Biocontrol of the emerald ash borer: an adapted Nicholson-Bailey model

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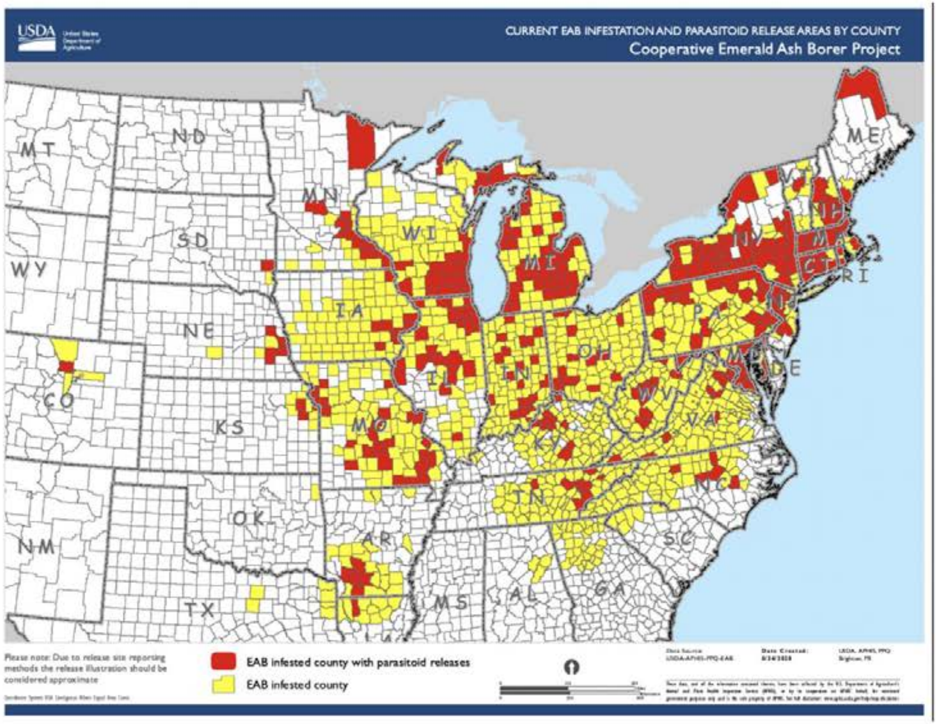
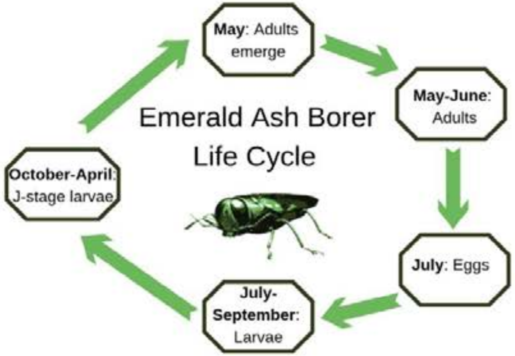
Outline of Talk

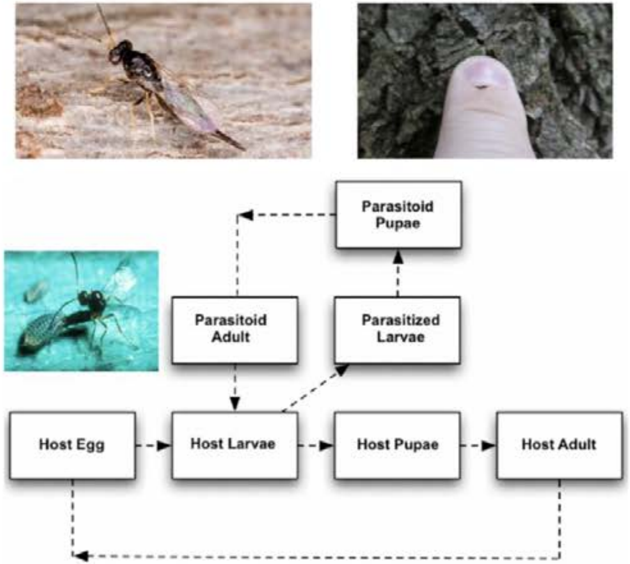
- *Agrilus planipennis* (EAB) and the larval parasitoid *Tetrastichus planipennisi* (TP)
- Nicholson-Bailey model
- Partial Refuge Model
  - model parameters
  - equilibria and stability
  - escape probabilities as coordinates
- Biocontrol Questions
- Future Work

Biocontrol Map (2020)



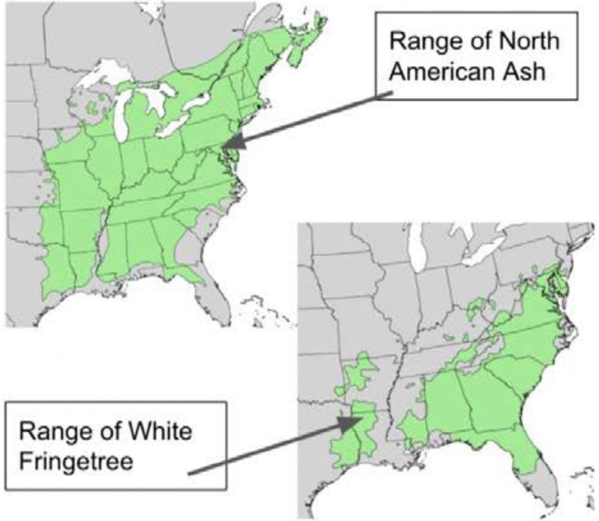
Host and Parasitoid





Ash and Fringetree

- Ash and White fringetree ranges overlap
- Fringetree is suboptimal for EAB
- Fringetree is also suboptimal for TP



Nicholson-Bailey Model (1935)

$$H_{t+1} = R\, H_t\, e^{-a P_t}$$

$$P_{t+1} = k\, R\, H_t \left(1 - e^{-a P_t}\right)$$

$e^{-a P_t}$ = escape probability

$1 - e^{-a P_t}$ = parasitism rate

H_t = host density at time t

P_t = parasitoid density

R = host growth rate

a = parasitoid attack rate

k = parasitoids per parasitized host

Unique unstable equilibrium

N-B Suboptimal Refuge

Assume fraction μ of the host population utilizes a suboptimal refuge with refuge growth rate αR. In the absence of parasitoids, the expected growth rate is

$$\gamma R = (\alpha \mu + (1 - \mu)) R$$

$$\underline{\text{Viability}}\ \underline{\text{assumption}} : \quad \gamma R > 1$$

Write

$$f(P_t) = \alpha \mu + (1 - \mu) e^{-a P_t}$$

$$H_{t+1} = R H_t f(P_t)$$
$$P_{t+1} = k R H_t (\gamma - f(P_t))$$

Equilibrium and Stability

$$H_{t+1} = R\,H_t\,f(P_t)$$
$$P_{t+1} = k\,R\,H_t\,(\gamma - f(P_t))$$

$$f(P_t) = \alpha\,\mu + (1-\mu)\,e^{-a\,P_t}$$

Equilibrium Conditions

$$1 = R\,f(P^*)$$
$$P^* = k\,H^*\,(\gamma\,R - 1)$$

Stability: Singh & Emerick (2020)

$$1 + k\,\gamma\,R^2\,H^*\,f_p^* > 0 \qquad \text{where } f_p^* = \partial_{P_t} f\,\Big|_{P_t = P^*}$$

Partial Refuge Model

Refuge is also suboptimal for the parasitoid.

Attack rate: βa, $0 < \beta < 1$.

$$H_{t+1} = R\, H_t\, f\,(P_t)$$

$$P_{t+1} = k\, R\, H_t\, (\gamma - f\,(P_t))$$

$$f = \alpha\,\mu\, e^{-\nu\,\beta\, a\, P_t} + (1 - \mu)\, e^{-(1-\nu)\, a\, P_t}$$

R, kR; a	ex-refuge growth; attack rates
α, β	discount factors (suboptimal)
μ, ν	% host, parasitoid using refuge

Refuge assumption: $\nu\,\beta < 1 - \nu$

Partial Refuge: Equilibrium and Stability

$$f = \alpha\,\mu\,e^{-\nu\,\beta\,a\,P_t} + (1-\mu)\,e^{-(1-\nu)\,a\,P_t}$$

Set $X^* = a\,P^*$ and y $\lambda = \alpha\,e^{(1-(1+\beta)\,\nu^*)\,X^*}$

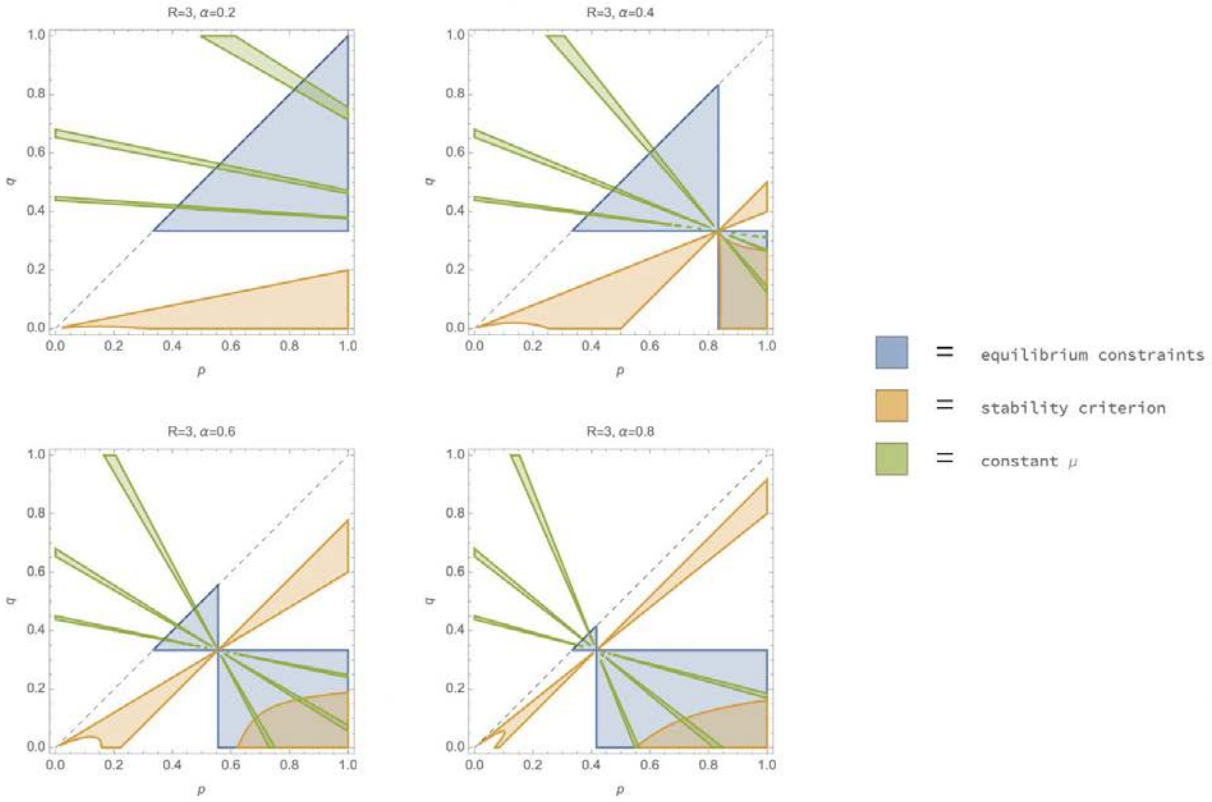
Equilibrium: an α, μ-weighted average of the escape probabilities

$$\frac{\alpha\,\mu^*}{\alpha\,\mu^* + (1-\mu^*)}\,e^{-\nu^*\,\beta\,X^*} + \frac{1-\mu^*}{\alpha\,\mu^* + (1-\mu^*)}\,e^{-(1-\nu^*)\,X^*} = \frac{1}{\gamma\,R}$$

Stability: a λ, μ-weighted average of their logarithms.

$$\frac{\lambda\,\mu^*}{\lambda\,\mu^* + (1-\mu^*)}\,\ln\left(e^{-\nu^*\,\beta\,X^*}\right) + \frac{1-\mu^*}{\lambda\,\mu^* + (1-\mu^*)}\,\ln\left(e^{-\nu^*\,\beta\,x^*}\right) > \frac{1}{\gamma\,R} - 1$$

Using the escape probabilities p and q as primary variables clarifies the picture.



Formulas in terms of *p*, *q*, *β*

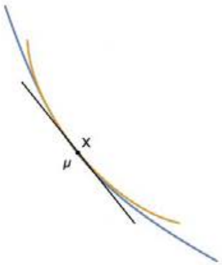
$$\mu^* = \frac{1 - q\,R}{R\,(\alpha\,p - q)} \qquad \nu^* = \frac{\ln(p)}{\ln(p) + \beta\ln(q)}$$

$$X^* = -\frac{1}{\beta}\,(\ln(p) + \beta\ln(q)) \qquad H^* = \frac{X^*}{a\,k\,(\gamma\,R - 1)}$$

In particular

$$\nabla H^* = \frac{1}{a\,k\,(\gamma\,R - 1)}\left(\nabla X^* - \frac{(1-\alpha)\,R}{\gamma\,R - 1}\,\nabla\,\mu^*\right)$$

Level curves of μ^*, H^*, X^*



Biocontrol Questions

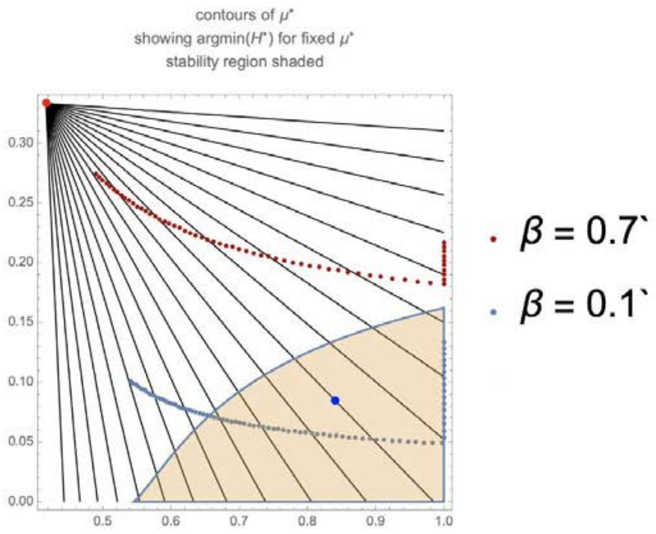
1. Suppose μ^* is proportional to $\varphi = \frac{\text{fringetree density}}{\text{ash+fringe density}}$. What is the minimum H^* that can be achieved for given β?

2. For a fixed parasitoid density X^* (again for a given β), what is the worst case maximum density H^*?

3. How do the answers change as β, i.e. the in-refuge attack rate, increases?

Biocontrol Answers μ^*, H^*, X^*, β

min H^* for given μ and max H^* for given X^*.



Data at blue point $(p, q) = (.84, .085)$

- $H^* = 1.74$, $X^* = 3.05$, $\mu^* = 0.423$, $v^* = 0.191$

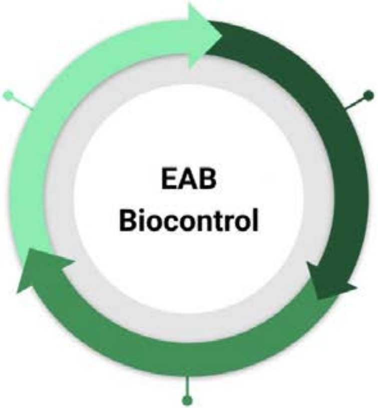
Conclusions

- Suboptimal refuge can stabilize N-B equilibria
  - reasonable in-refuge host growth rate
  - low ex-refuge escape probability
  - high in-refuge escape probability
- Model provides insight for biocontrol questions
  - best- and worst-case scenarios
  - parasitoid response to host range expansion
  - effect of increased efficiency of parasitoids

Future Work

Forest Regeneration

Population dynamics among Ash saplings, Mature Ash(refuge), EAB and larval parasitoids



Life-stages Model

Life cycle synchronization, application of parasitism in series and parasitism in parallel.

Negative Binomial Distribution

Express escape probability for EAB in white fringetree as negative binomial distribution (Hassell, 2000)

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Thank You!