Data-driven mathematical models for the assessment and control of Huanglongbing

Rachel Taylor, Jason Rohr, Leah Johnson

Department of Integrative Biology, University of South Florida
Tampa, Fl, 33620. Email: rataylor@usf.edu

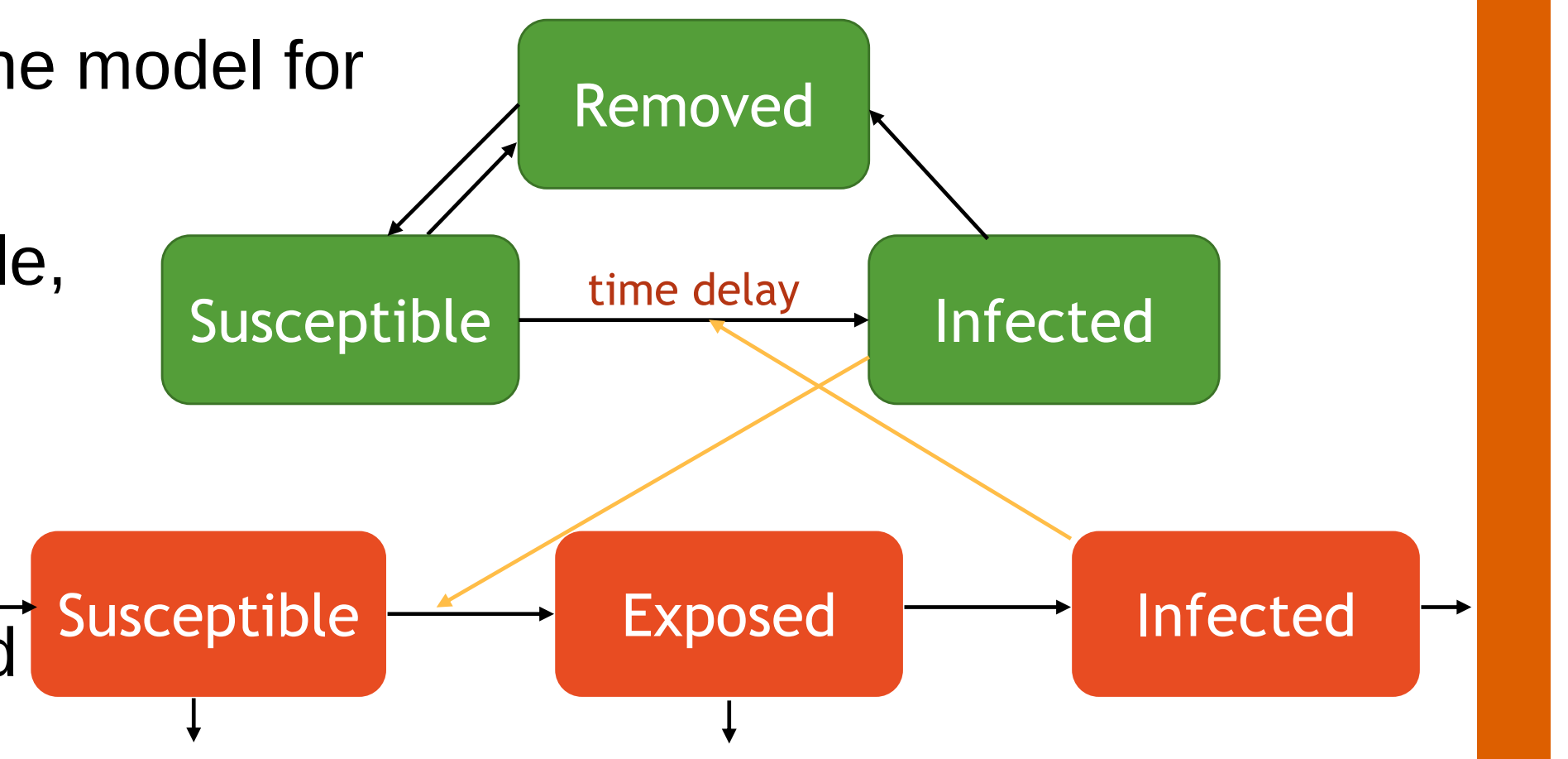
Introduction

Huanglongbing (HLB, or citrus greening) is a vector-borne disease of citrus trees globally. It arrived in Florida in 2005 and has spread rapidly throughout the whole state and beyond[1,2]. It reduces yields of marketable citrus fruit due to fruit dropping early, being smaller in size and more bitter. Trees can be difficult to diagnose with an asymptomatic stage dependent on tree age. Further, not all parts of the tree will show infection.
The disease is transmitted during feeding of the vector, the Asian citrus psyllid, *Diaphornia citri*[1,2]. The ability to control the spread of HLB requires a better understanding of the interactions between the pathogen, psyllid and tree, and the abiotic factors that impact transmission.
Nowhere in the world is HLB under adequate control, with insecticide the only control currently in use in Florida[3]. Mathematical models can help determine cost-effective strategies or combinations thereof quickly and efficiently without the need for large-scale field manipulations.

Our Aims

- How is disease transmission affected by abiotic factors?
- How sensitive is disease transmission to psyllid traits?
- What are the most cost-effective control strategies?

Model



- We extend a previous vector-borne model for malaria[4]
- We model the trees as Susceptible, Infected or Removed
- Removed trees are from natural death or removal due to infection
- Psyllids are Susceptible, Exposed or Infected. Once infected, they remain so for their whole lifespan
- We use three Exposed classes to represent more accurately the time delay until psyllids become infected

$$
\begin{aligned}
\frac{dS}{dt} &= -\frac{ab}{N}I_V S + r_1 I \\
\frac{dI}{dt} &= \frac{ab}{N}I_V(t-\tau)S(t-\tau) - r_1 I \\
\frac{dR}{dt} &= rS + r_1 I \\
\frac{dS_V}{dt} &= \lambda - \frac{ac}{N}IS_V - \mu S_V \\
\frac{dE_{V1}}{dt} &= \frac{ac}{N}IS_V - 3\phi E_{V1} - \mu E_{V1} \\
\frac{dE_{V2}}{dt} &= 3\phi E_{V1} - 3\phi E_{V2} - \mu E_{V2} \\
\frac{dE_{V3}}{dt} &= 3\phi E_{V2} - 3\phi E_{V3} - \mu E_{V3} \\
\frac{dI_V}{dt} &= 3\phi E_{V3} - \mu I_V \\
N &= S + I \\
V &= S_V + E_{V1} + E_{V2} + E_{V3} + I_V.
\end{aligned}
$$

Parameter	Definition
a	Feeding rate
b	Prob of transmission from psyllid to tree
c	Prob of transmission from tree to psyllid
τ	Time delay until tree infected
r	Death rate of healthy tree
r_1	Removal rate of infected trees
λ	Psyllid birth rate
μ	Psyllid death rate
ϕ	Pathogen development rate in psyllid

Parameter Fitting

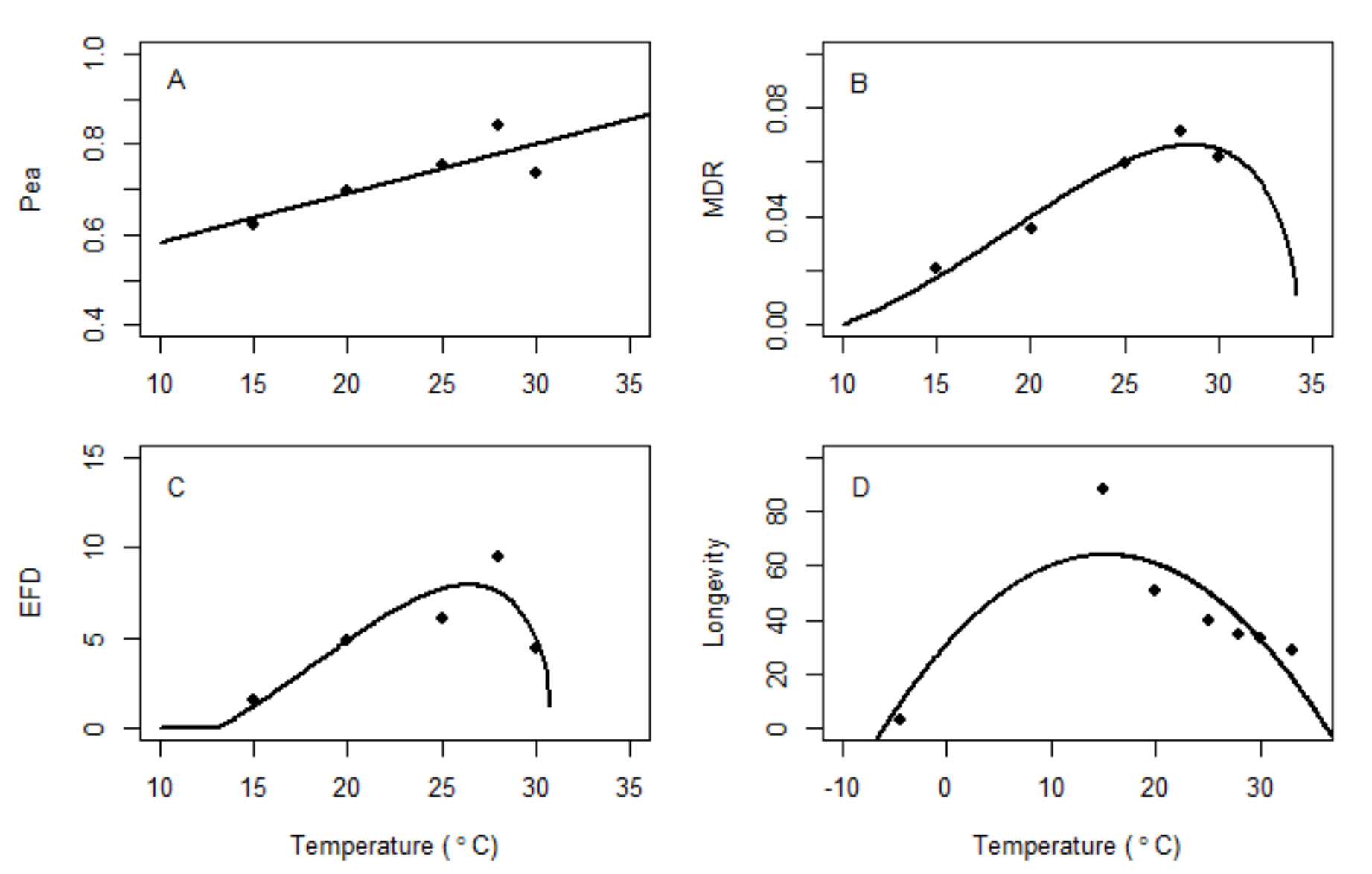


Fig 2. Thermal response plots for psyllid vital rates. Data for each parameter are plotted with their best fit line.

- We model psyllid birth rate by[4]: $\lambda(T) = \frac{EFD(T)p_{ea}(T)MDR(T)}{\mu(T)}$
- Temperature (T) enters the model as: $T = 25(1 + 0.5\sin(2\pi t))$
- Thermal response curves are fit from experimental data[5]
- We fit linear, Brière and quadratic curves[4] and determine best fit by AICc

Parameter	Definition	Best fit curve
p_{ea}	Egg to adult survival probability	$0.4719 + 0.0109\,T$
EFD	Eggs per female per day	$0.0107\,T(T-13)(30.8-T)^{0.5}$
MDR	Development rate	$5.286\text{x}10^{-5}\,T(T-10.02)(34.17-T)^{0.5}$
L $(^1/_\mu)$	Longevity	$-0.14221\,T^2 + 4.31998\,T + 31.255$

Sensitivity of R_0

- We test the sensitivity of R_0 to changes in each of the parameters at different temperatures
- EFD is important in determining when R_0 reduces below 1 as R_0 stays positive longer when EFD is constant (Fig 3).
- If μ is constant the shape of R_0 changes, with a lower peak occurring at higher temperatures (Fig 3).
- At low and high temperatures EFD has the biggest effect on changing R_0 (Fig 4).
- For intermediate temperatures (24-28˚C), death rate μ pulls R_0 lower than expected (Fig 4).

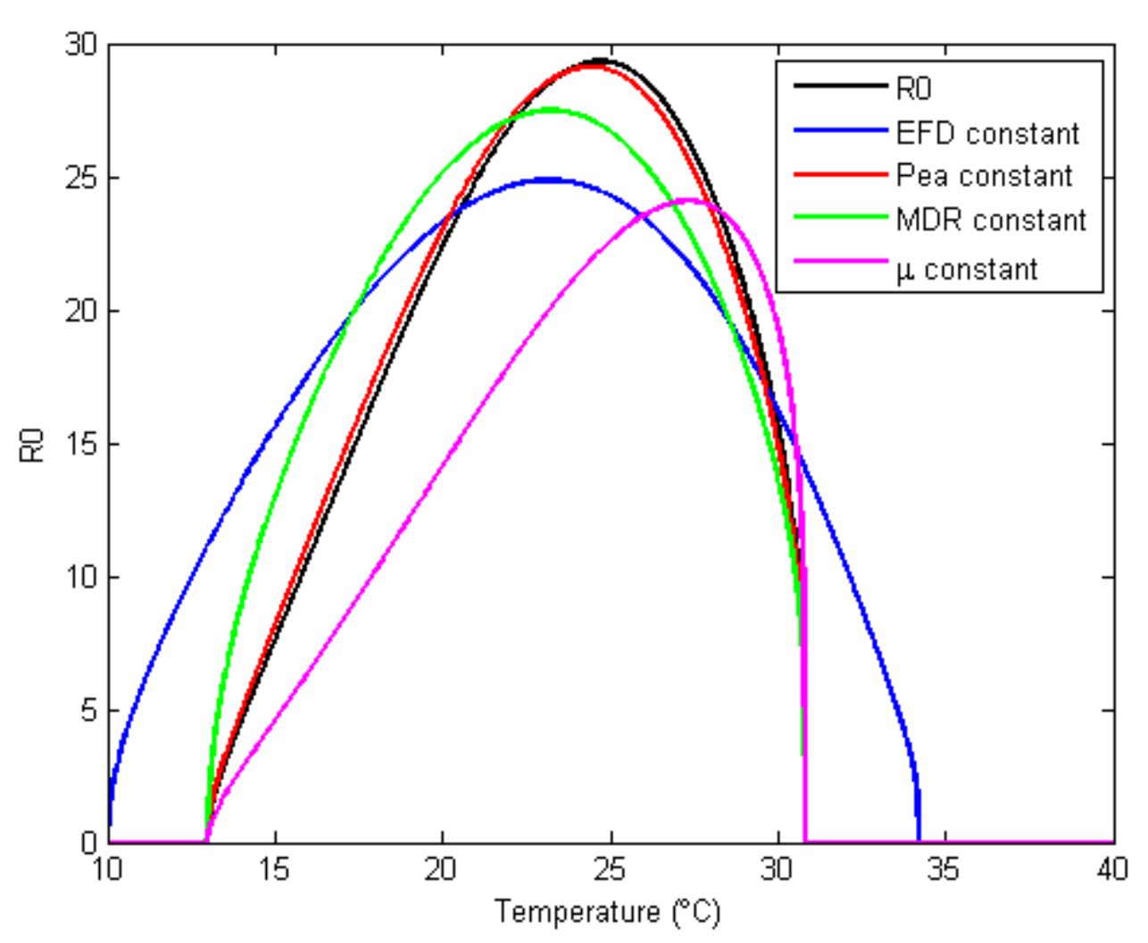


Fig 3. A plot of R_0 against temperature. The black line is the full model for R_0, while each of the colored curves shows how R_0 would change if one parameter is constant at its average value.

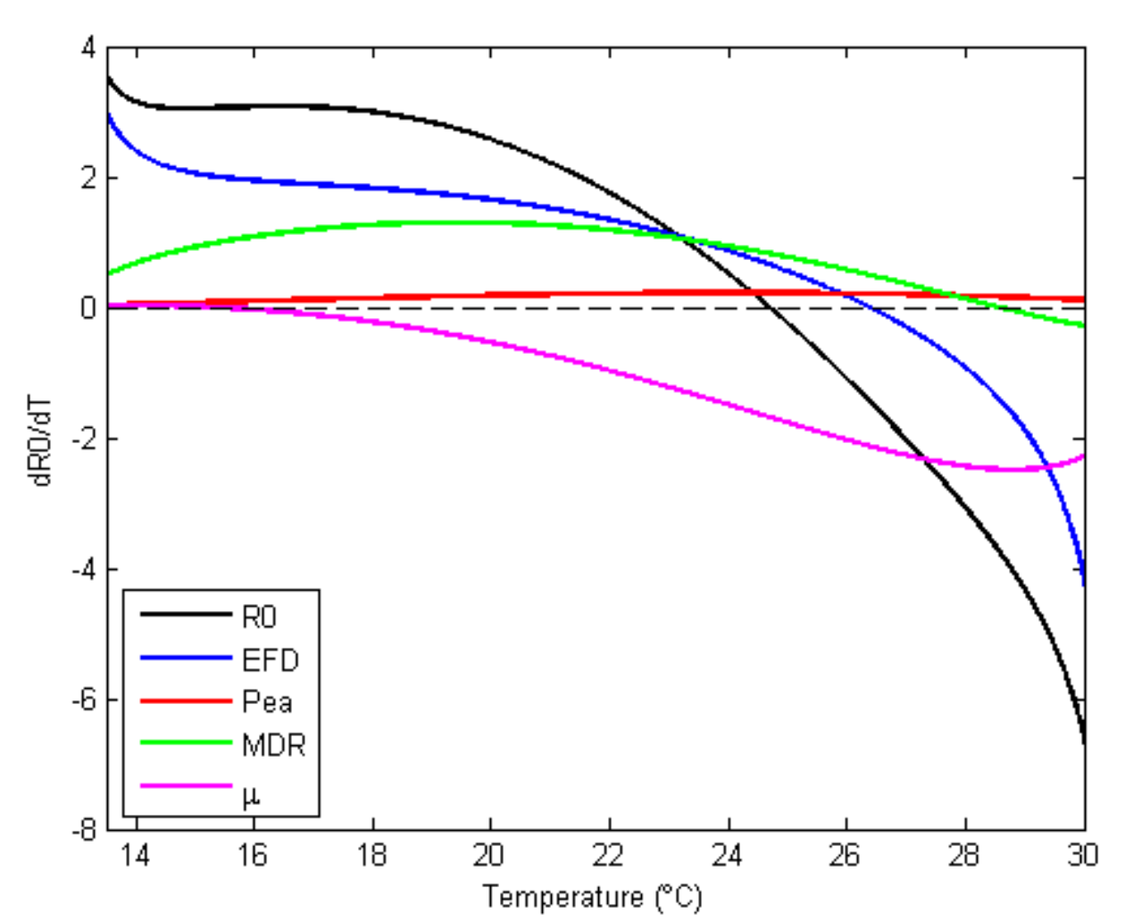


Fig 4. A plot of the change in R_0, ${}^{dR0}/_{dT}$, as temperature is increased. In black is the full equation for ${}^{dR0}/_{dT}$ while each colored line shows the relative contribution of each parameter to changes in R0.

Antibiotic Intervention

- Antibiotics have been tested[6] in lab experiments with one group performing with 85% efficiency ("high") and the second group at 60% ("low")
- Treated trees can still transmit infection but at a reduced rate depending on the efficiency of the antibiotic
- We assume the different antibiotics cost the same to implement

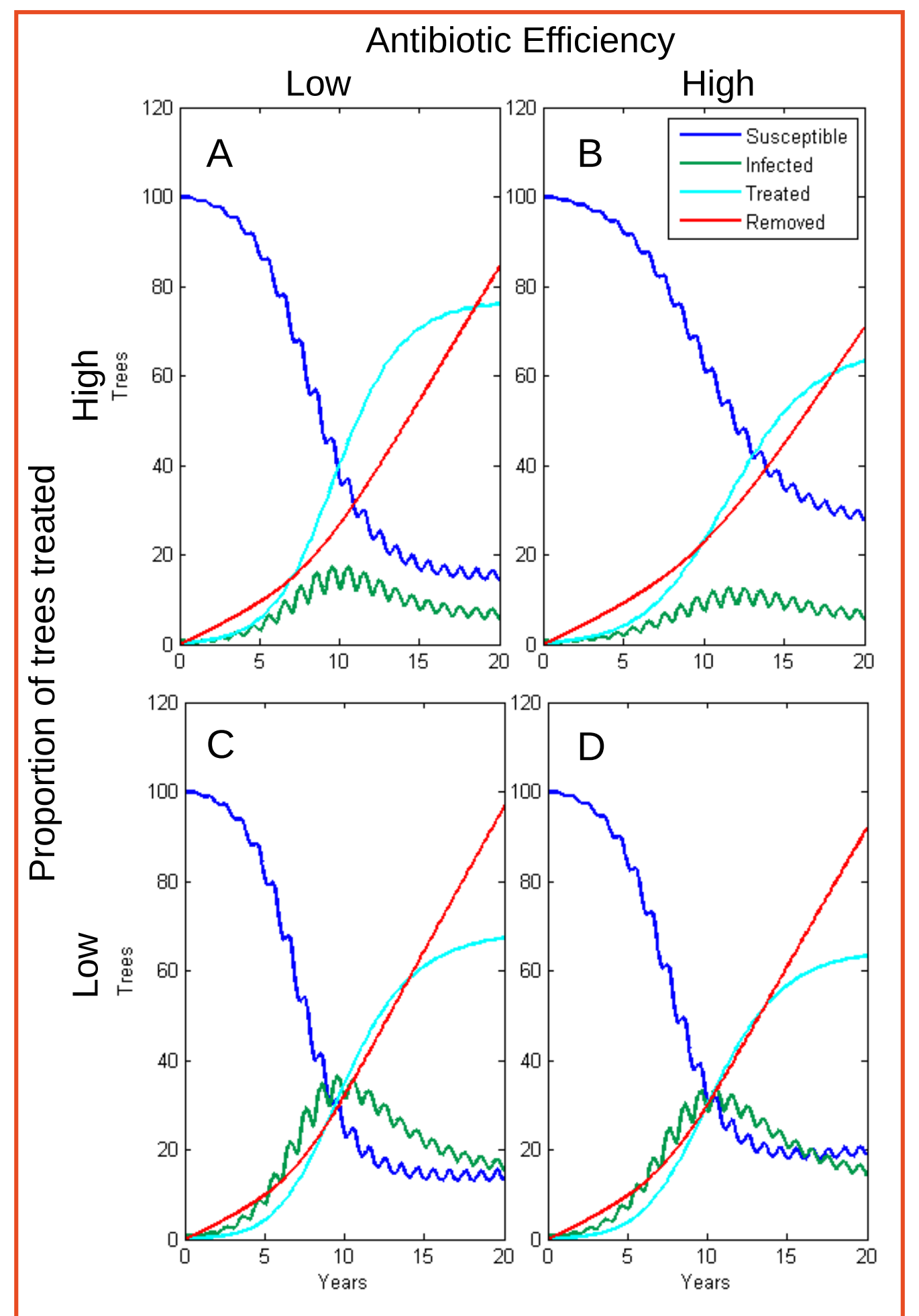


Fig 5. Testing different antibiotic strategies. Antibiotic efficiency is either high (80%) or low (60%). Proportion of trees treated is high (80%) or low (30%).

- Without treatment, peak number of infected trees can be above 80% thus all strategies are better than no intervention
- In A and C, more trees are treated in comparison to B and D, because lower efficiency leads to more infection
- Higher efficiency is more impactful when more trees are treated

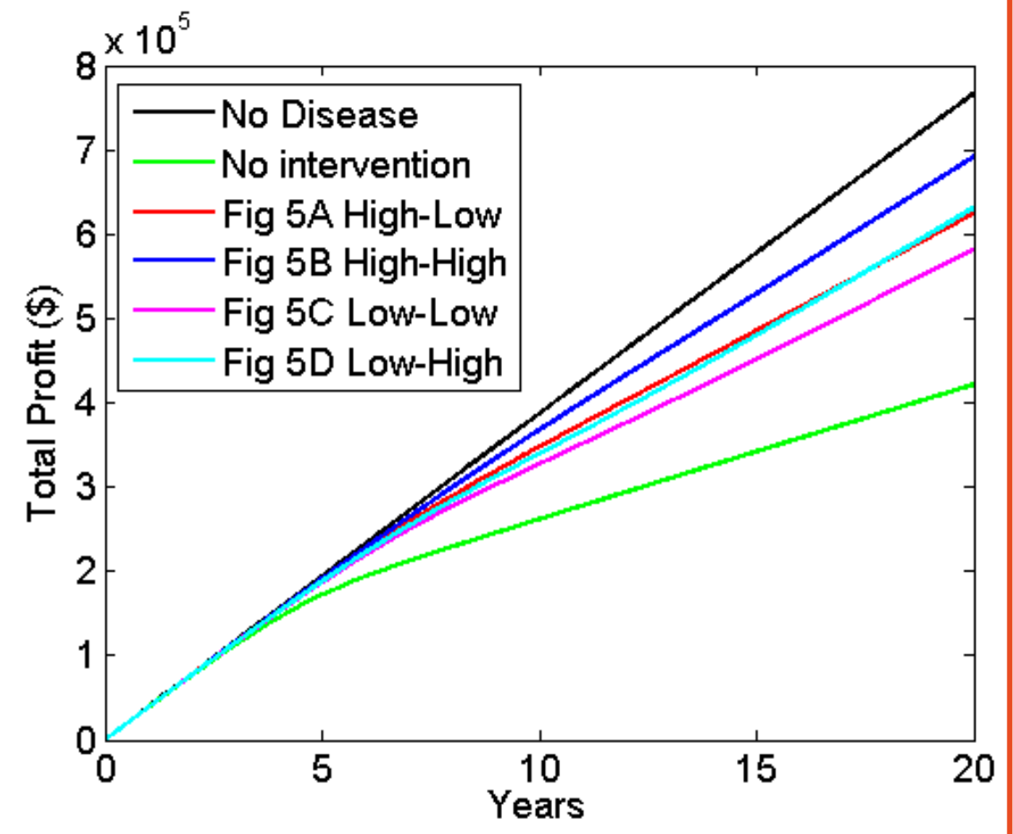


Fig 6. The profits made in one grove over a 20 year time span since disease introduction. Each of the four cases in Fig 5 are shown.

- Most profits made when the better antibiotic is used in high proportions
- Less money spent on treatment is balanced by more costs removing trees (Low-High = High-Low costs)

Conclusion

- Based on sensitivity of R_0, a combined control strategy of reducing psyllid fecundity at low and high temperatures (winter & summer), and increasing psyllid death rate at mid temperatures (spring & fall) could be the most successful at reducing disease transmission
- Antibiotics have the potential to reduce infection to manageable levels if used in high proportions of trees
- The cost-effectiveness of this strategy could change if better antibiotics cost more

References

Photo credit: By Ellen Levy Finch (Elf) (Own work) [GFDL (http://www.gnu.org/copyleft/fdl.html) or CC-BY-SA-3.0 (http://creativecommons.org/licenses/by-sa/3.0/)], via Wikimedia Commons

1. Bove, J. M. 2006 Huanglongbing: A destructive, newly-emerging, century-old disease of citrus. *J. Plant Pathol.* **88**, 7-37.
2. Gottwald, T. R. 2010. Current epidemiological understanding of citrus Huanglongbing. *Annu Rev Phytopathol*, *48*, 119-139.
3. Qureshi, J. A., et al. 2014. Insecticidal Suppression of Asian Citrus Psyllid *Diaphorina citri* (Hemiptera: Liviidae) Vector of Huanglongbing Pathogens.
4. Mordecai,E. et al. 2013. Optimal temperature for malaria transmission is dramatically lower than previously predicted, *Ecol Letters*, 16(1):22-30.
5. Liu, Y. H. & Tsai, J. H. 2000. Effects of temperature on biology and life table parameters of the Asian citrus psyllid, *Diaphorina citri* Kuwayama (Homoptera : Psyllidae). *Ann. Appl. Biol.* 137, 201-206.
6. Zhang, M. et al. 2014. Effective Antibiotics against '*Candidatus* Liberibacter asiaticus' in HLB-Affected Citrus Plants Identified via the Graft-Based Evaluation. *Plos One*: e111032

Explore dynamics and try out interventions yourself! Interactive simulations available at `http://leah.johnson-gramacy.com/HLB.html`