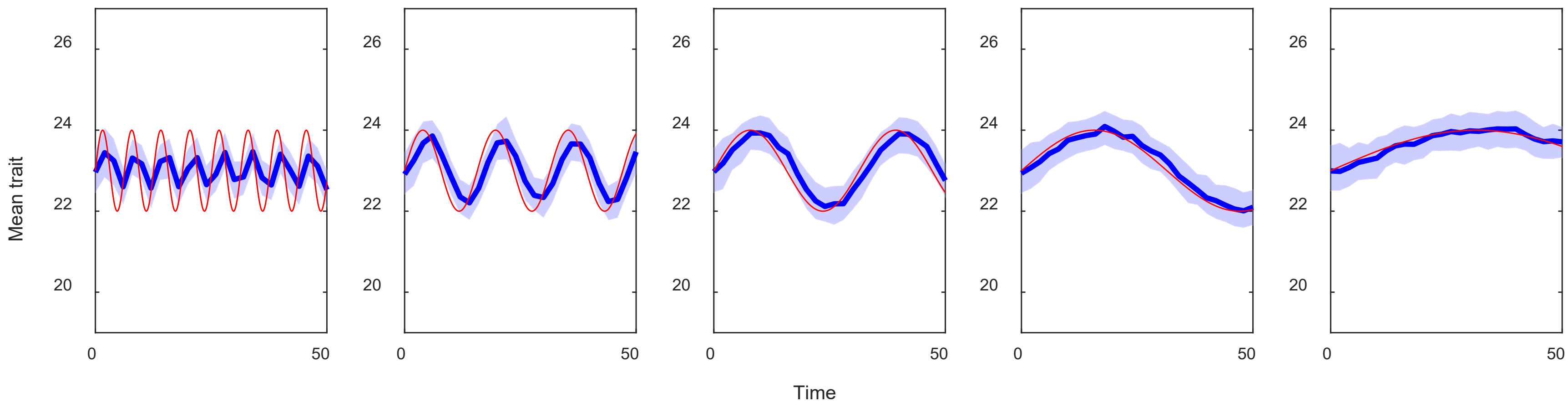
Climate change and scaling up across levels with evolution



John P. DeLong
University of Nebraska – Lincoln

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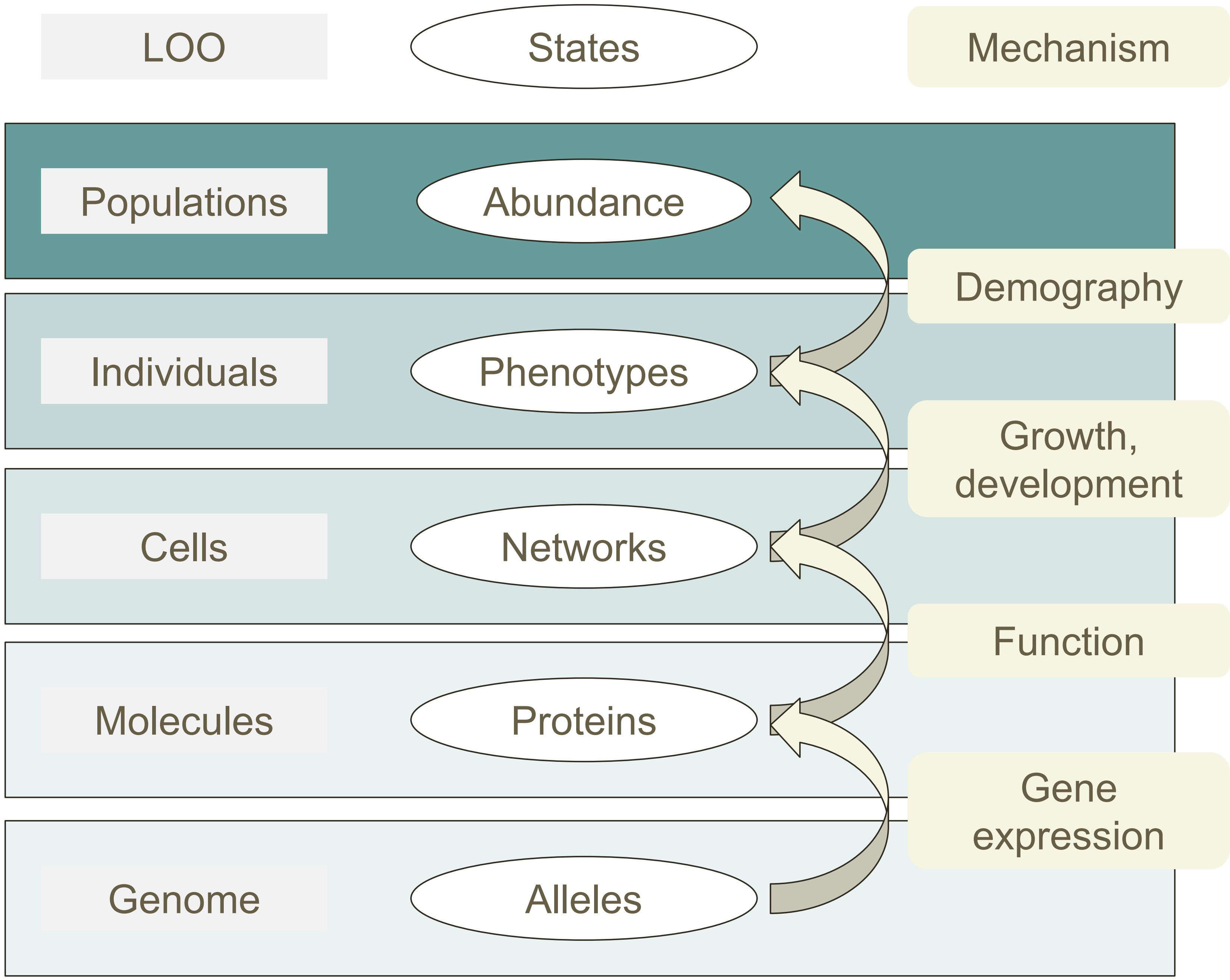
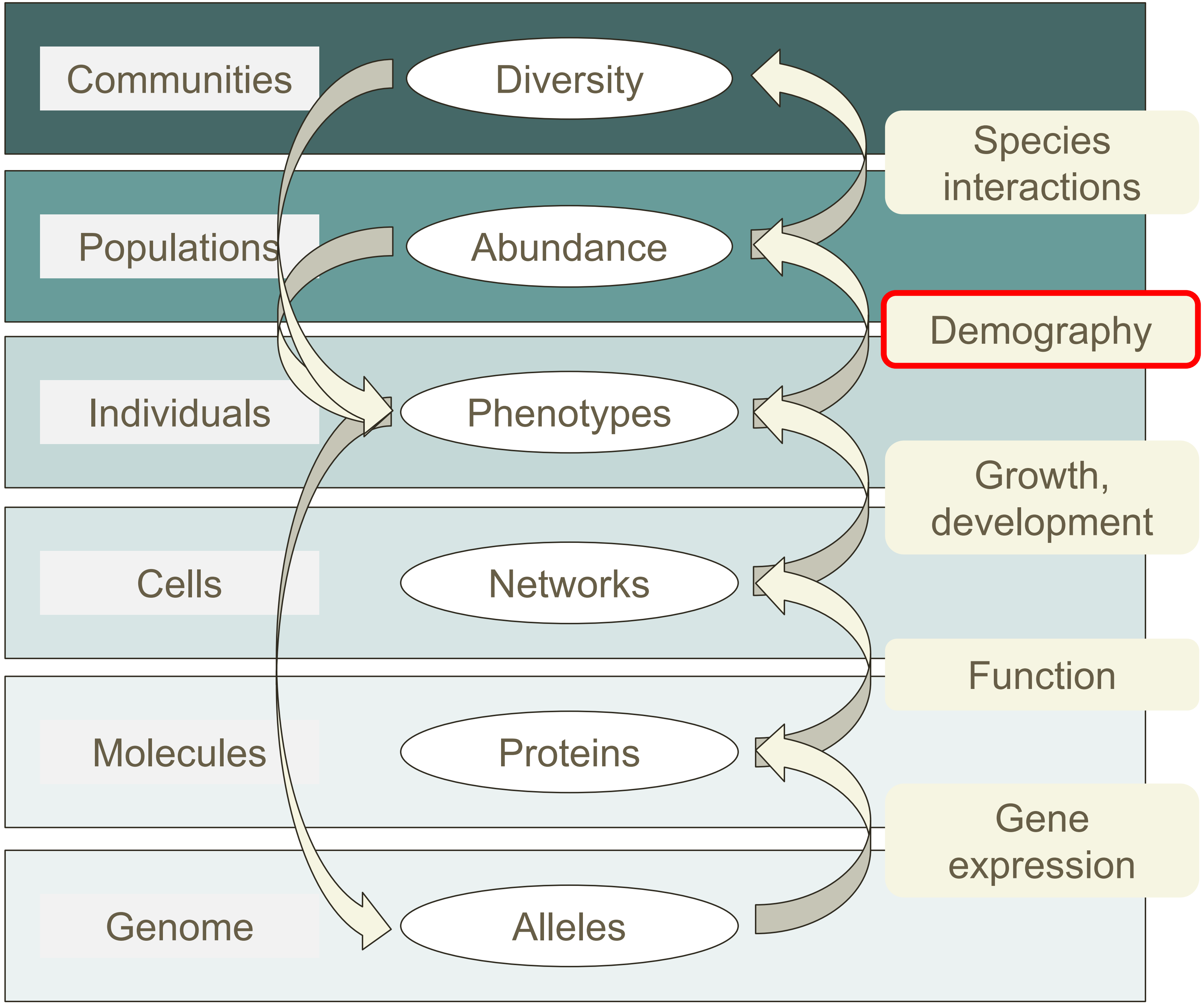
g2p2pop website

Goal: "…predicting how populations and species of vertebrates will respond to a changing climate by integrating knowledge across levels of biological organization."

Four suggestions today:

- Anchor models at points that *must be true*
- Visualize parameters of dynamic models as emergent properties of lower levels – dissect them to access mechanism
- Allow for changes in allele frequencies through evolution
- Try out Gillespie eco-evolutionary models (GEMs) as a tool


LOO
States
Mechanism
Populations
Abundance
Demography
Individuals
Phenotypes
Growth, development
Cells
Networks
Function
Molecules
Proteins
Gene expression
Genome
Alleles


Communities
Diversity
Populations
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Cells
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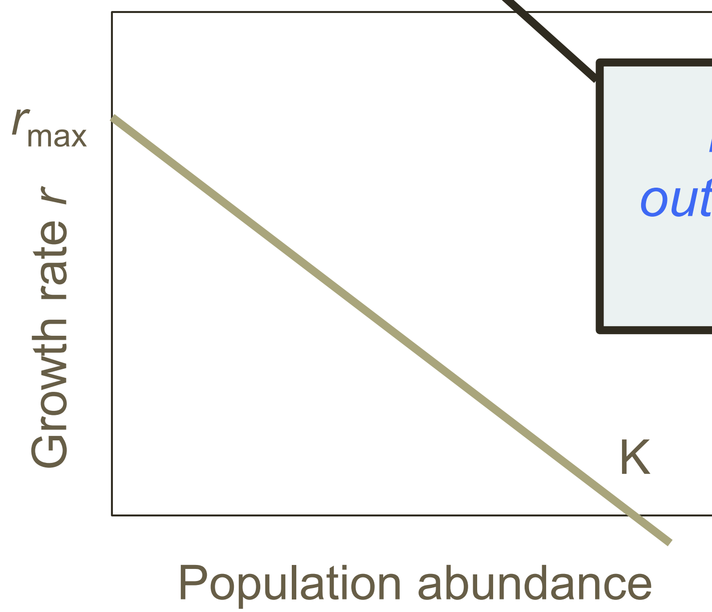
Molecules
Proteins
Genome
Alleles
Species interactions
Demography
Growth, development
Function
Gene expression

Chapter 1. A very simple example.

Logistic model

$$\frac{dR}{dt} = \left[r_{max}\left(1 - \frac{R}{K}\right)\right] R$$

$$\frac{dR}{dt} = r_{max} R$$

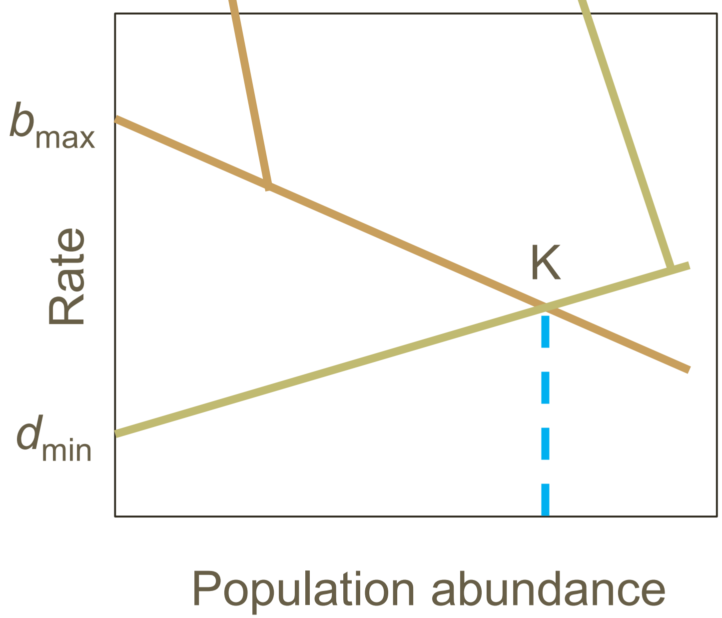


Parameters are an outcome of mechanisms at lower level

bd logistic

Birth — Death

$$\frac{dR}{dt} = [b_{max}(1 - b_s R) - d_{min}(1 + d_s R)]R$$

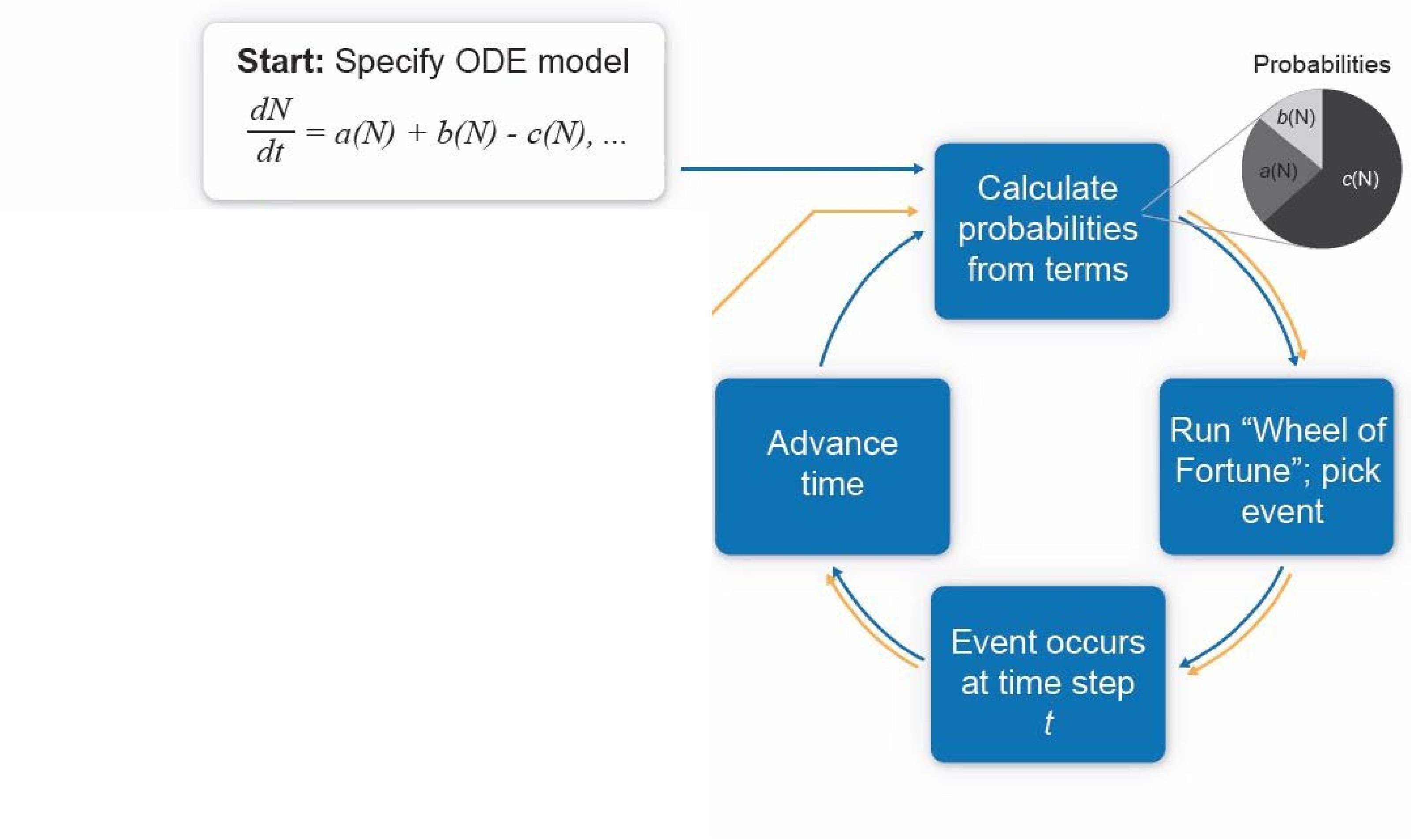


$$r = b_{max} - d_{min}$$

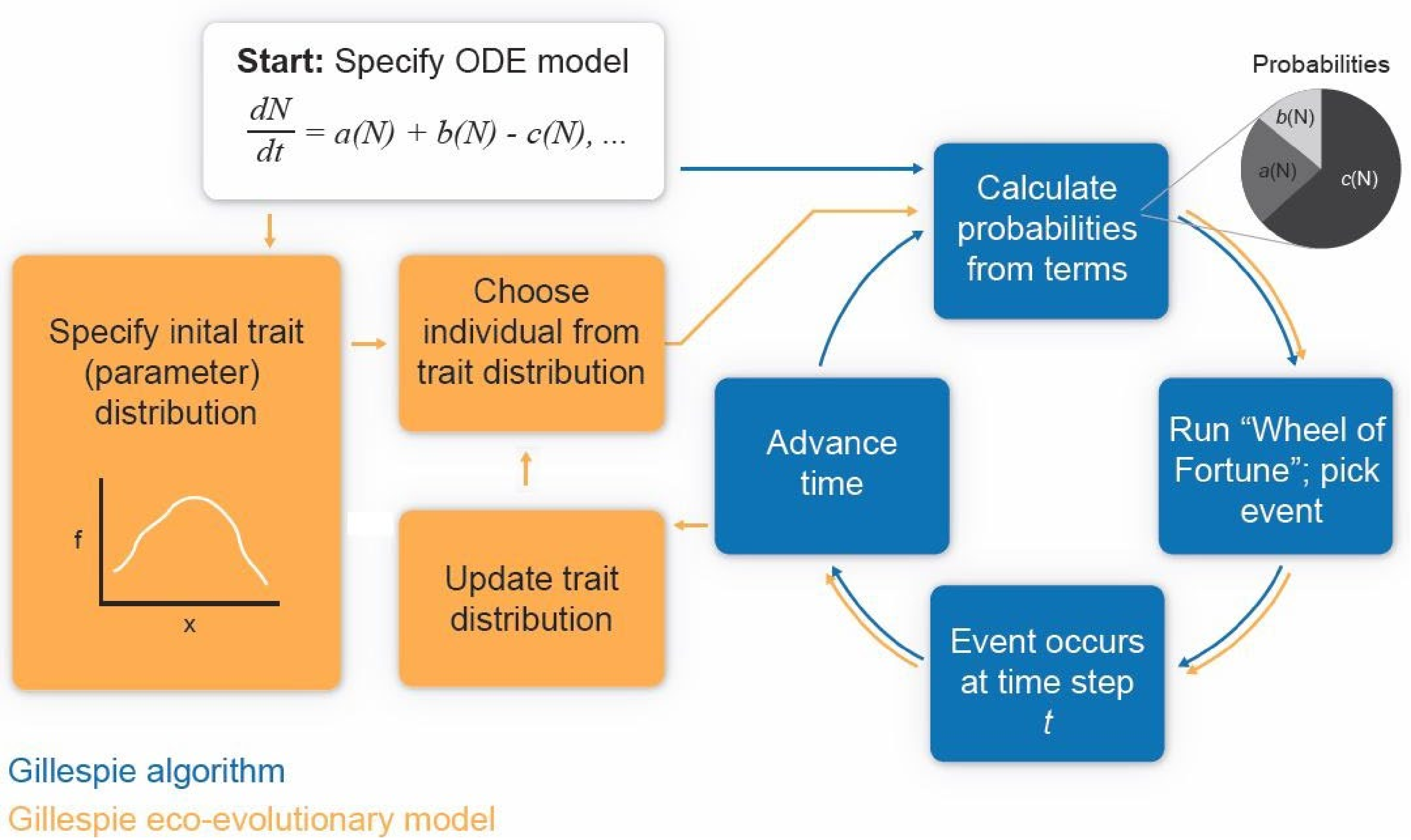
$$K = \frac{b_{max} - d_{min}}{b_s + d_s}$$

Parameters are an outcome of mechanisms at lower level

Gillespie algorithm

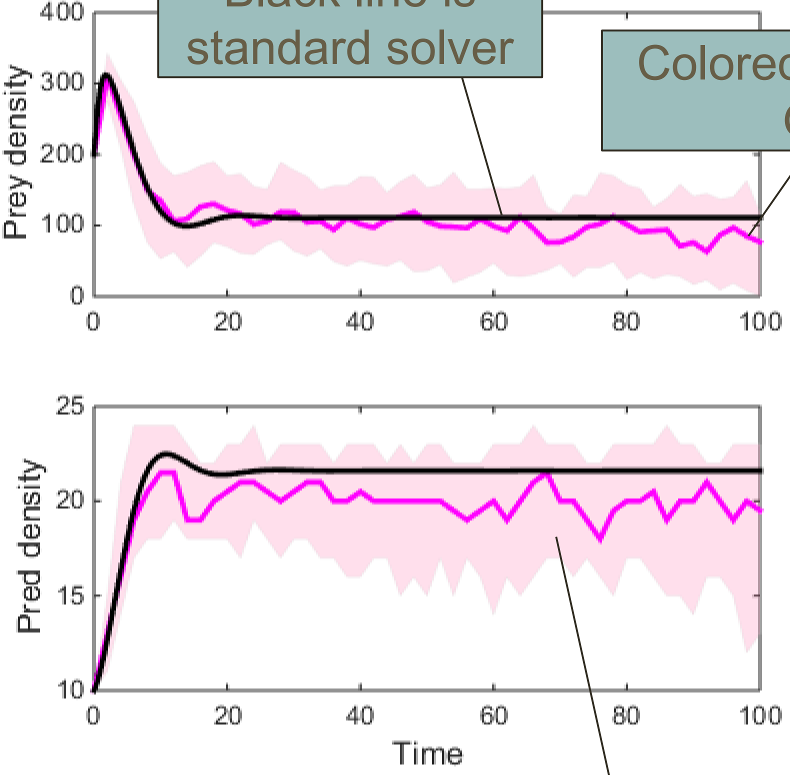


GEMs



Start: Specify ODE model
$$\frac{dN}{dt} = a(N) + b(N) - c(N), \ldots$$
Specify inital trait (parameter) distribution
f
x
Choose individual from trait distribution
Update trait distribution
Calculate probabilities from terms
Probabilities
b(N)
a(N)
c(N)
Run "Wheel of Fortune"; pick event
Event occurs at time step t
Advance time
Gillespie algorithm
Gillespie eco-evolutionary model

Figure primer



Black line is standard solver

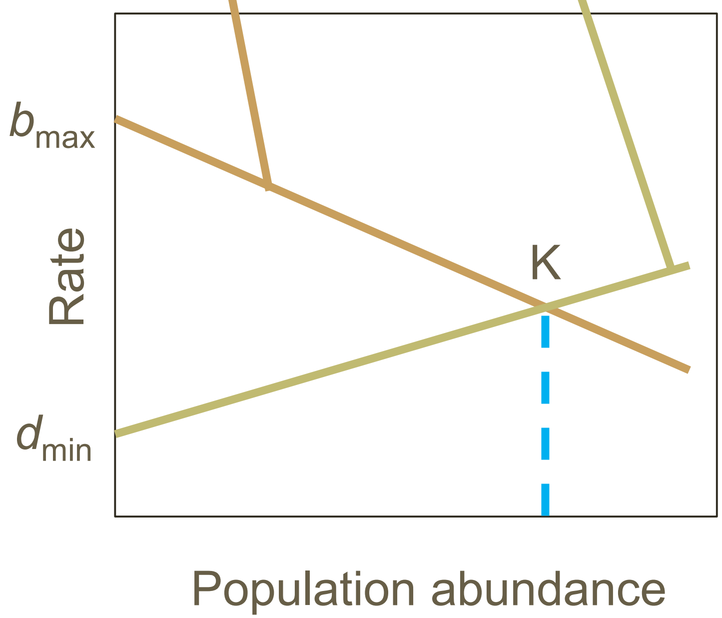
Colored line is median Gillespie

Shaded area is middle 50% of simulations

bd logistic

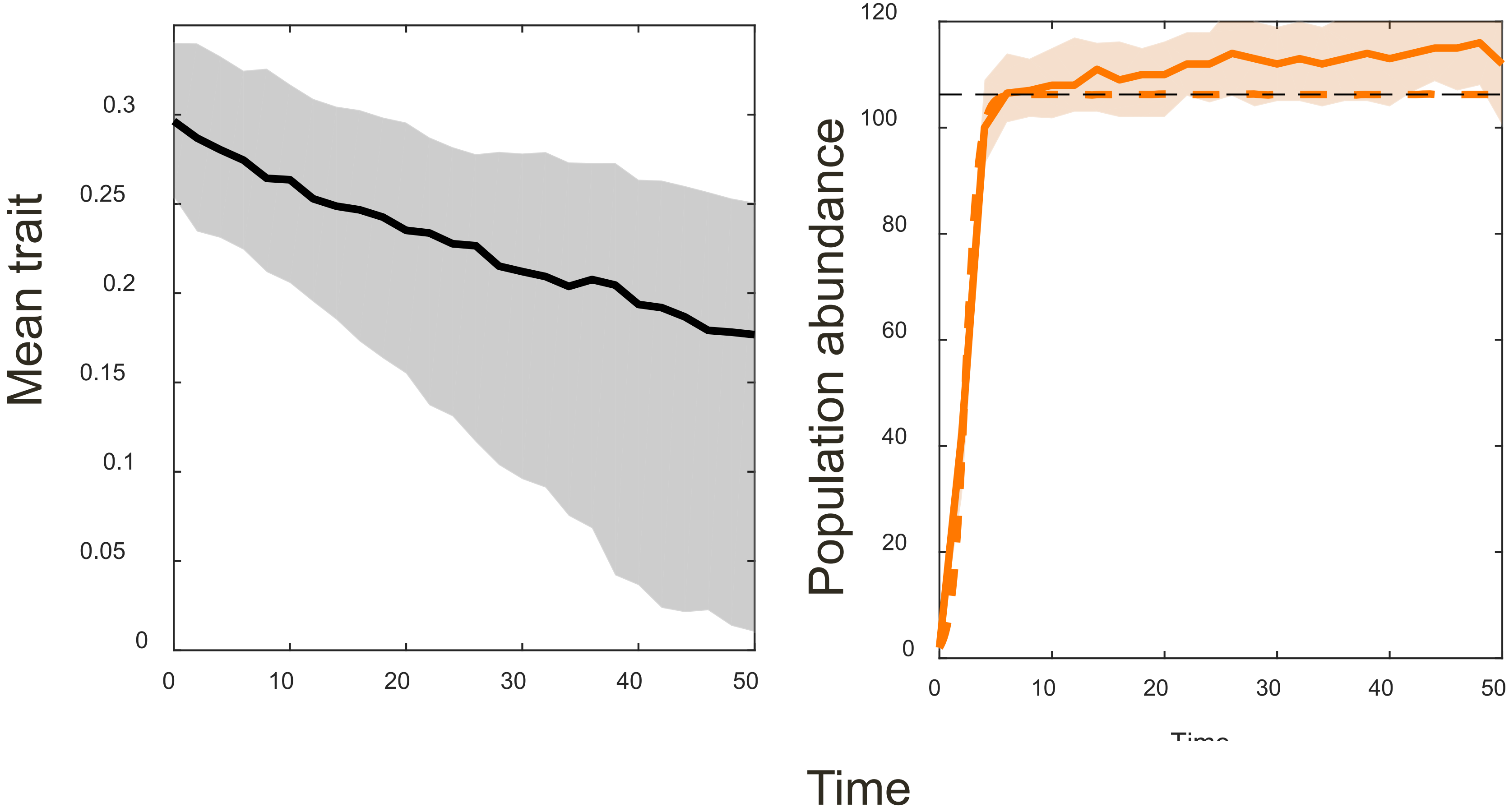
Birth Death

$$\frac{dR}{dt} = [b_{max}(1 - b_s R) - d_{min}(1 + d_s R)]R$$



$$r = b_{max} - d_{min}$$

$$K = \frac{b_{max} - d_{min}}{b_s + d_s}$$

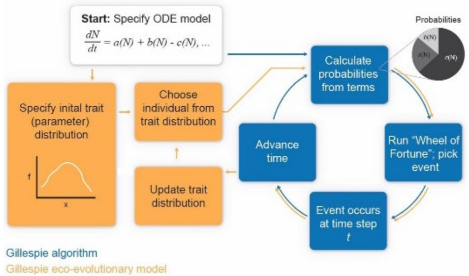


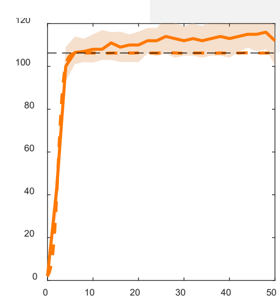
Mean trait
0.3
0.25
0.2
0.15
0.1
0.05
0
0
10
20
30
40
50
Population abundance
120
100
80
60
40
20
0
0
10
20
30
40
50
Time

Eco-evolutionary dynamics

$$\frac{dR}{dt} = rR\left(1 - \frac{R}{K}\right)$$

$$[b_{max}(1 - b_s R) - d_{min}(1 + d_s R)]$$

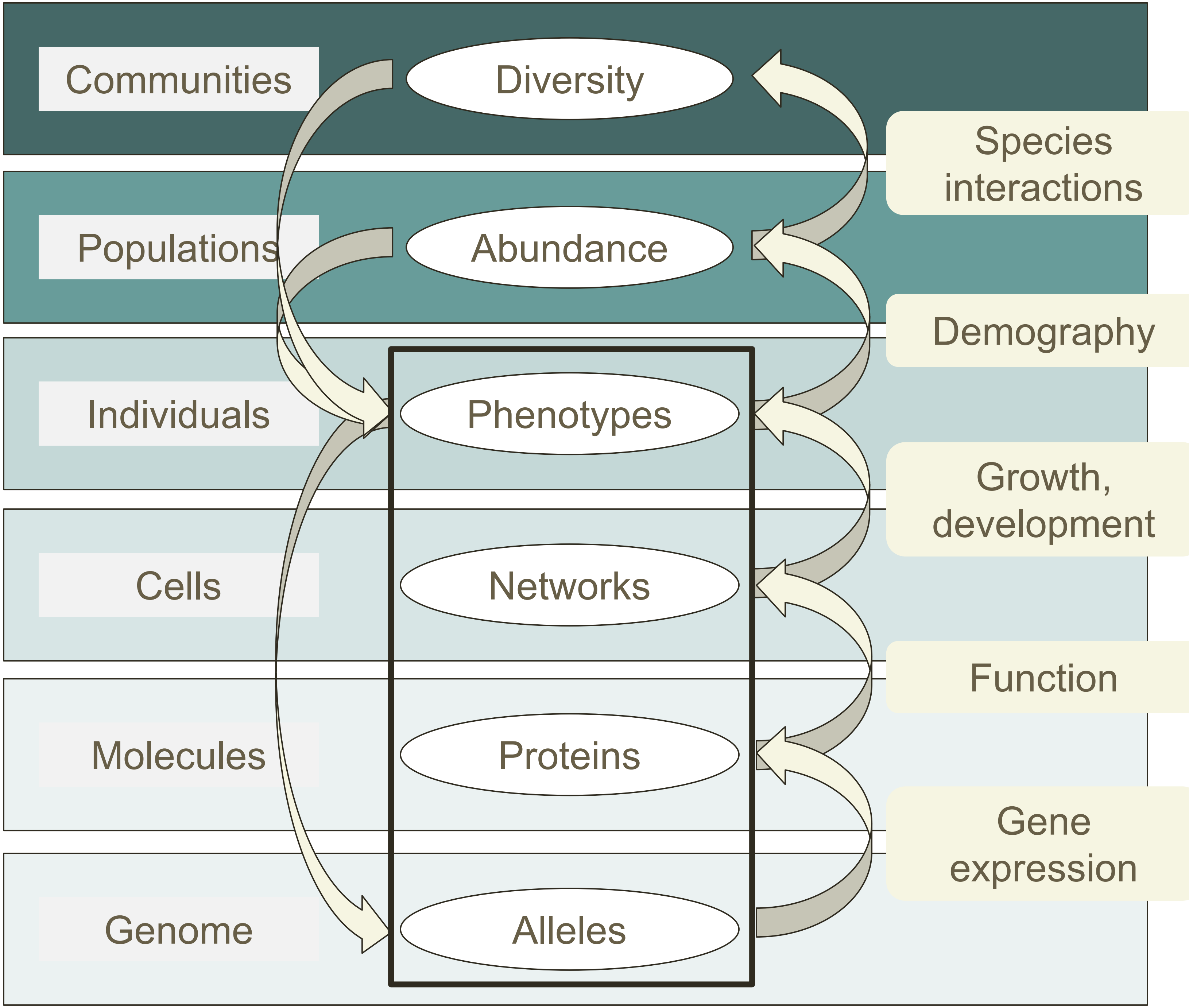




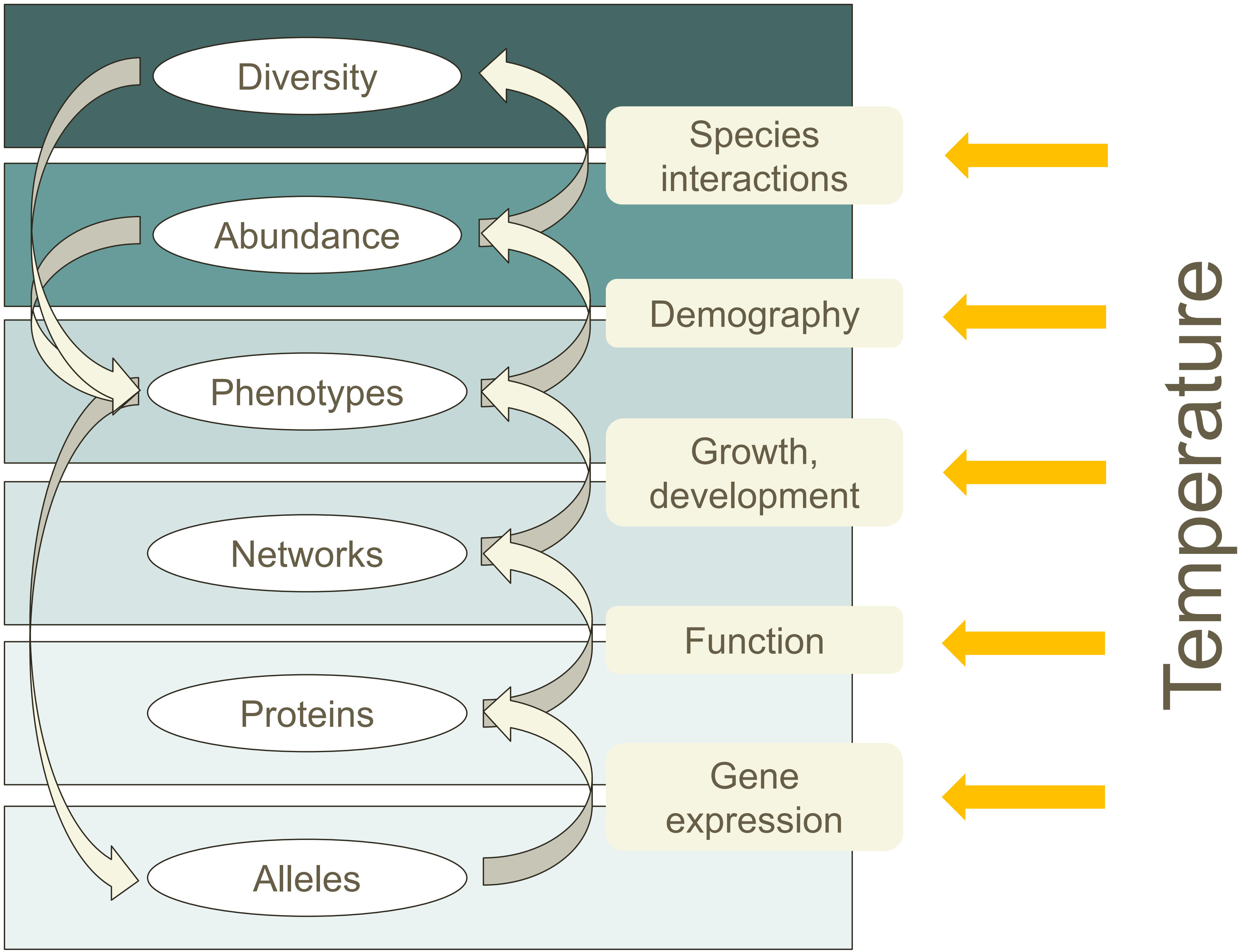
1. Take a population model as a mass-balance constraint

2. Take apart parameters to get at their mechanistic underpinnings

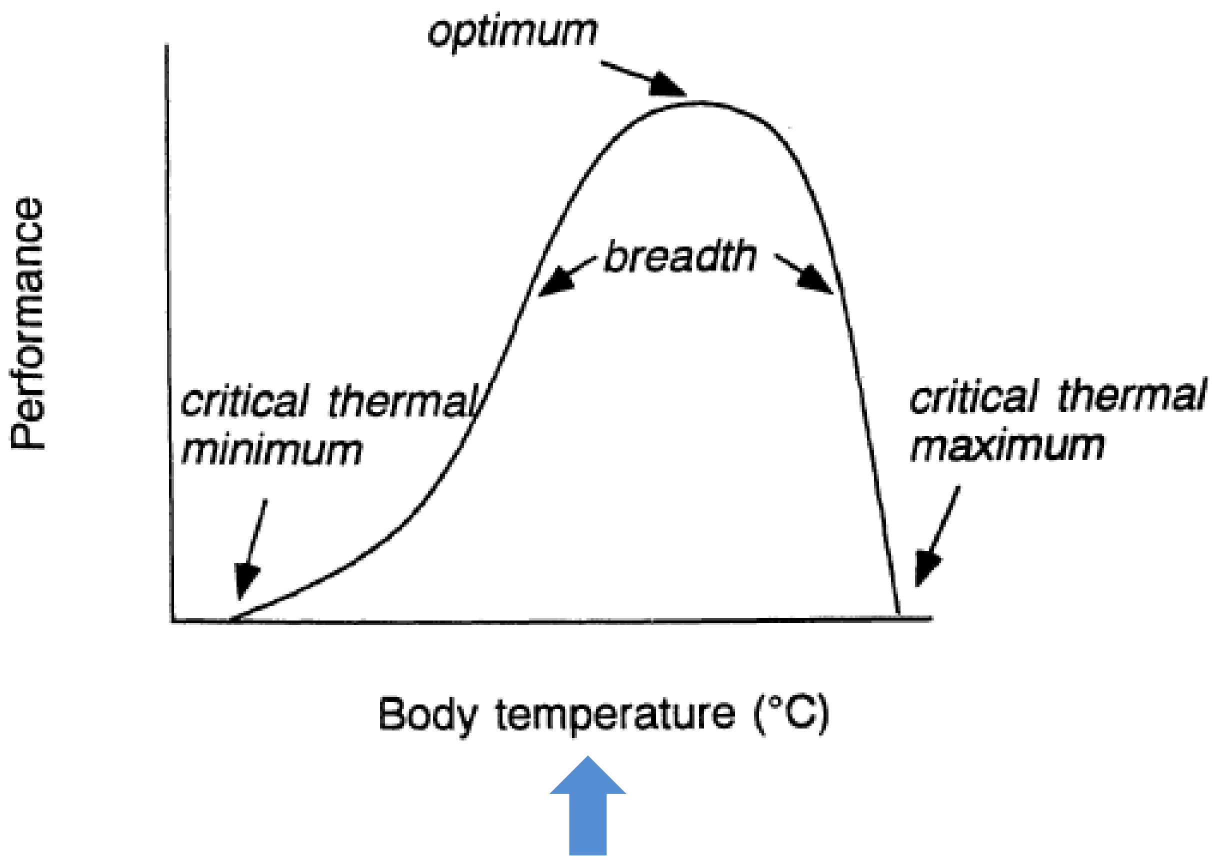
3. Use a GEM to assess real-time evolutionary effects on population outcomes


Communities
Populations
Individuals
Cells
Molecules
Genome
Diversity
Abundance
Phenotypes
Networks
Proteins
Alleles
Species interactions
Demography
Growth, development
Function
Gene expression

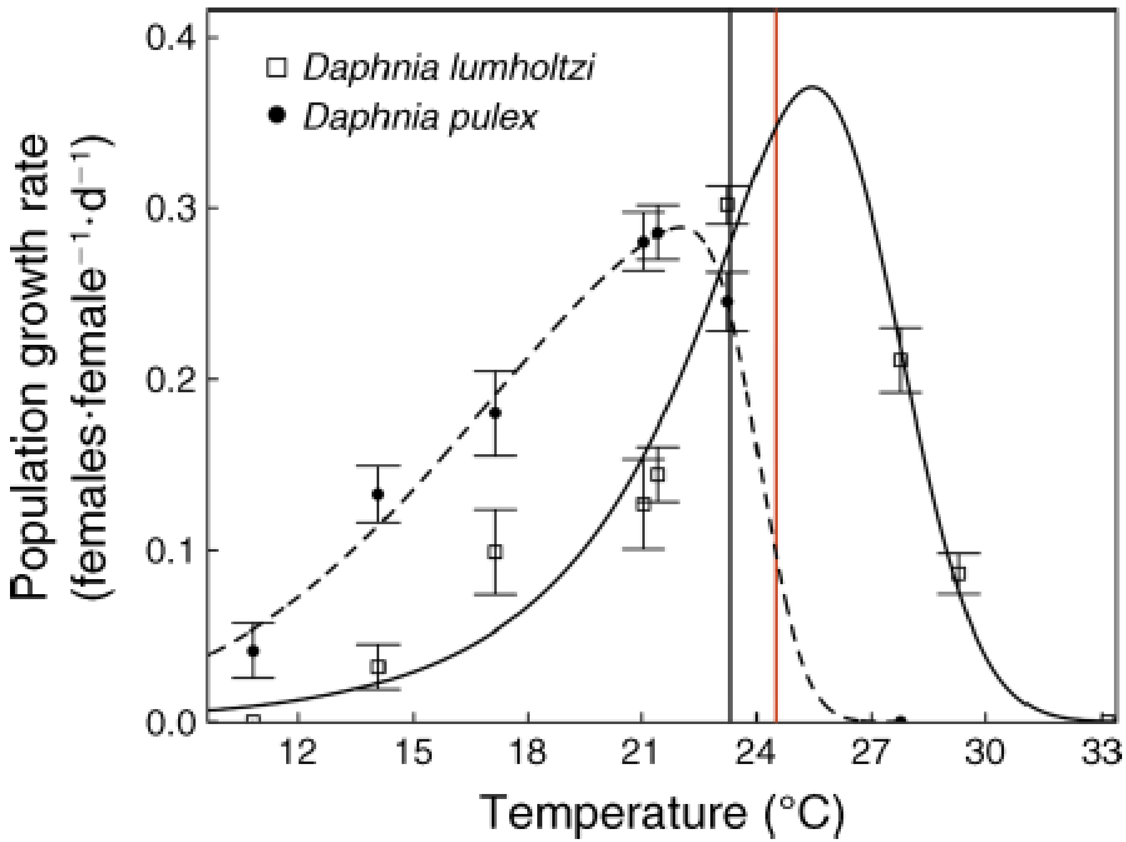
Chapter 2. Evolution of thermal niches.


Diversity
Abundance
Phenotypes
Networks
Proteins
Alleles
Species interactions
Demography
Growth, development
Function
Gene expression
Temperature

Thermal performance curve (TPC)

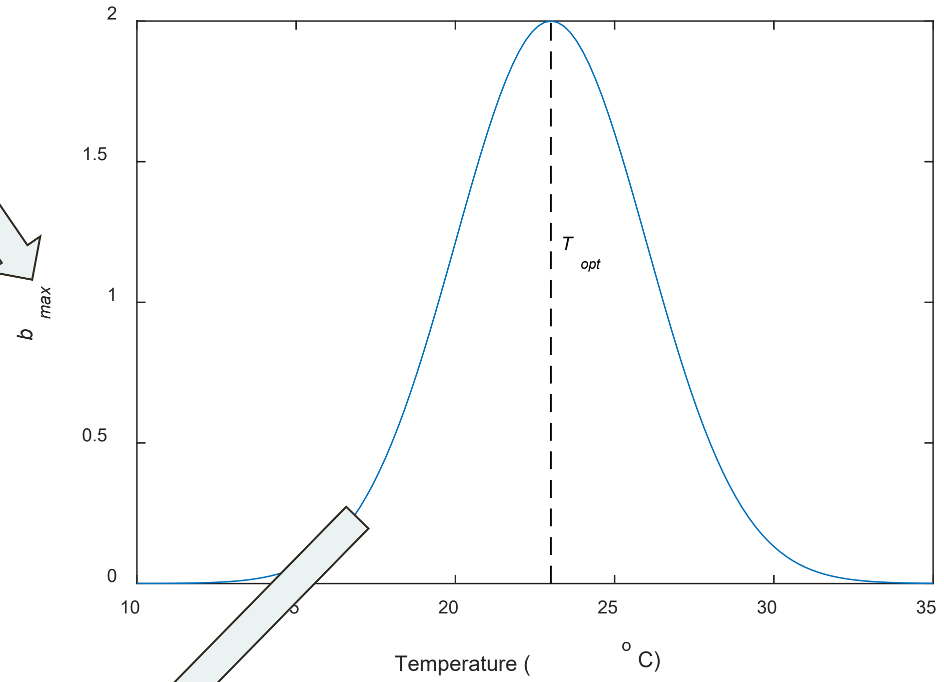


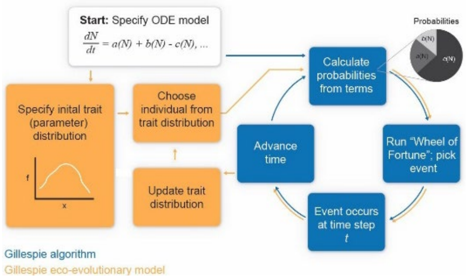
Huey and Kingsolver 1993



Fey and Cottingham 2012 ECOL

$$[b_{max}(1 - b_s R) - d_{min}(1 + d_s R)]$$

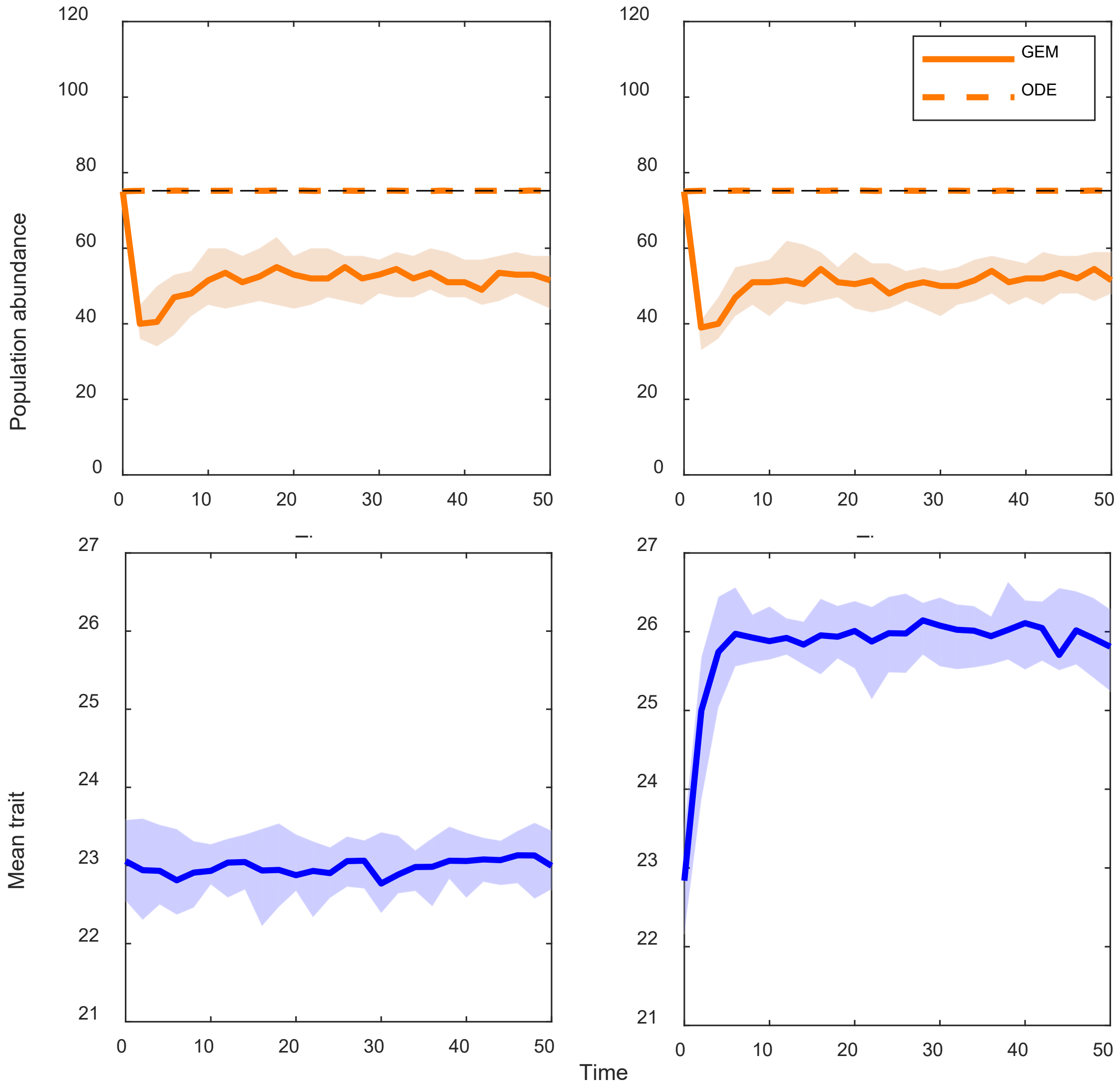


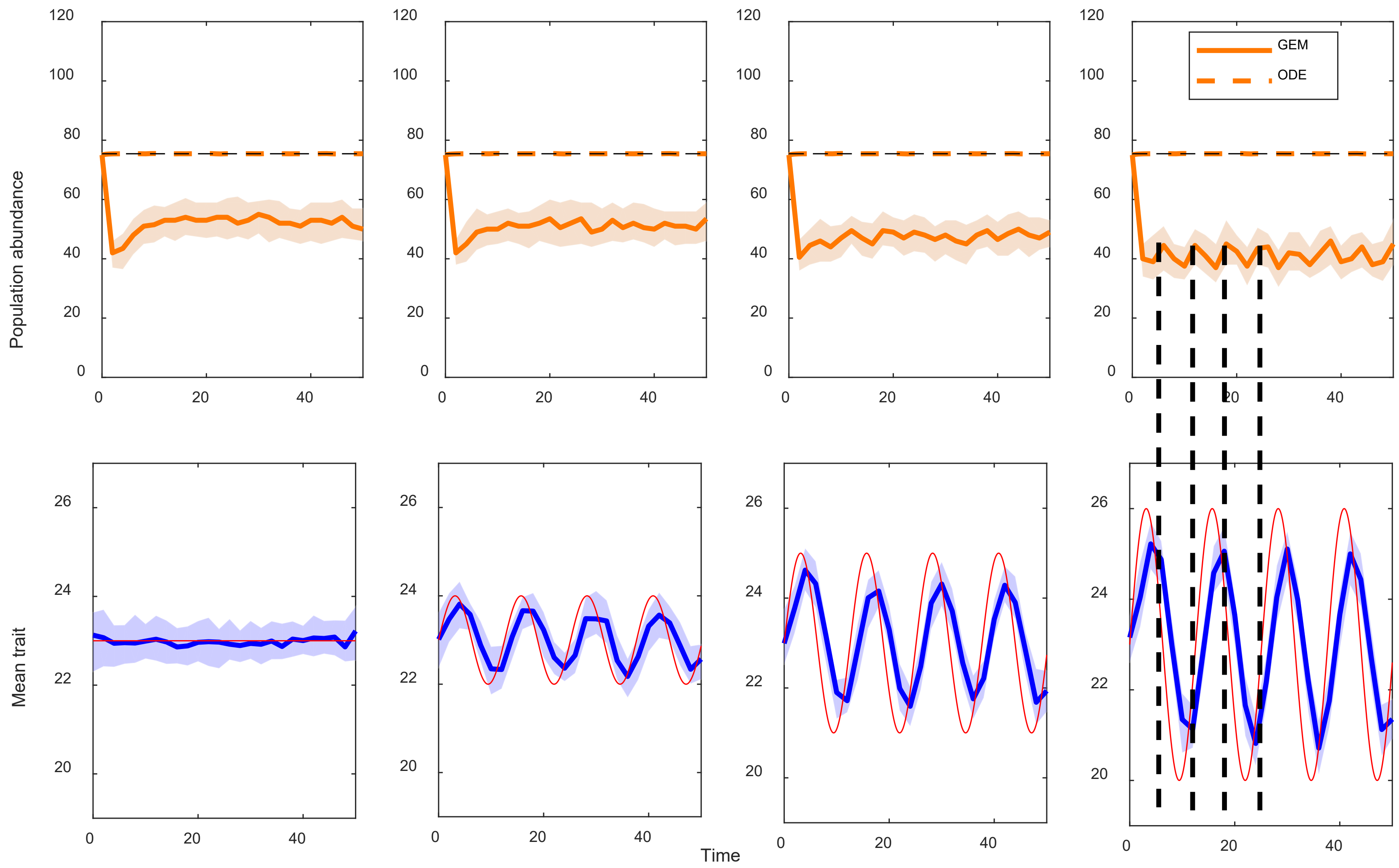


Two things:

1. Leave temp at 23°C
2. Shift temp to 26°C

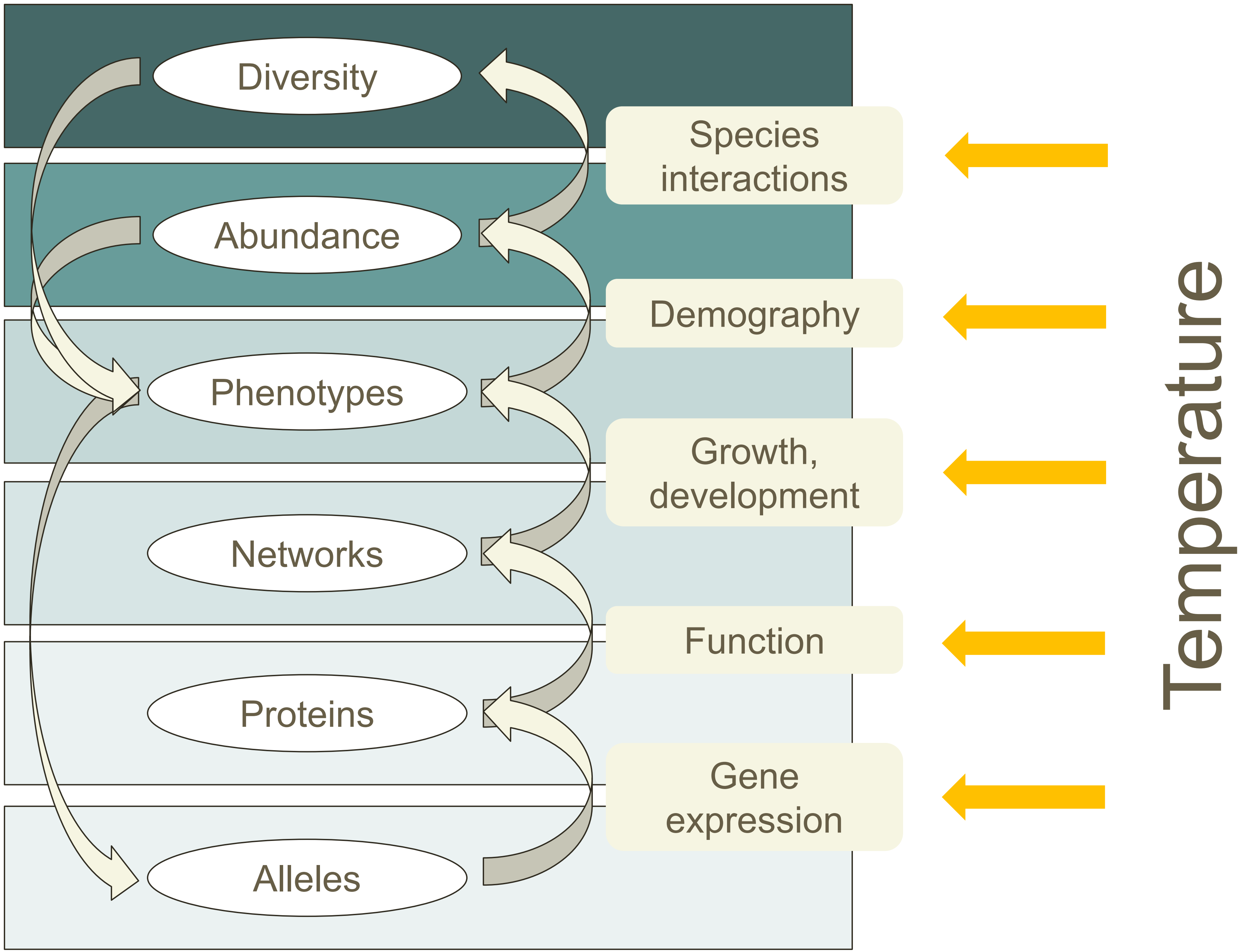
Temp = 23°C   Temp = 26°C





Population abundance
Mean trait
Time
GEM
ODE

Chapter 3. Mechanisms of temperature dependence.


Diversity
Abundance
Phenotypes
Networks
Proteins
Alleles
Species interactions
Demography
Growth, development
Function
Gene expression
Temperature

Arrhenius equation

$$R = A_0 e^{-E_a/kT}$$

Activation energy

Proportion of reaction occurring

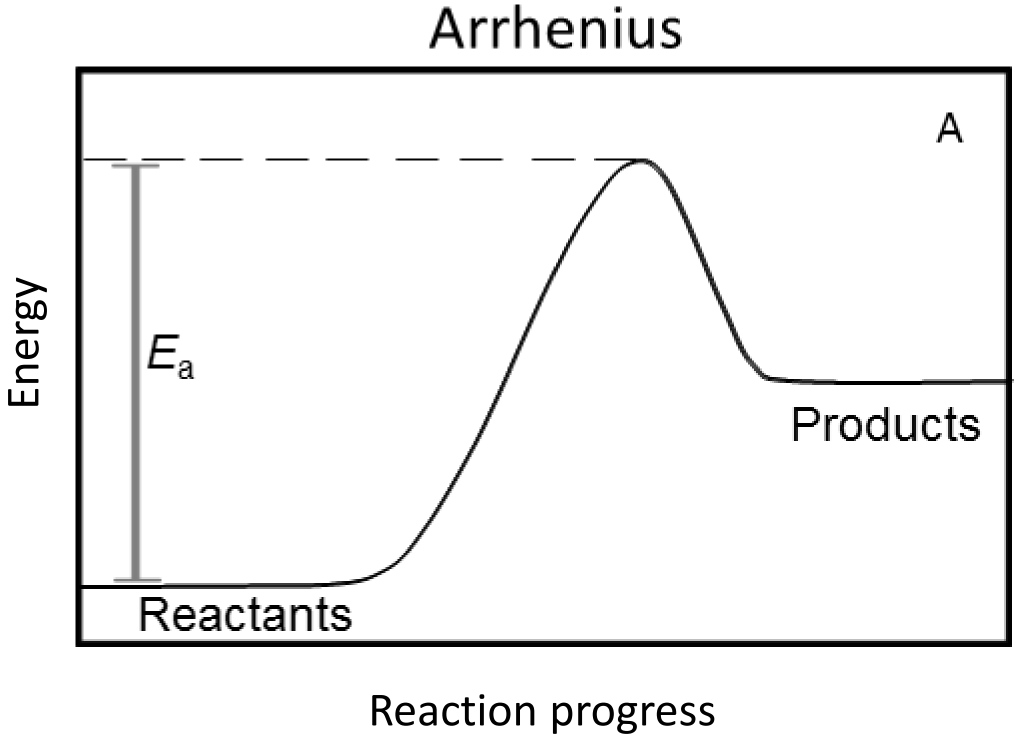
Temperature

Reaction rate

Boltzmann's constant

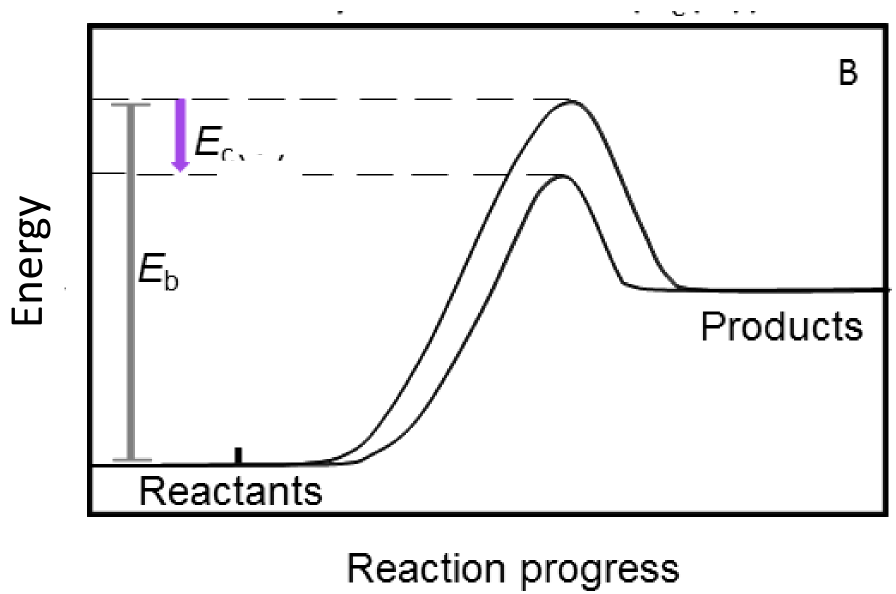
Reaction rate potential (mass action)

Activation energy



$$R = A_0 e^{-E_a/kT}$$

Enzyme assist



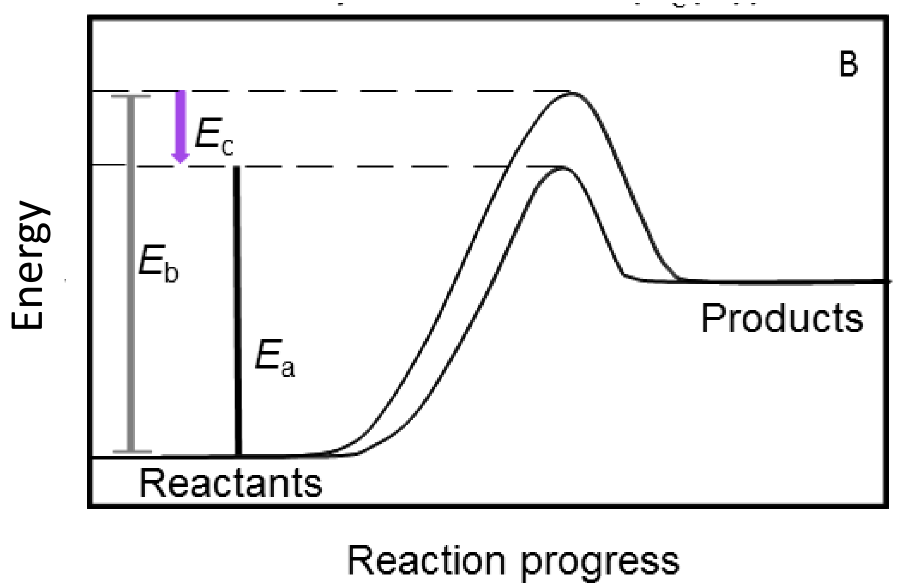
Baseline activation energy

Contributed energy

$$R = A_0 e^{-(E_b - E_c)/kT}$$

DeLong et al 2017 Ecology & Evolution

Enzyme assist



Baseline activation energy

Contributed energy

$$R = A_0 e^{-(E_b - E_c(T))/kT}$$

DeLong et al 2017 Ecology & Evolution

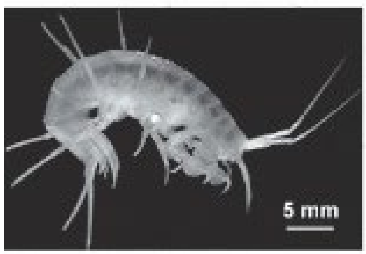
Enzyme-assisted Arrhenius (EAAR)

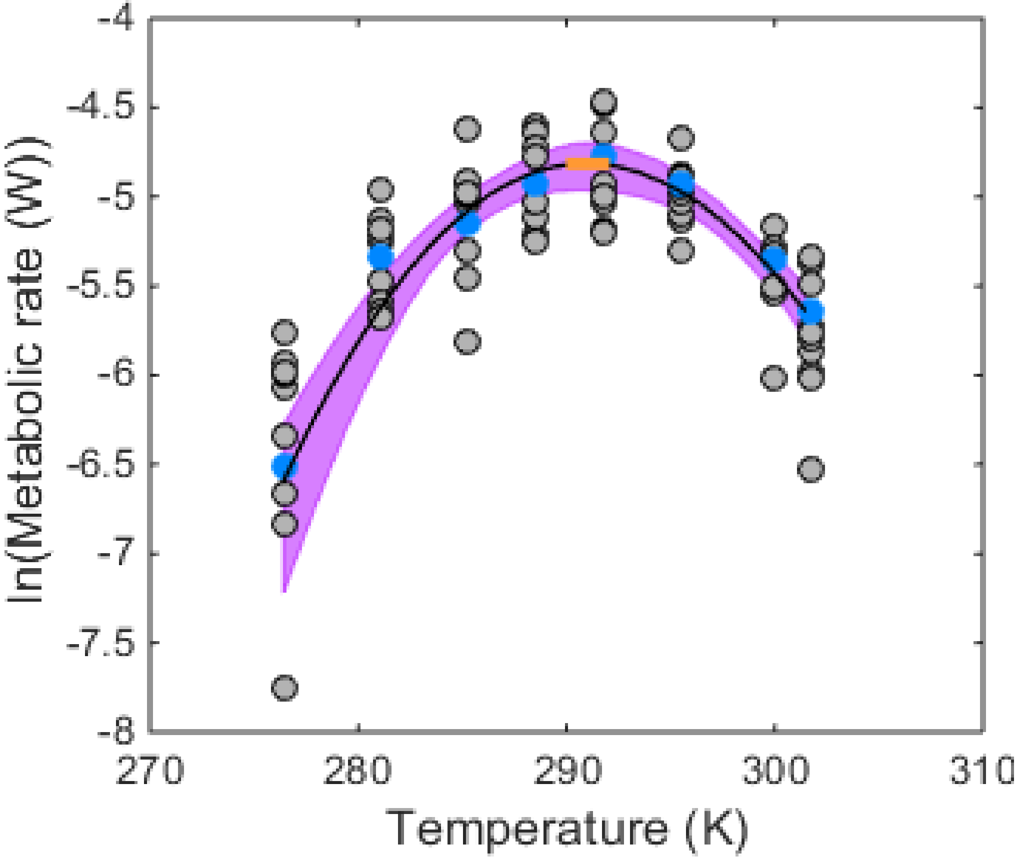
$$R = A_0 e^{-\left(E_b - E_c(T)\right)/kT}$$

DeLong et al 2017 Ecology & Evolution

Metabolism

Amphipod
(*Niphargus virei*)

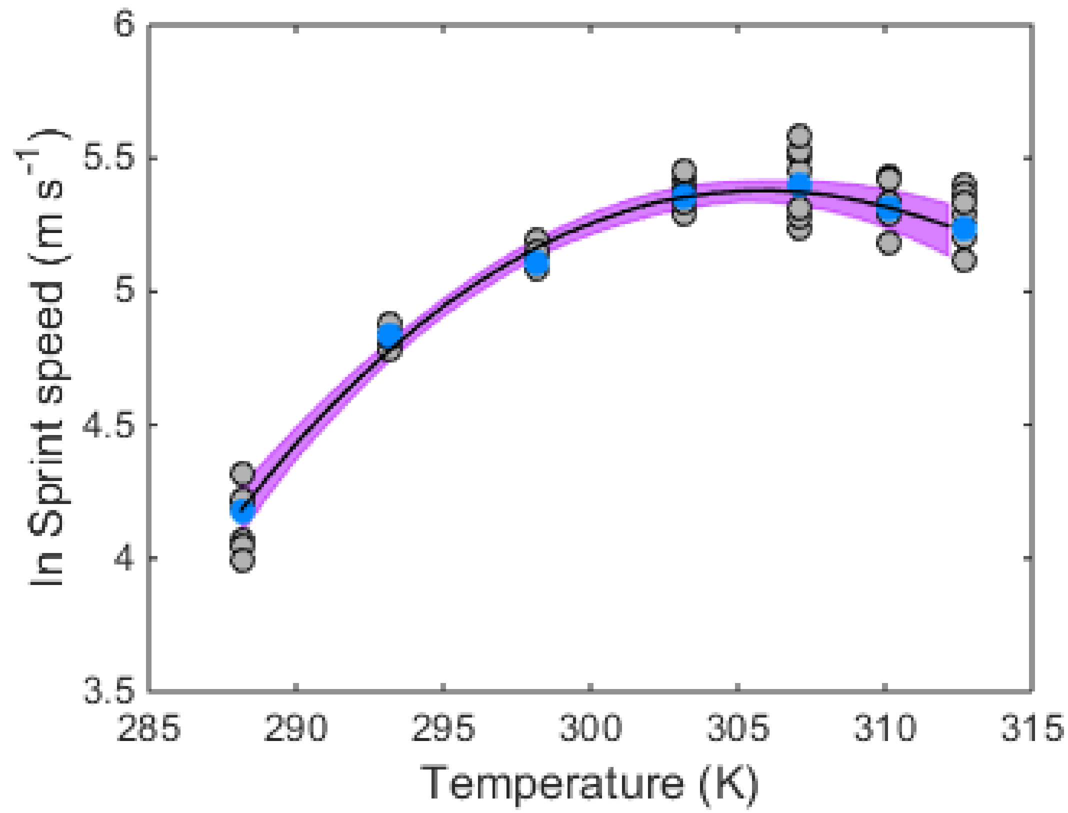




Issartel 2005; DeLong et al 2017

Metabolism-fueled movement

Common house gecko
Hemidactylus frenatus

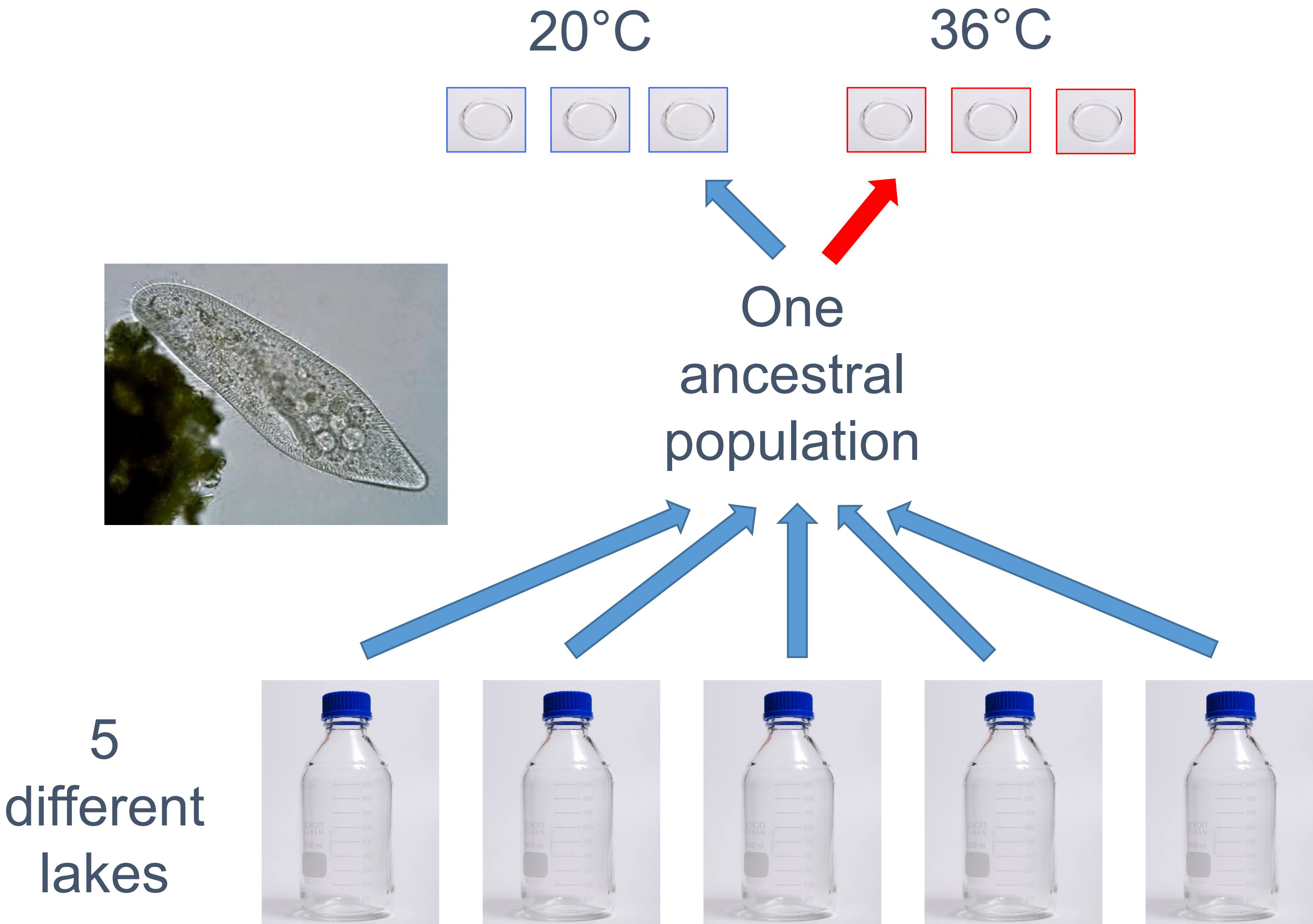


Huey et al 1989

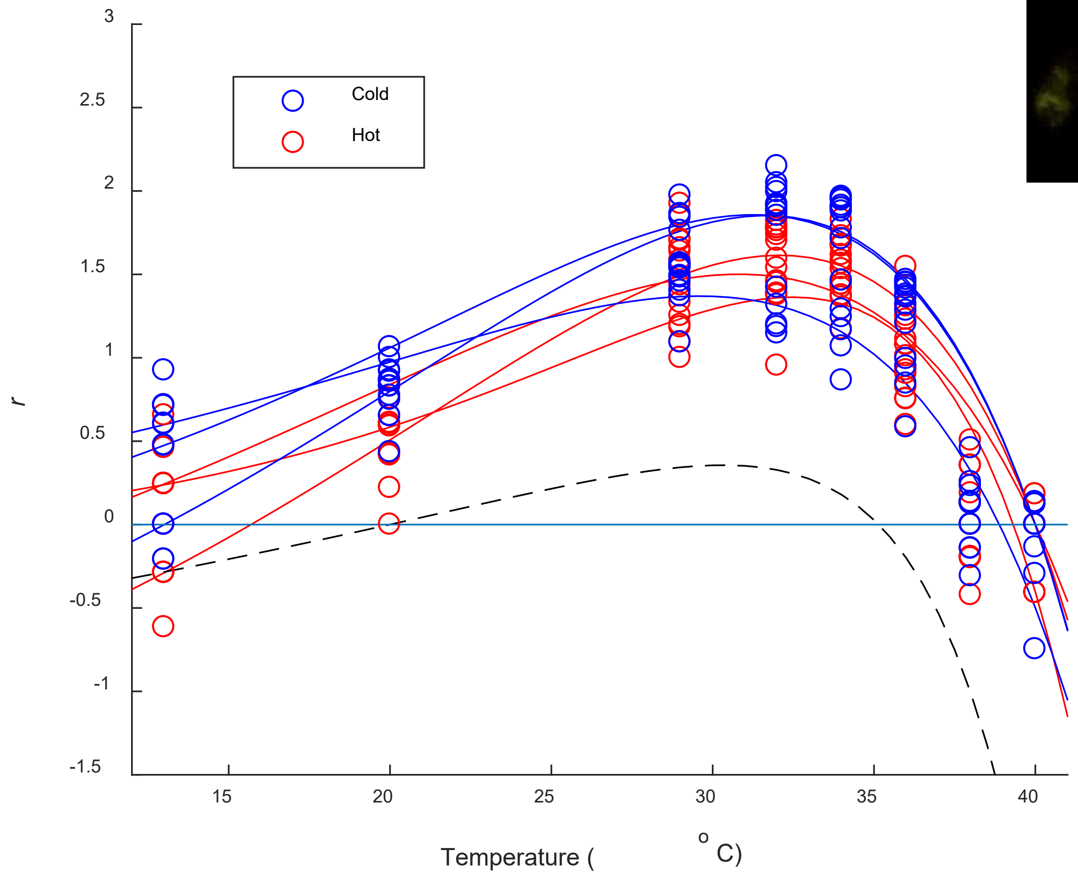
Climate adaptation experiment

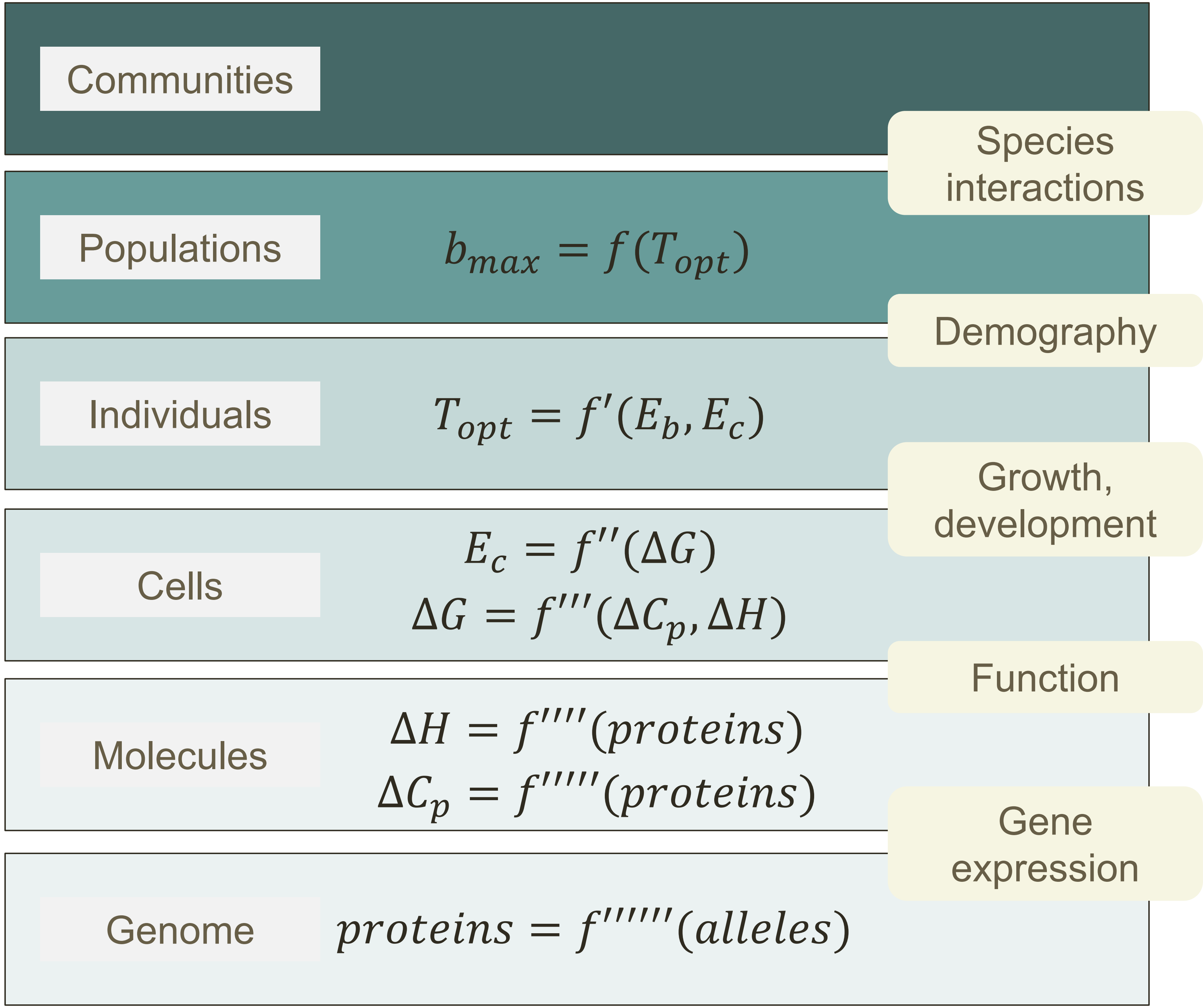
Paramecium caudatum

Drosophila melanogaster


20°C
36°C
One ancestral population
5 different lakes

After ~350 generations





Communities
Species interactions
Populations
$b_{max} = f(T_{opt})$
Demography
Individuals
$T_{opt} = f'(E_b, E_c)$
Growth, development
Cells
$E_c = f''(\Delta G)$
$\Delta G = f'''(\Delta C_p, \Delta H)$
Function
Molecules
$\Delta H = f''''(proteins)$
$\Delta C_p = f'''''(proteins)$
Gene expression
Genome
$proteins = f''''''(alleles)$

Four suggestions today:

- Anchor models at points that must be true
  - *e.g., population*
- Visualize parameters of dynamic models as emergent properties of lower levels
  - *e.g., r is b – d, b is f(topt)*
- Allow for changes in allele frequencies through evolution
  - *e.g., climate adaptation changes abundance*
- Try out Gillespie eco-evolutionary models (GEMs) as a tool

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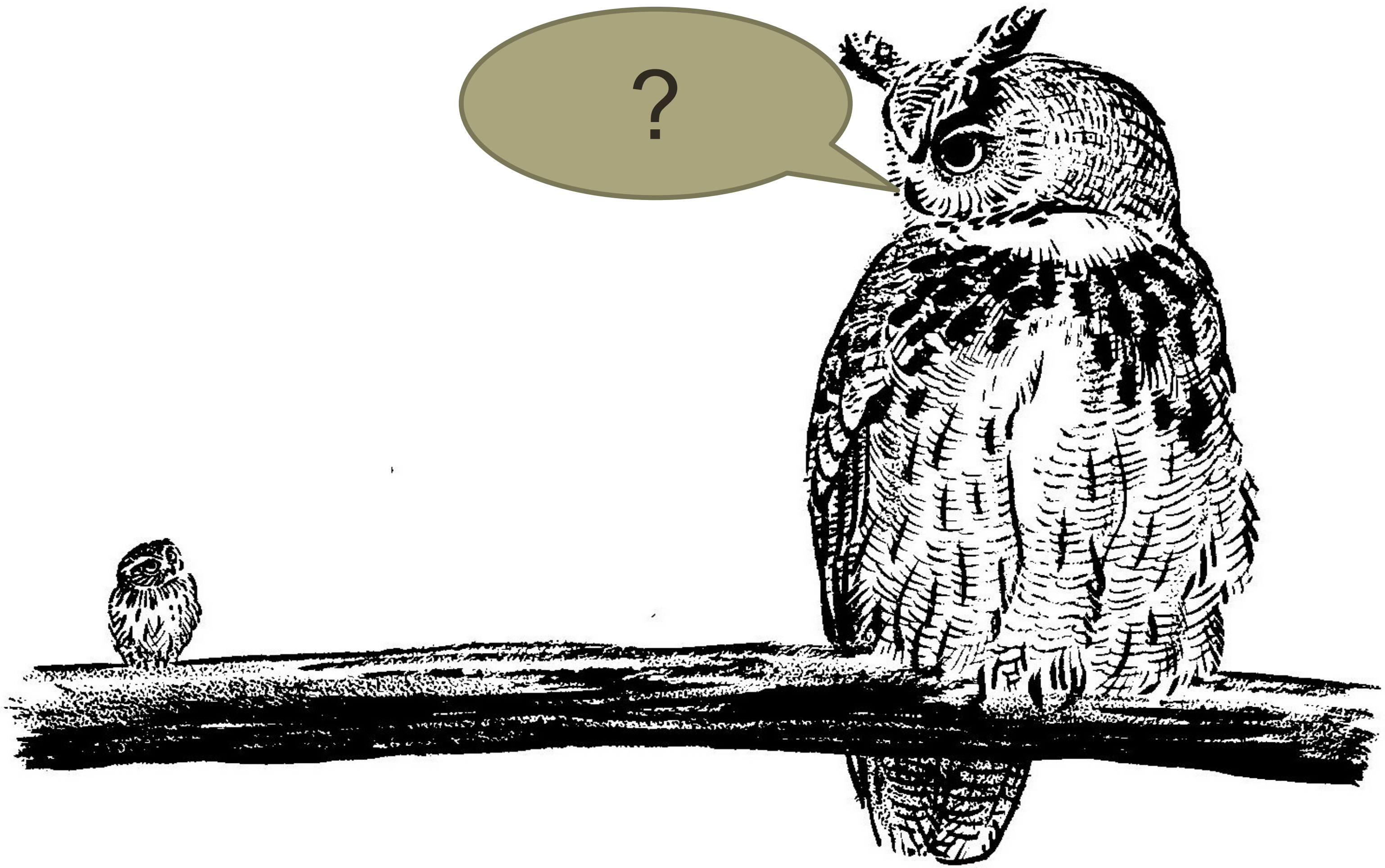
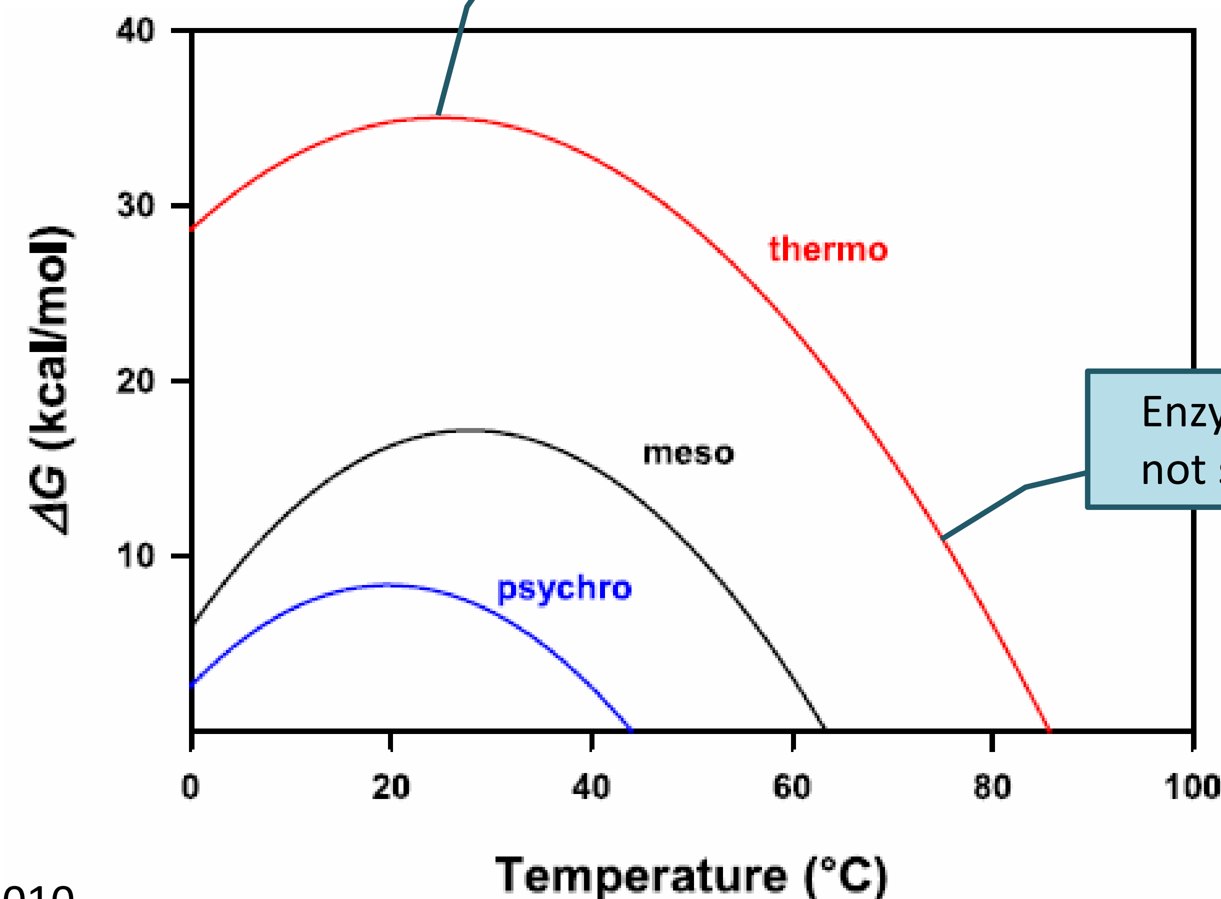


Chapter 4. Scaling up TPCs, empirically and mathematically.

E_c related to protein stability

Enzyme lowers E_b maximally here

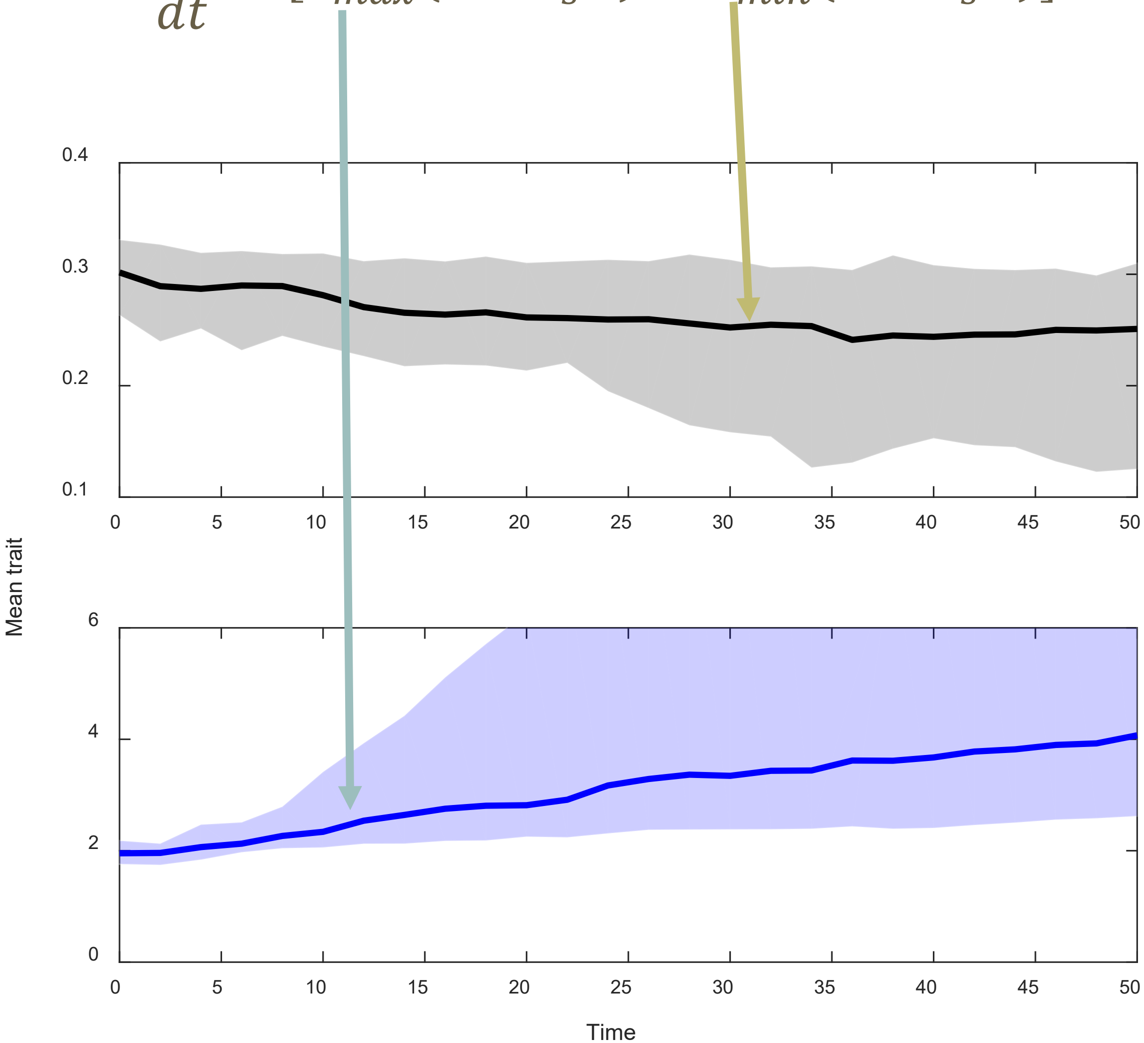
$$E_c = f(\Delta G)$$



Enzyme lowers E_b not so much here

Feller 2010

$$\frac{dR}{dt} = [b_{max}(1 - b_s R) - d_{min}(1 + d_s R)]R$$



Translating Gibbs-Helmholtz

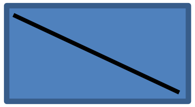
$$\Delta G = \Delta H - T\Delta S$$

These are functions not constants

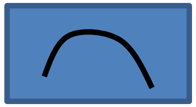
Becktel and Shellman 1988

$$\Delta G = \Delta H^0\left(1 - \frac{T}{T_m}\right) + \Delta C_p\left(T - T_m - T\ln\frac{T}{T_m}\right)$$

‘Robustness’



‘Thermal sensitivity’



Feller 2010

$$\Delta G = \Delta H^0\left(1 - \frac{T}{T_m}\right) + \Delta C_p\left(T - T_m - T\ln\frac{T}{T_m}\right)$$

$$E_c = E_L\,\frac{\Delta G}{\Delta G_{max}}$$

$$E_{\Delta H} = E_L\,\frac{\Delta H}{\Delta G_{max}} \qquad E_{\Delta Cp} = E_L\,\frac{\Delta C_p}{\Delta G_{max}}$$

$$E_c = E_{\Delta H}\left(1 - \frac{T}{T_m}\right) + E_{\Delta Cp}\left(T - T_m - T\ln\frac{T}{T_m}\right)$$

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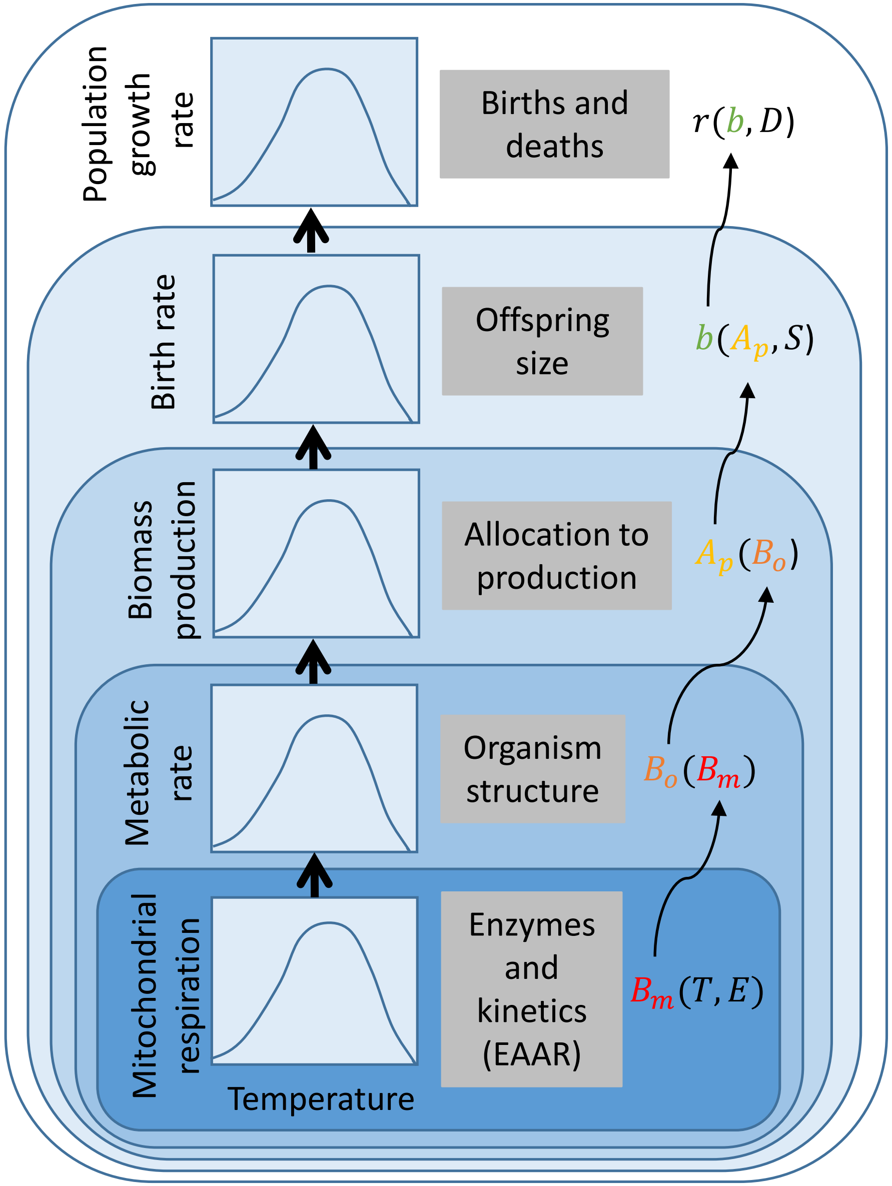
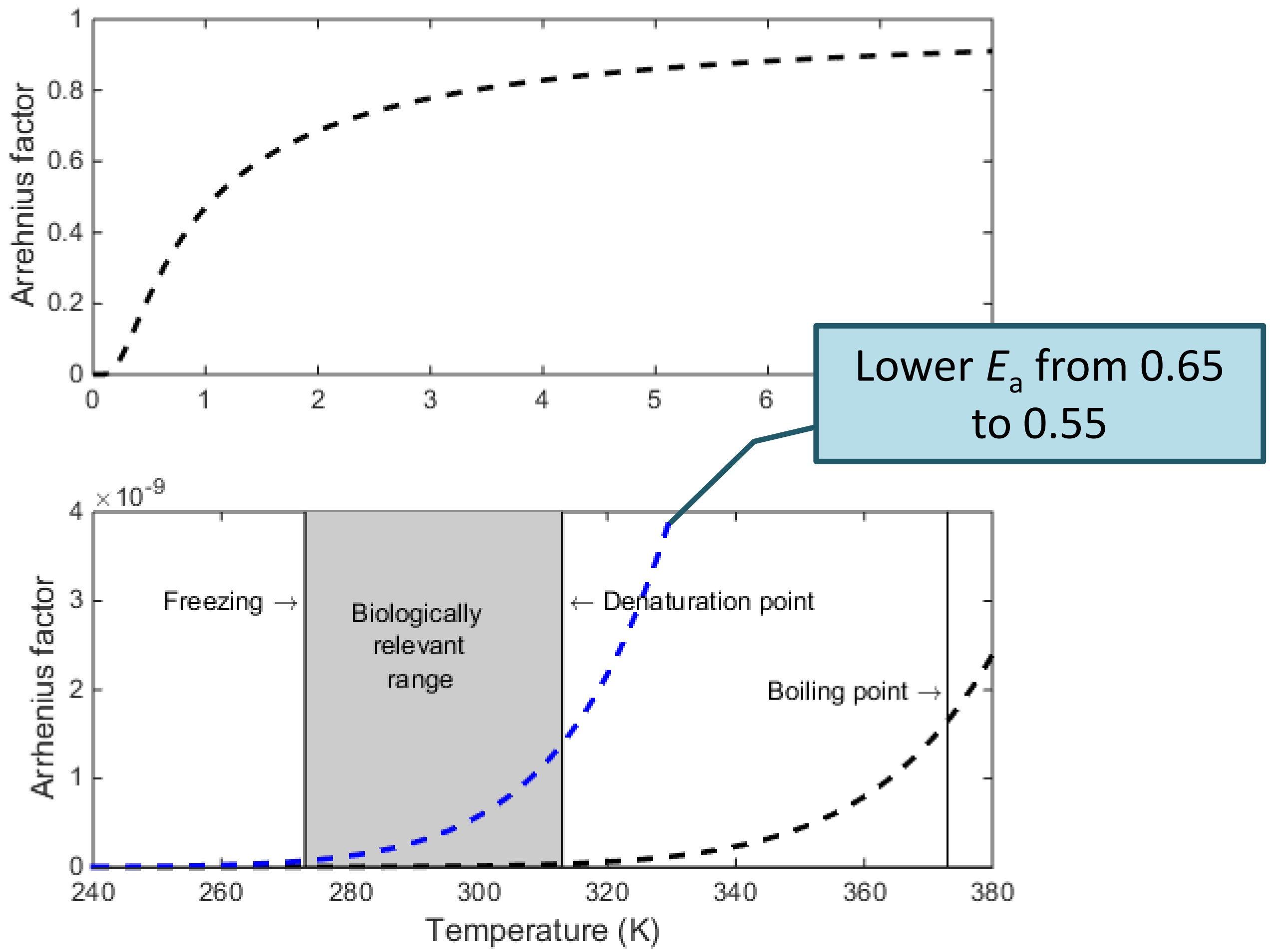

Population growth rate
Births and deaths
$r(b, D)$
Birth rate
Offspring size
$b(A_p, S)$
Biomass production
Allocation to production
$A_p(B_o)$
Metabolic rate
Organism structure
$B_o(B_m)$
Mitochondrial respiration
Enzymes and kinetics (EAAR)
$B_m(T, E)$
Temperature

Arrhenius factor



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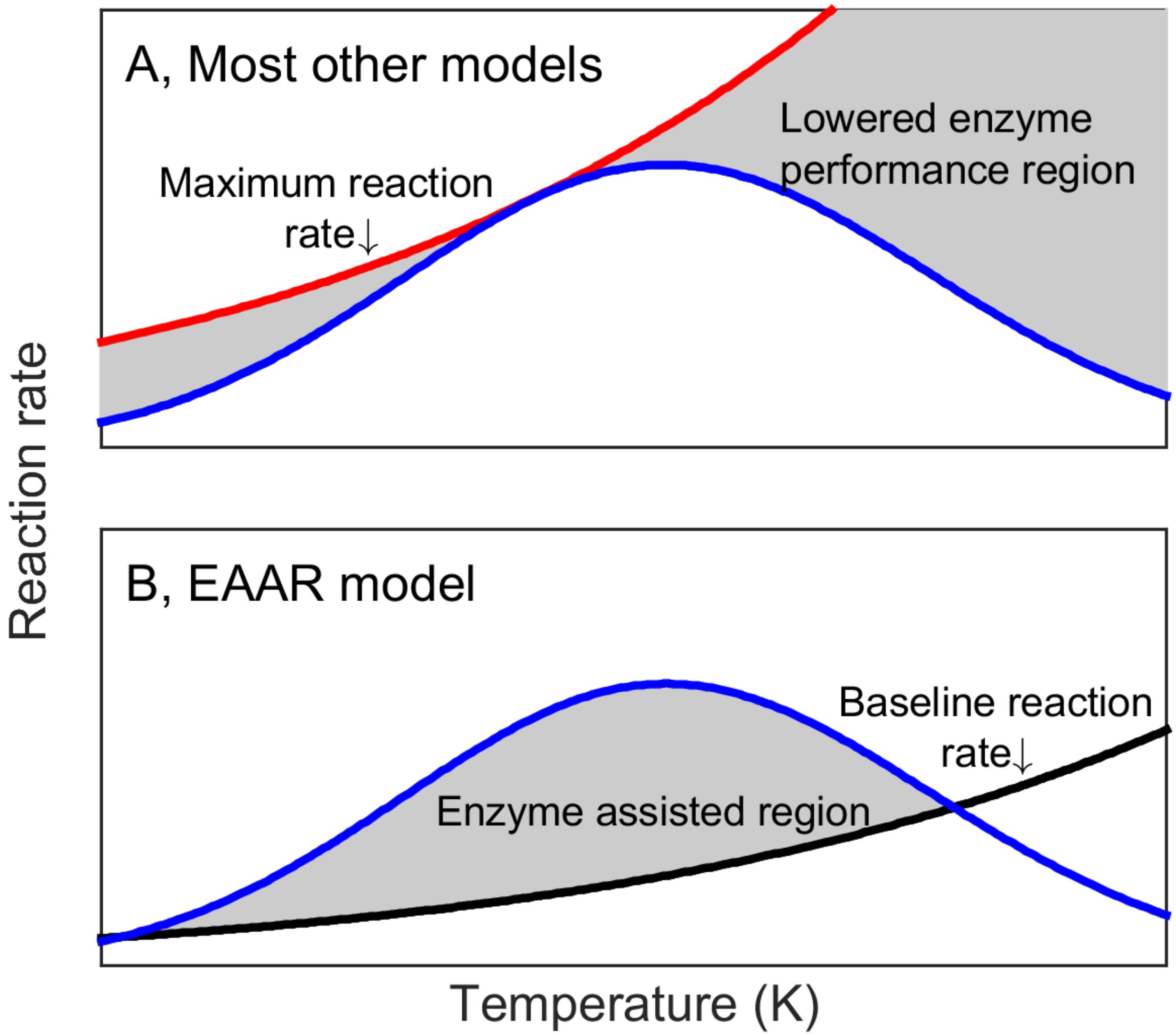

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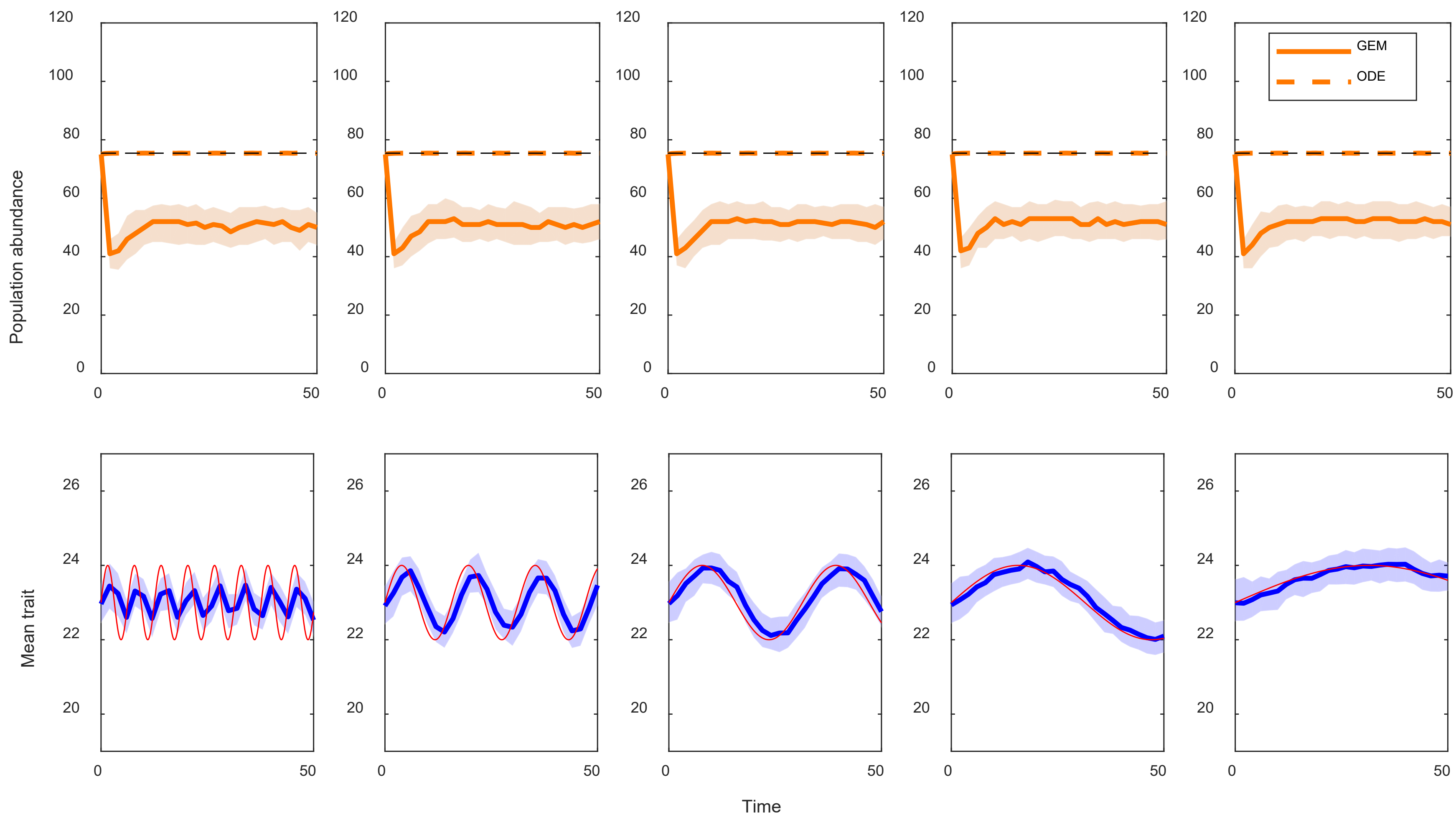
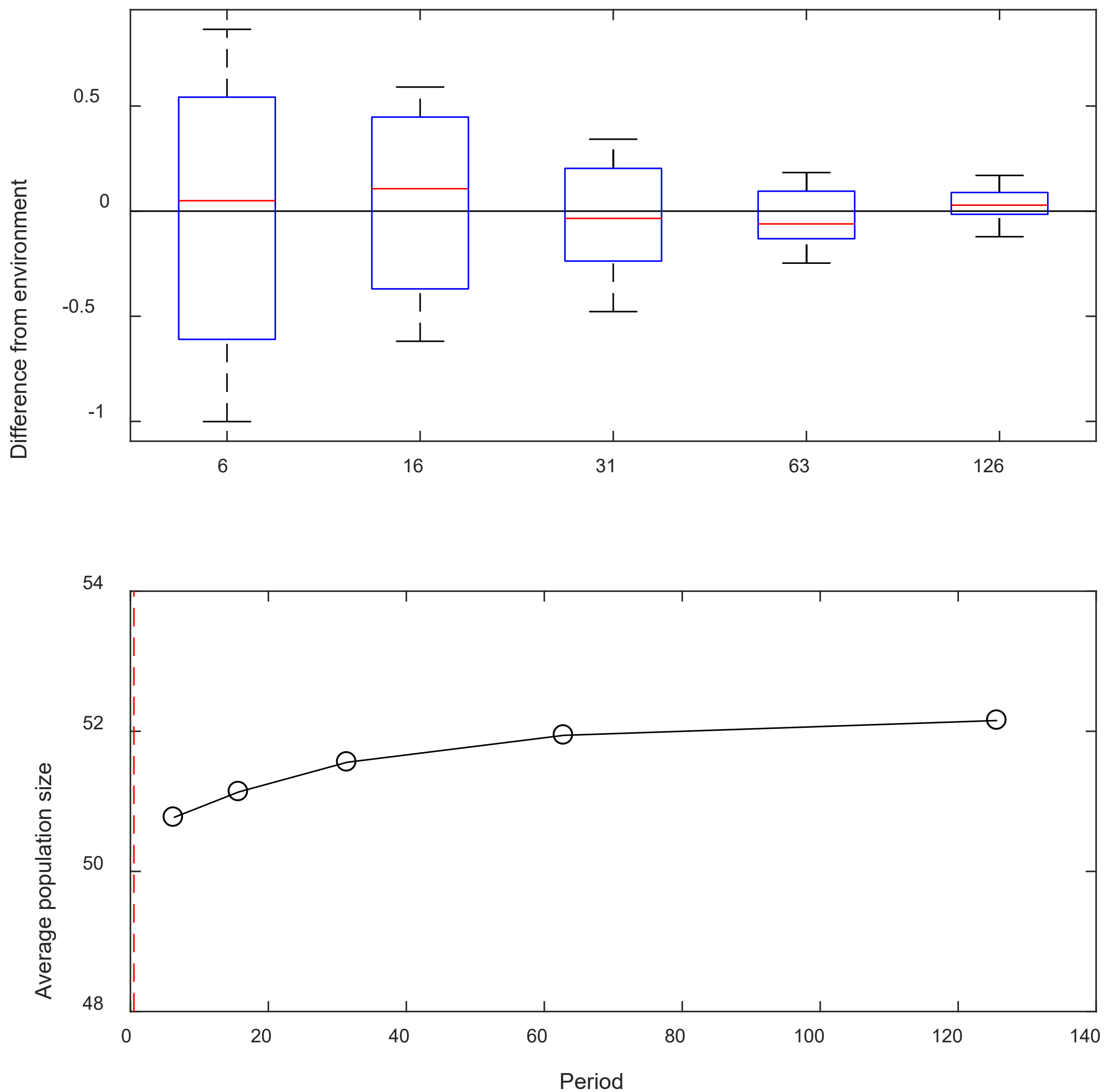
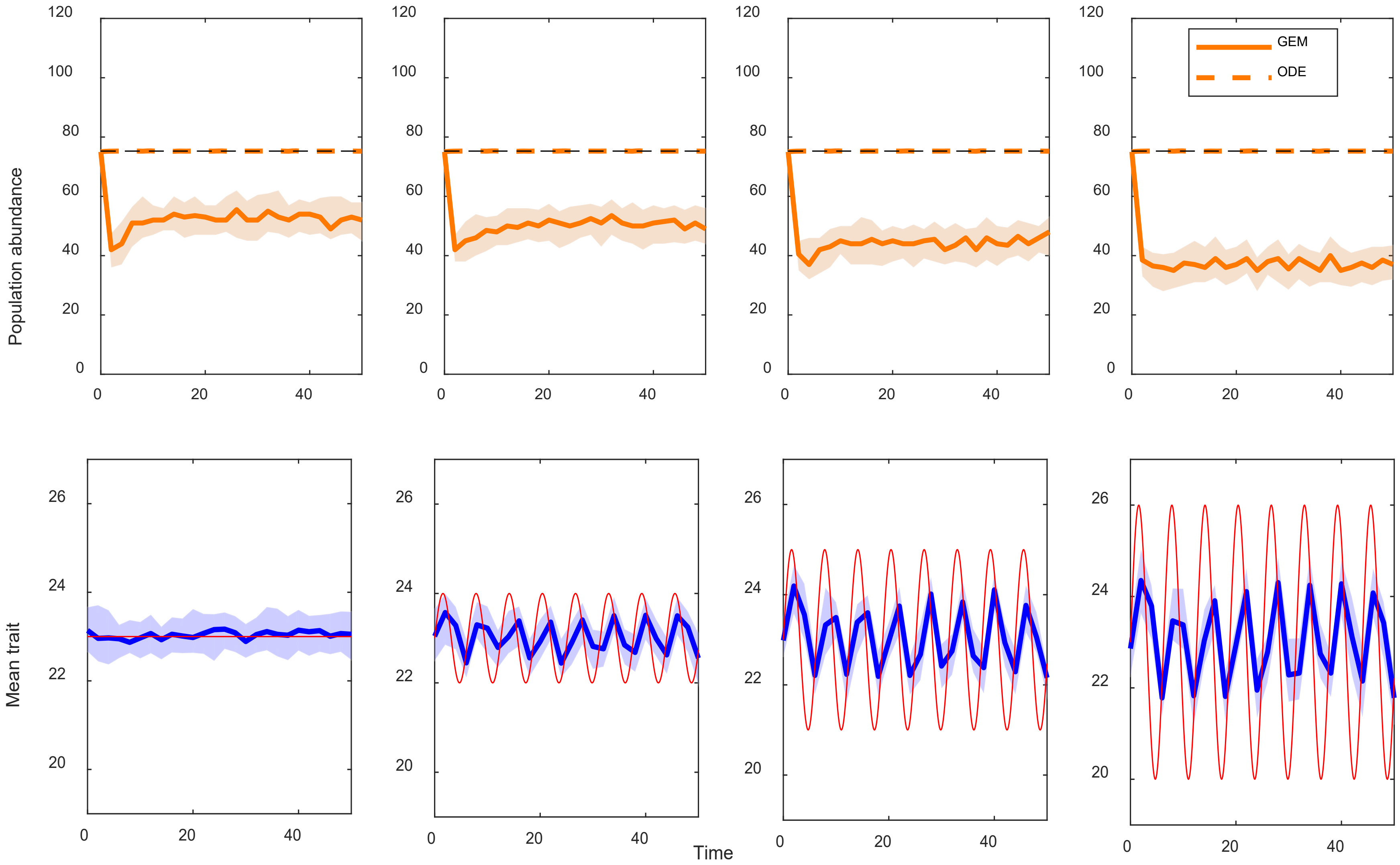
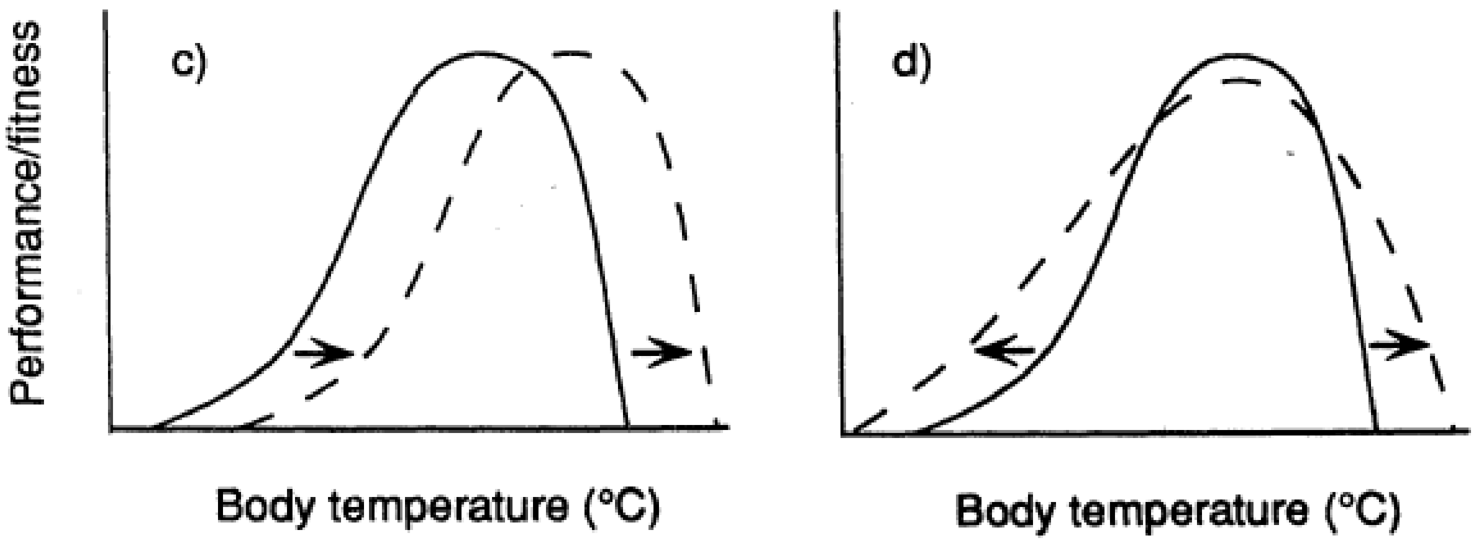


Population abundance
Mean trait
Time
GEM
ODE



0.5
0
-0.5
-1
Difference from environment
6
16
31
63
126
54
52
50
48
Average population size
0
20
40
60
80
100
120
140
Period


Population abundance
GEM
ODE
Mean trait
Time



Huey and Kingsolver 1993