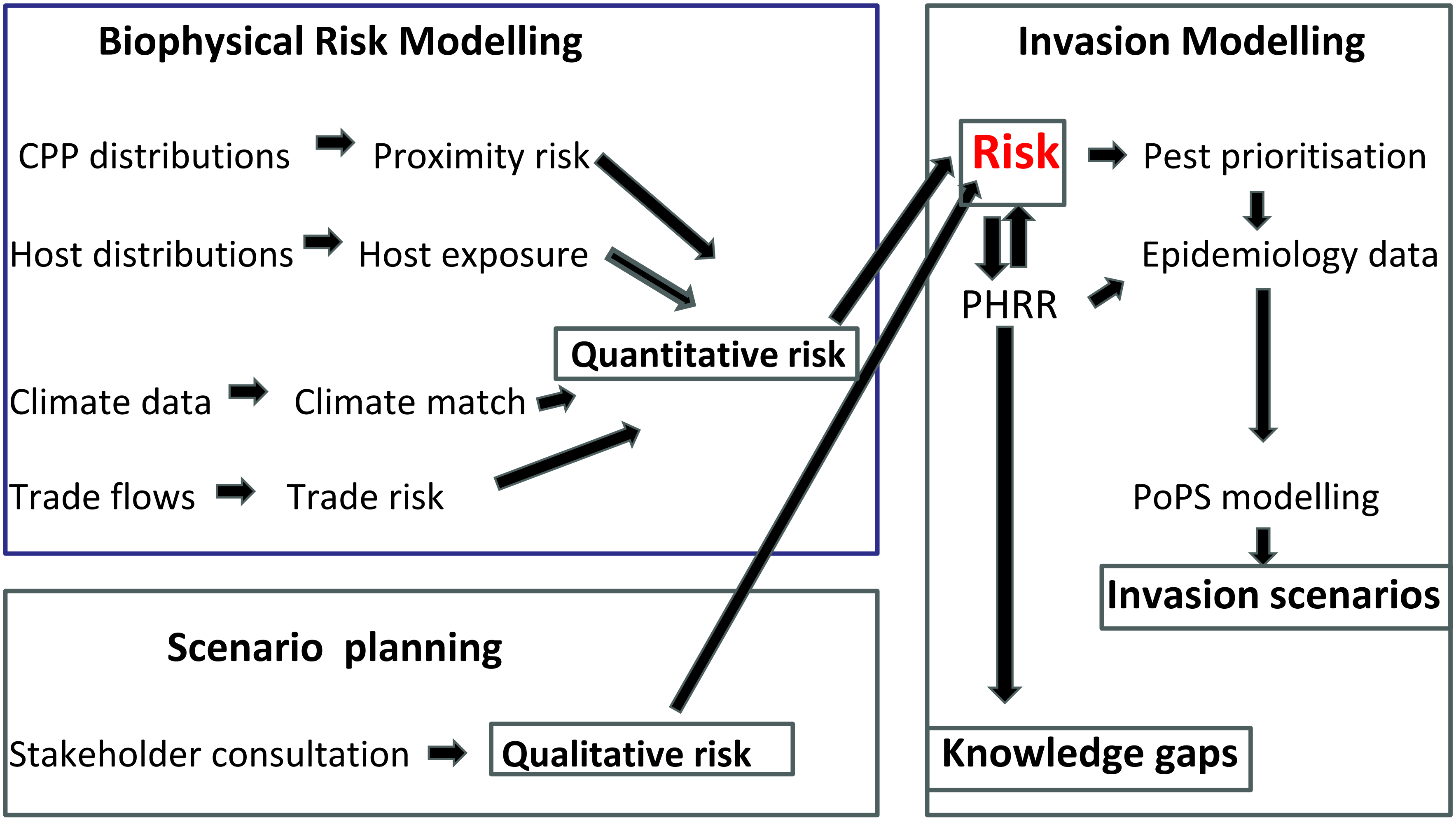
So, Zt can a) survive up to 34^{0}C and b) survive heat shocks when primed

Building blocks for future STB disease resilient wheat but many knowledge gaps



Images; Weetabix; Alamy

Interdisciplinary analysis of plant health threats global crops / wheat UK



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