Simon A. Levin Mathematical, Computational and Modeling Sciences Center

Dispersal Evolution in *Tribolium* Metapopulations: a Game Theory Approach

Quantitative Research in the Life and Social Sciences Program
Arizona State University

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Abstract

Dispersal is a critical ecological process that influences population dynamics, gene flow, and species distribution across landscapes. Factors that affect dispersal rate include environmental variability, habitat fragmentation, density-dependent interactions, and interspecific interactions. In this work, we study metapopulations dynamics of *Tribolium* beetles.

- We expanded Constantino et al.'s LPA Model to study dispersal in a 4-patch or 5-patch metapopulations.
- We show that the evolution of dispersal rates can be predicted under various environmental conditions.
- Using evolutionary game theory, we predict ESS dispersal rates in *Tribolium* beetles in both types of metapopulations when catastrophic extinctions occur on individual patches.

Research Questions

Here, we study the evolutionary dynamics of dispersal and its implications for population stability and species survival, specifically:

How does natural selection determine dispersal rate in metapopulations?

Model

In addition to the LPA assumptions, we assume that *Tribolium* will only disperse to an adjacent patch. Also dispersal is density-independent and non-biased. Furthermore, only adults will disperse. Dispersal happens at a rate γ with an associated cost ϵ. Additionally, phenotypes breed true.

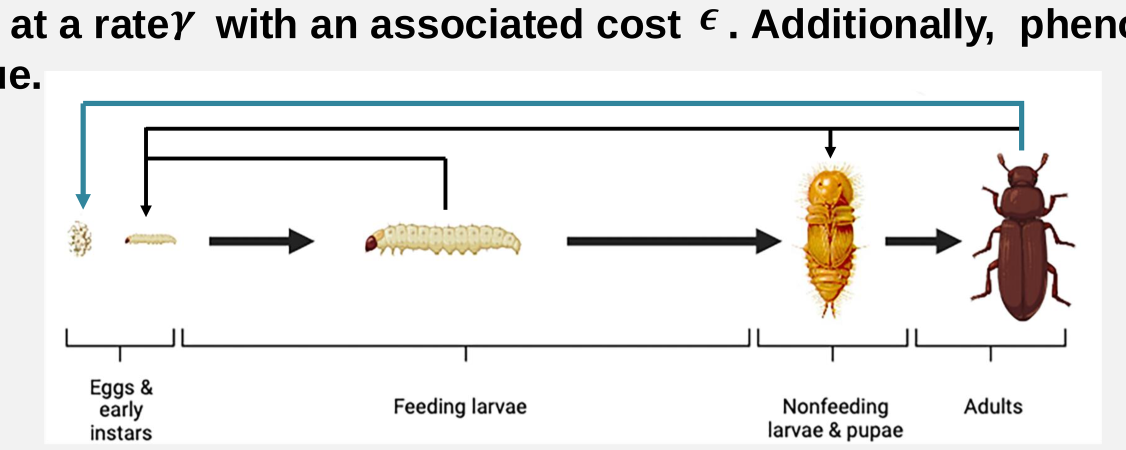

Figure 1. Tribolium Beetle Life History

❖ 4-Patch Metapopulation

$$L_{n+1,i} = bA_{n,i}e^{-c_{ea}A_{n,i}-c_{el}L_{n,i}}$$
$$P_{n+1,i} = P_{n,i}(1-\mu_l)$$
$$A_{n+1,i} = P_n \underbrace{e^{-c_{pa}A_{n,i}}}_{\text{Cannibalism}} + \underbrace{(1-\mu_a)}_{\text{Survival}} \underbrace{(1-\gamma)}_{\text{Philopatric}} A_{n,i} + \underbrace{\frac{1}{2}\gamma(1-\mu_a)(1-\epsilon)(A_{n,j}+A_{n,k})}_{\text{Migration}}$$

❖ 5-Patch Metapopulation

$$L_{n+1,i} = bA_{n,i}e^{-c_{ea}A_{n,i}-c_{el}L_{n,i}}$$
$$P_{n+1,i} = P_{n,i}(1-\mu_l)$$
$$A_{n+1,i} = P_n e^{-c_{pa}A_{n,i}} + (1-\mu_a)(1-\gamma)A_{n,i} + \overbrace{\gamma(1-\mu_a)(1-\epsilon)A_{n,5})}^{\text{Migration from patch 5}}$$
$$A_{n+1,5} = P_n e^{-c_{pa}A_{n,5}} + (1-\mu_a)(1-\gamma)A_{n,5} + \underbrace{\frac{1}{4}\gamma(1-\mu_a)(1-\epsilon)\sum_{j=1}^{4} A_{n,j}}_{\text{Immigration from 4-patches}}$$

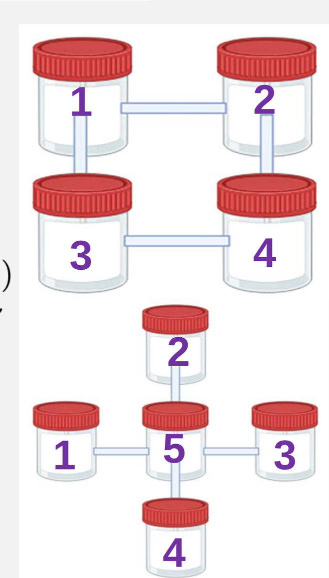

Figure 2. 4-patch & 5-patch metapopulations.

Metapopulation Dynamics

We are using the 4 & 5 patch LPA model combined with Brozak et al. best data fitting of the original LPA model. This most accurately represents our *Tribolium* population dynamics data

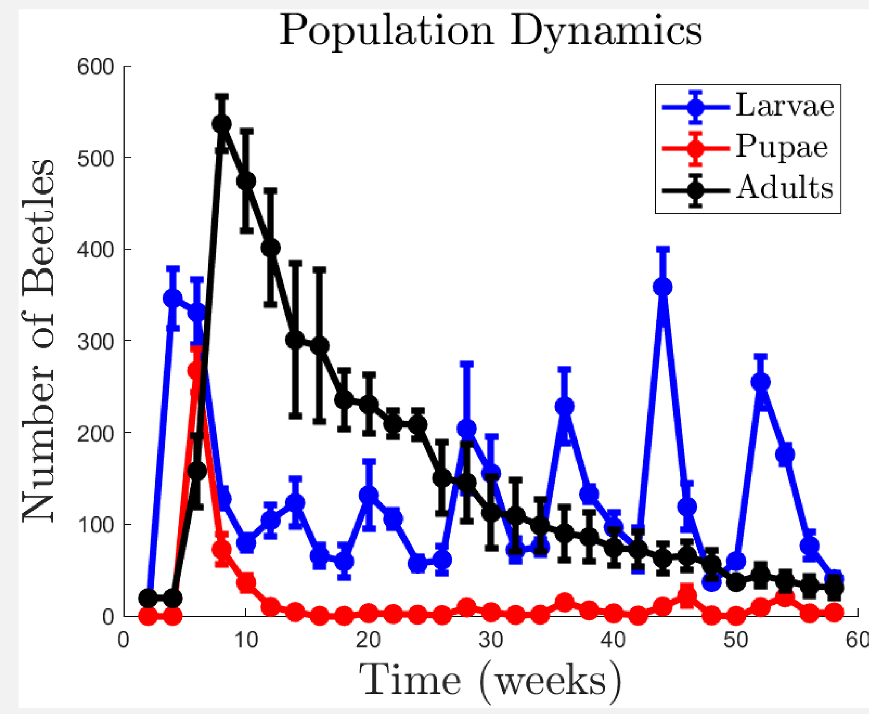

Figure 3. Data set of *Tribolium* population dynamics.

Population Persistence

$$R_0 = \frac{b(1-\mu_l)}{\mu_a + \gamma\epsilon} > 1$$

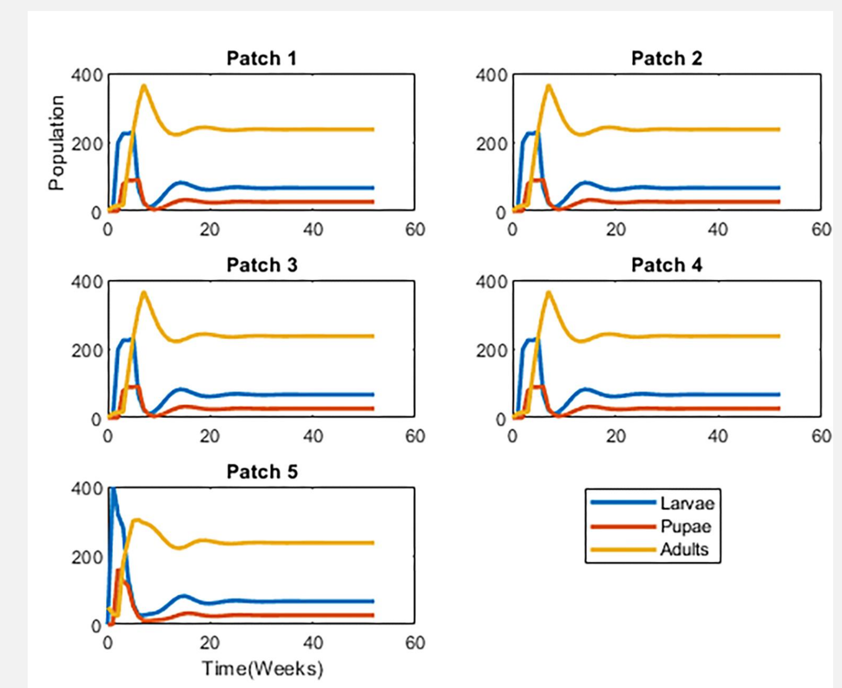

Figure 4. Solution to the 5-patch metapopulation models.

Evolutionary Dynamics

Fitness – 4-Patch Metapopulation

$$E[A] = \text{Average number of adults in the long run}$$
$$E[L] = \text{Average number of larvae in the long run}$$
$$\theta = be^{-c_{ea}E[A]-c_{el}E[L]-c_{pa}E[A]}(1-\mu_l)$$
$$F_r = \frac{\theta}{\mu_a + \gamma_r\epsilon} \qquad F_m = \frac{\theta}{\mu_a + \gamma_m\epsilon}$$

Invasion Exponent

$$\lambda = \ln\left(\frac{F_m}{F_r}\right)$$

Invasion criterion:

$$\lambda > 0 \implies \gamma_r > \gamma_m$$

Will emulating extinction in different patches generate enough heterogeneity for dispersal to evolve?

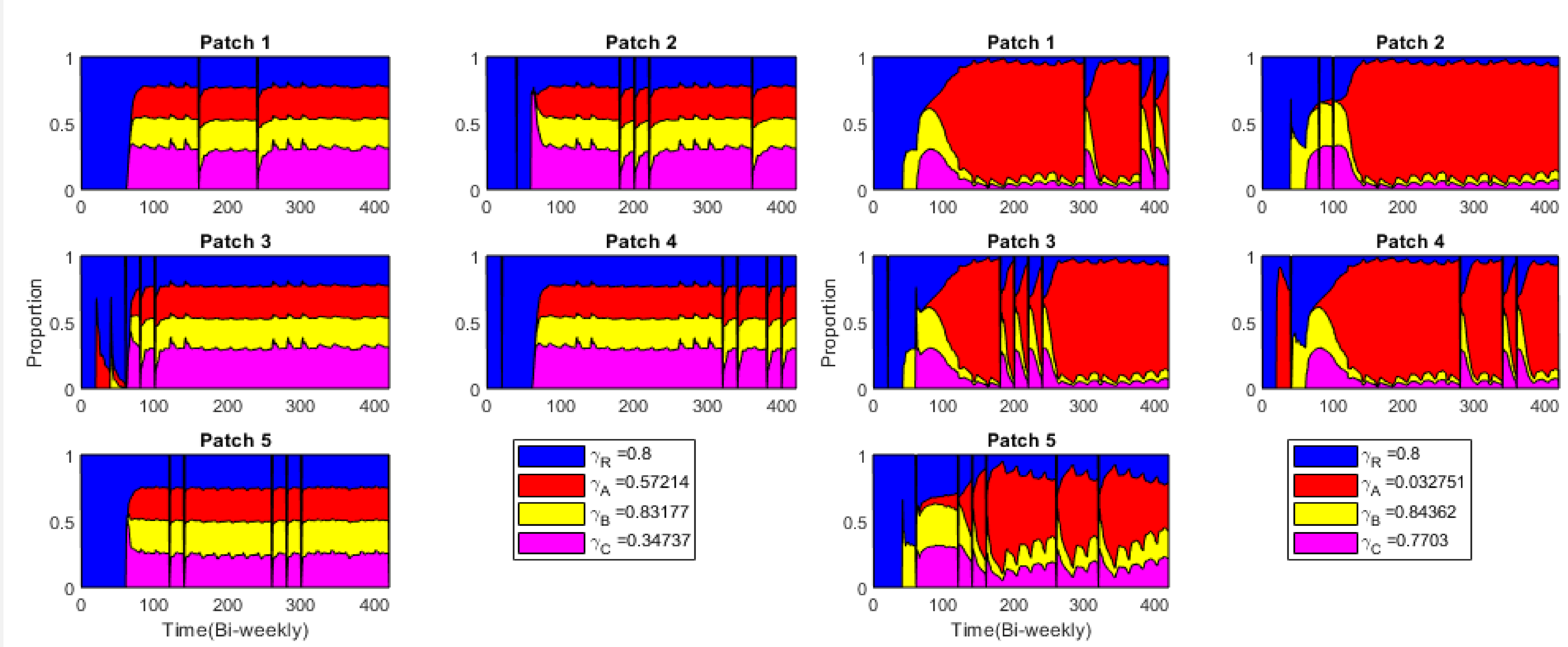

Figure 5. simulations of the proportion of dispersal evolution in a 5-patch metapopulation using patch graphs. The graphs show how the different γ values determine the rate at which the classes take up the space.

Conclusions

- If all patches are physically identical, then evolution will not evolve in either 4 or 5 patch metapopulations.
- In 4-patch configuration random extinction does not appear to generate enough heterogeneity to move the ESS away from 0 dispersal.
- However, in 5-patch metapopulations, stable polymorphisms in dispersal propensity appear to be common.

Future Scope

1. Expand our metapopulations to have different dynamics which could result in heterogeneity
2. Investigate both biased and density-dependent dispersal and their effects on heterogeneity.
3. Age-Structured Model:

$$\frac{\partial p}{\partial t} = \begin{cases} -g(s)\frac{\partial p}{\partial s} - c_{ea}A(t) - c_{el}\int_{s_1}^{s_2} p(s,t)\,ds - \mu_j(s)p(s,t), & \text{if } s \in (0, s_1) \\ -g(s)\frac{\partial p}{\partial s} - \mu_j(s)p(s,t), & \text{if } s \in [s_1, s_2) \\ -g(s)\frac{\partial p}{\partial s} - c_{pa}A(t) - \mu_j(s)p(s,t), & \text{if } s \in [s_2, s_3) \end{cases}$$
$$\frac{dA}{dt} = gp(s_3,t) - \mu_a A(t), \quad \text{if } s \in [s_3, \infty)$$

Boundary Condition (B.C.):

$$p(0,t) = bA(t) \quad \text{at } s = 0$$

Continuity Conditions (C.C.):

$$\frac{\partial p(s_1,t)}{\partial t} = g(s_1)p(s_1,t) \quad \text{at } s = s_1$$
$$\frac{\partial p(s_2,t)}{\partial t} = g(s_2)p(s_2,t) \quad \text{at } s = s_2$$

Parameter/ Variable	Description
$p(s,t)$	Population density at stage s and time t
$A(t)$	Adult population at time t
$g(s)$	Growth function
c_{ea}	Cannibalism rate of eggs by adults
c_{el}	Cannibalism rate of eggs by larvae
c_{pa}	Cannibalism rate of pupae by adults
b	Birth rate of new eggs
μ_e	Natural death rate of eggs and early instar larvae
μ_l	Natural death rate of feeding larvae
μ_p	Natural death rate of non-feeding larvae, pupae, and callow adults
μ_a	Natural death rate of adults
s_1, s_2, s_3	Stage boundaries

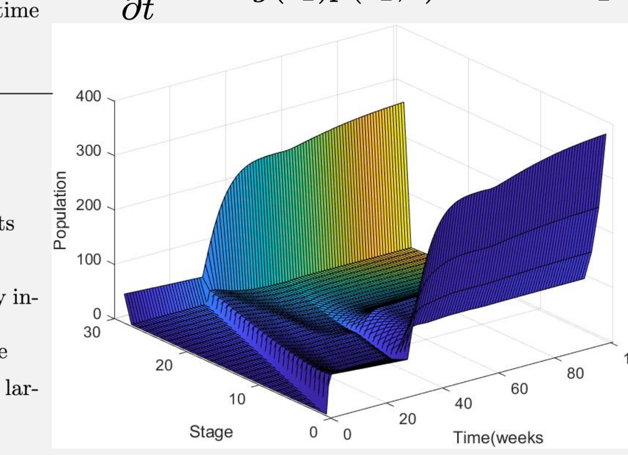

Figure 2 . 3D plot of age structured model.

Acknowledgements

We would like to thank Dr. Fabio Milner, Director of the Simon A. Levin Mathematical, Computational and Modeling Sciences Center (Levin Center), and Co-Director Dr. John Nagy for giving us the opportunity to participate in the Quantitative Research in the Life and Social Sciences program. We also recognize the work of the many administrative staff and tutors who supported this effort. This research was conducted as part of 2024 QRLSSP at the Levin Center (MCMSC) at Arizona State University (ASU) and has been partially supported by a grant from the National Science Foundation (NSF Grant FAIN-2150492), and by the Office of the President of ASU, and the Office of the Provost of ASU.

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