Metapopulations

Daphne Munroe & many others

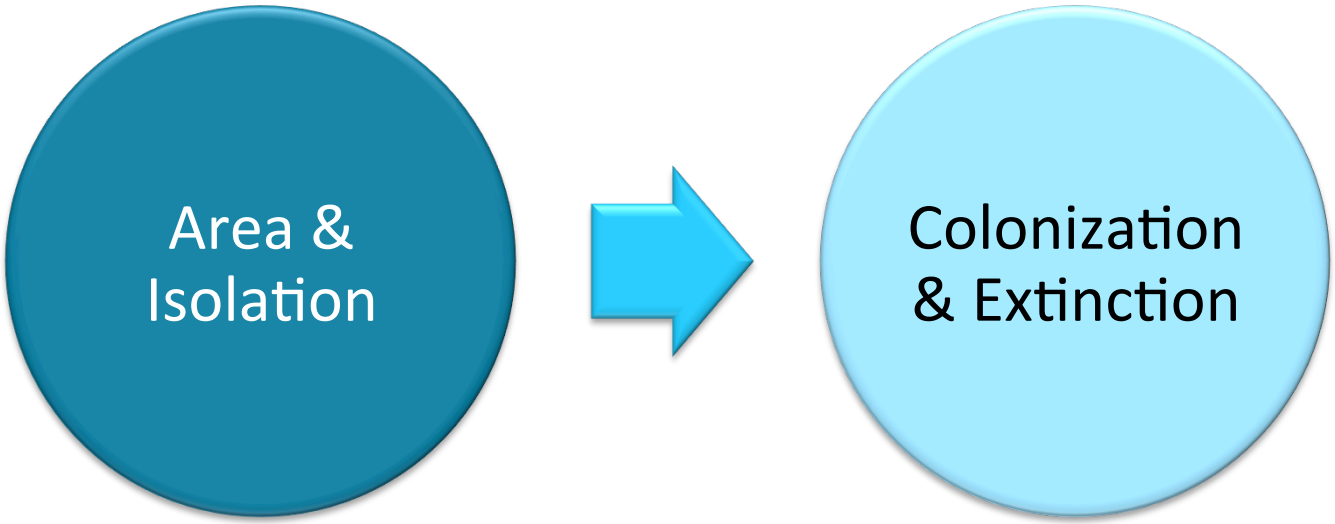
4th Research Coordination Network Workshop

Marine Disease Modeling & Transmission

Old Dominion University

May 11-15 2015

Metapopulation theory



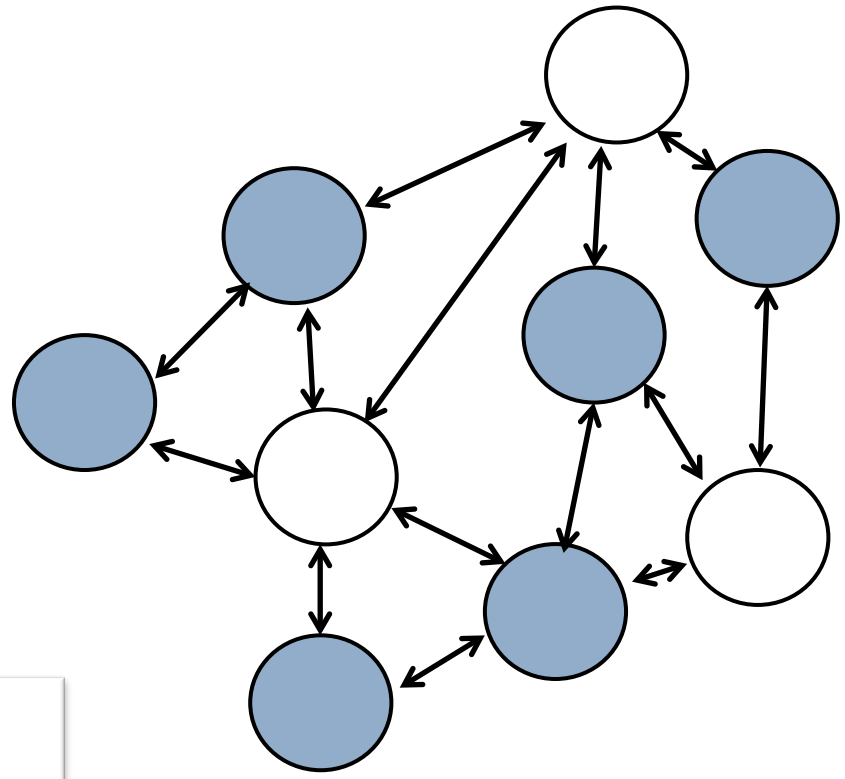
- 2 important ecological concepts:
  - species-area relationship - Watson (1859)
  - island biogeography - MacArthur & Wilson (1967)
    - patch-matrix and mosaic approaches

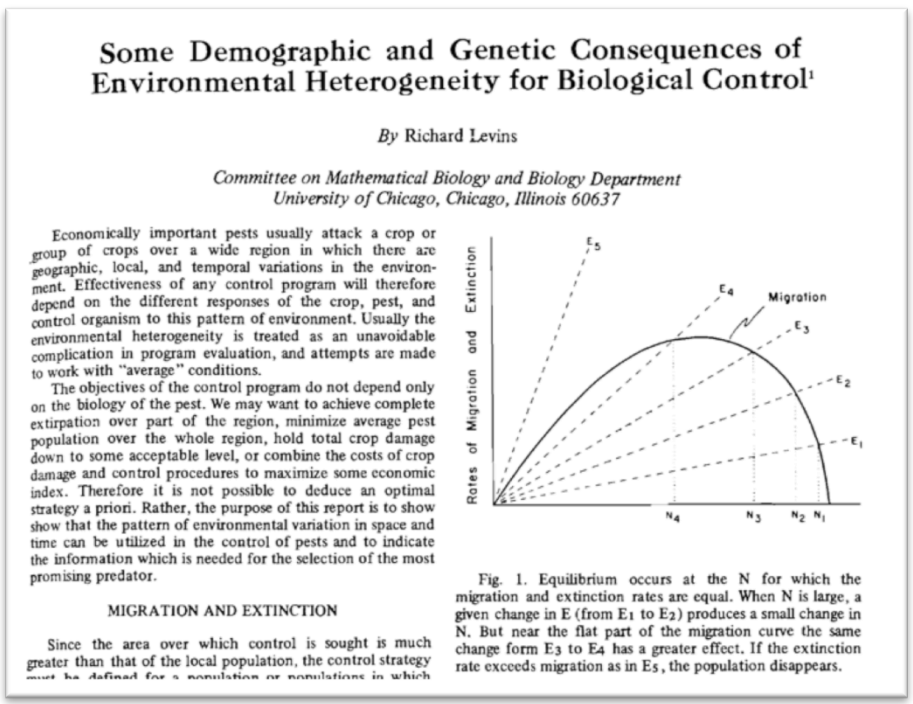
- Metapopulation
  - A population of populations

Richard Levins

$$\frac{dp}{dt} = mp(1-p) - xp$$

p proportion of occupied patches
m migration
x extinction





Some Demographic and Genetic Consequences of Environmental Heterogeneity for Biological Control[1]

By Richard Levins

Committee on Mathematical Biology and Biology Department
University of Chicago, Chicago, Illinois 60637

Economically important pests usually attack a crop or group of crops over a wide region in which there are geographic, local, and temporal variations in the environment. Effectiveness of any control program will therefore depend on the different responses of the crop, pest, and control organism to this pattern of environment. Usually the environmental heterogeneity is treated as an unavoidable complication in program evaluation, and attempts are made to work with "average" conditions.

The objectives of the control program do not depend only on the biology of the pest. We may want to achieve complete extirpation over part of the region, minimize average pest population over the whole region, hold total crop damage down to some acceptable level, or combine the costs of crop damage and control procedures to maximize some economic index. Therefore it is not possible to deduce an optimal strategy a priori. Rather, the purpose of this report is to show show that the pattern of environmental variation in space and time can be utilized in the control of pests and to indicate the information which is needed for the selection of the most promising predator.

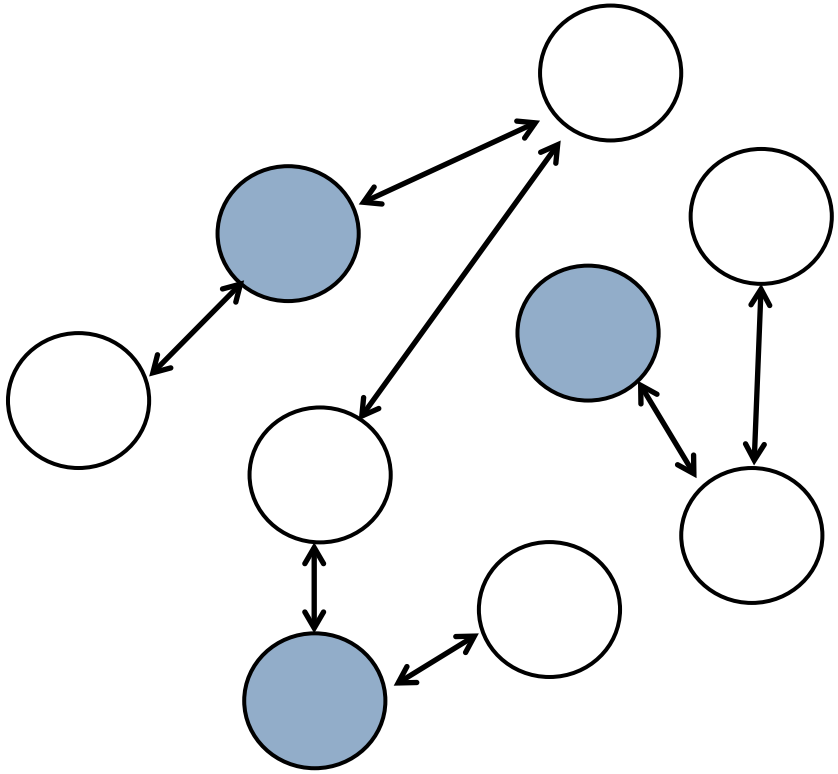
MIGRATION AND EXTINCTION

Since the area over which control is sought is much greater than that of the local population, the control strategy

Fig. 1. Equilibrium occurs at the N for which the migration and extinction rates are equal. When N is large, a given change in E (from E_1 to E_2) produces a small change in N. But near the flat part of the migration curve the same change form E_3 to E_4 has a greater effect. If the extinction rate exceeds migration as in E_5, the population disappears.

$$\frac{dp}{dt} = mp(1-p) - xp$$

p proportion of occupied patches
m migration
x extinction



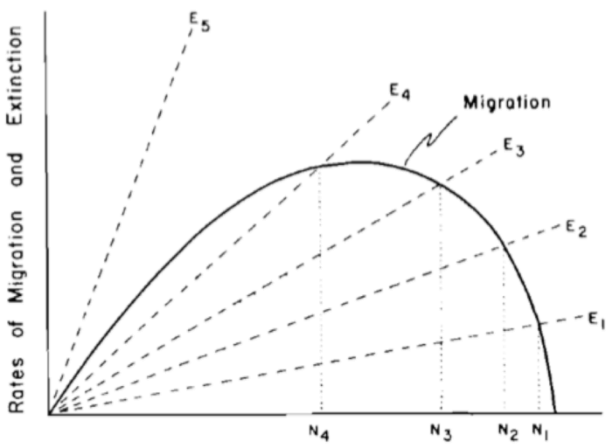
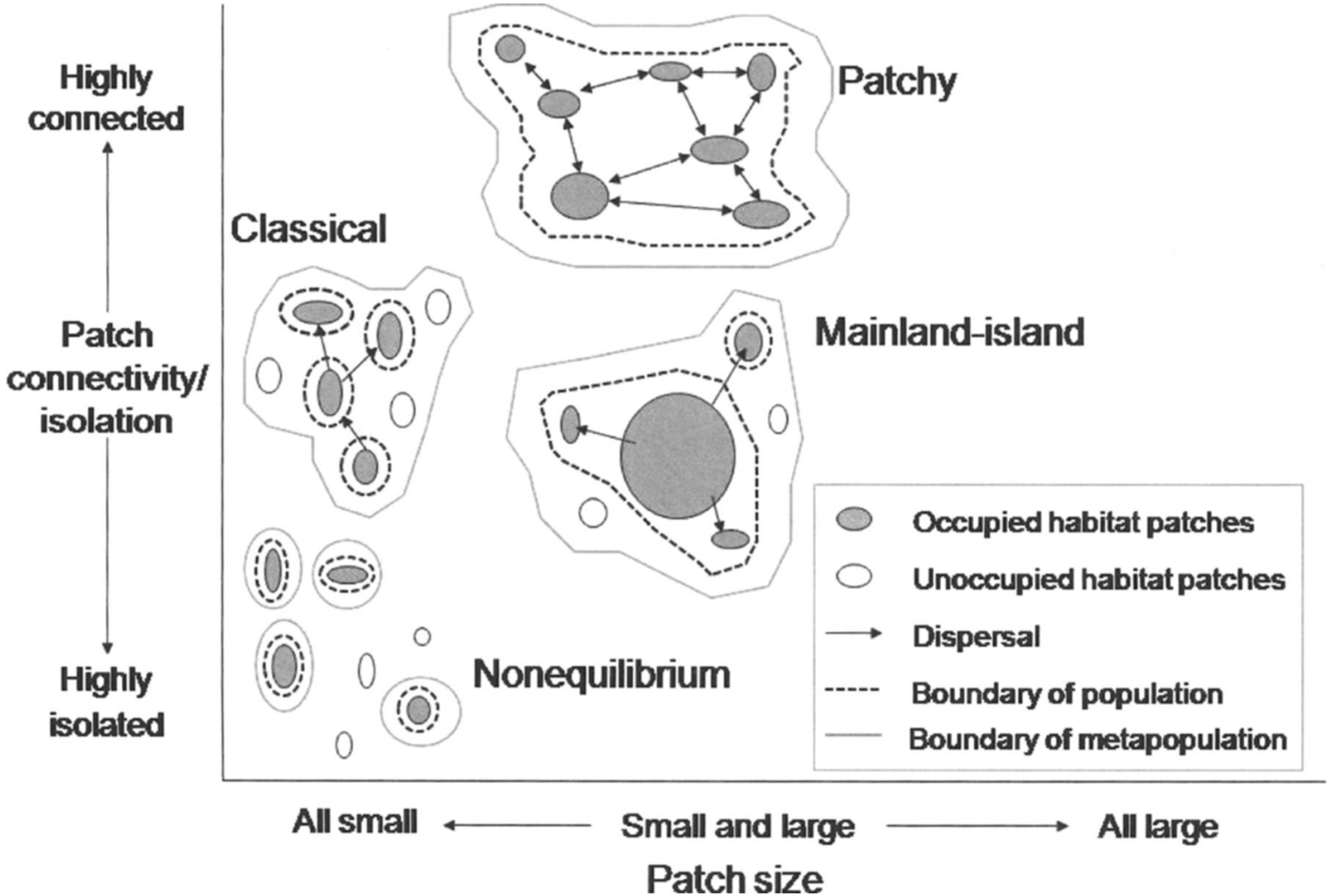


Fig. 1. Equilibrium occurs at the N for which the migration and extinction rates are equal. When N is large, a given change in E (from E_1 to E_2) produces a small change in N. But near the flat part of the migration curve the same change form E_3 to E_4 has a greater effect. If the extinction rate exceeds migration as in E_5, the population disappears.

- The Levins model is useful for:
  - Understanding basic dynamics of metapopulation and population stability
  - Studying how m and e affect population dynamics.
  - Understanding how number of occupied patches affects local extinction.
- Restriction to only two states is limiting

Empirical models of metapopulation structure expanded from the classical metapopulation structure.



Jocelyn L. Aycrigg, and Edward O. Garton J Mammal 2014;95:597-614

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Journal of Mammalogy

Core-Satellite (Hanski) Model

- Extinction depends on patch occupancy
  - Extinction rate increases when more patches are occupied
  - Predicts two types of species
    - Common and high abundance (Core)
    - Rare and patchy (Satellite)

OIKOS 38: 210–221. Copenhagen 1982

Dynamics of regional distribution: the core and satellite species hypothesis

Ilkka Hanski

Stepping Stone Model

- New Dispersal Terms
  - Propagules are more likely to disperse to occupied patches
  - Probability of dispersal between each patch is specified

Biological Journal of the Linnean Society (1991), *42:* 123–134. With 5 figures

The effect of conspecific attraction on metapopulation dynamics

CHRIS RAY, MICHAEL GILPIN

Department of Biology, University of California at San Diego, La Jolla, CA 92093-C0116, U.S.A.

ANDREW T. SMITH

Department of Zoology, Arizona State University, Tempe, AZ 85287-1501, U.S.A.

Deterministic to Numerical

- Models include greater realism
  - Dynamics can be affected by many things
    - Demographic stochasticity
    - Environmental gradients
    - Genetic variability
    - Dispersal patterns
    - Biological interactions: competition/predation/parasitism
    - Density-dependent effects
- Relaxation of the colonization:extinction paradigm
  - Focus on dynamics within the system
- Emergent properties

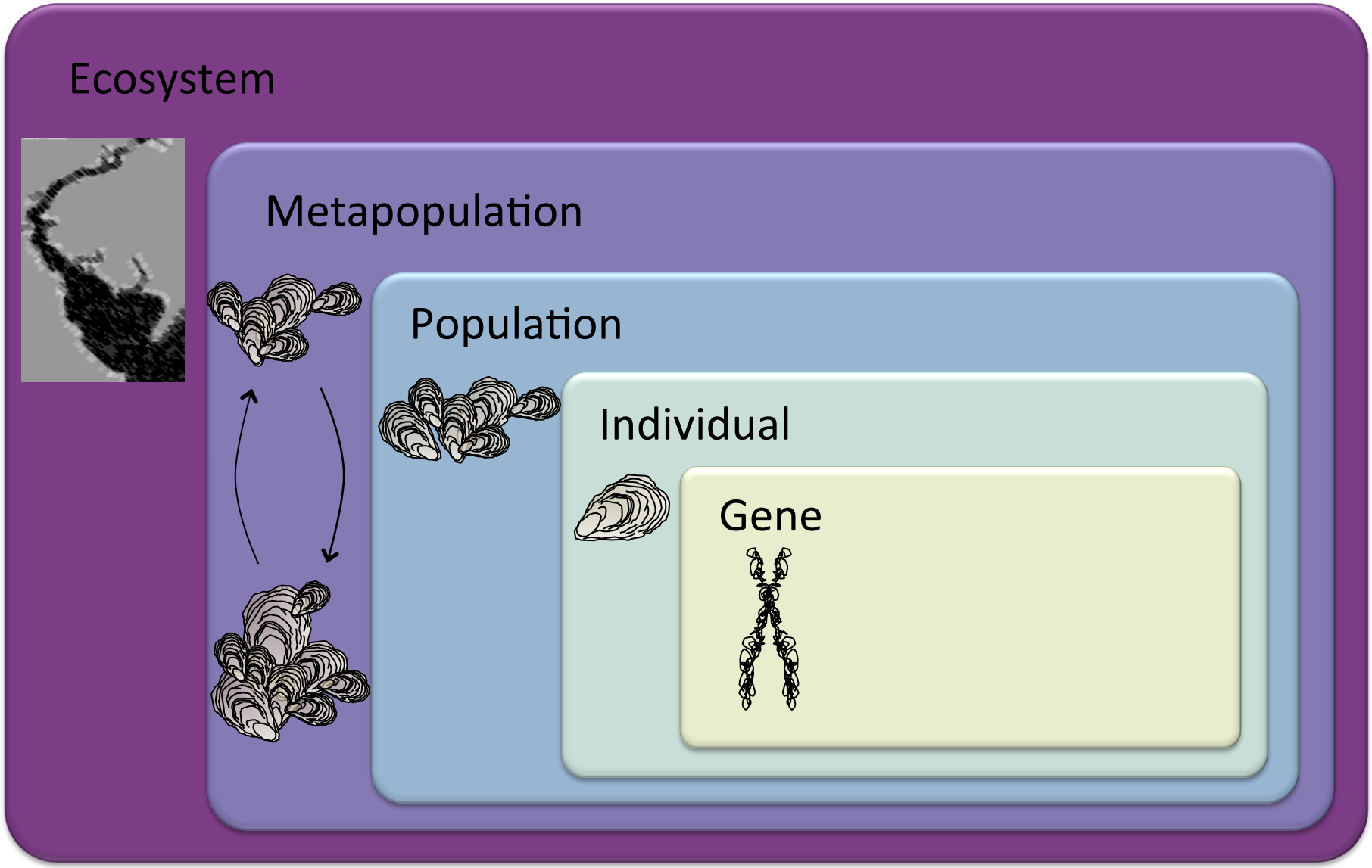
Terrestrial to Marine

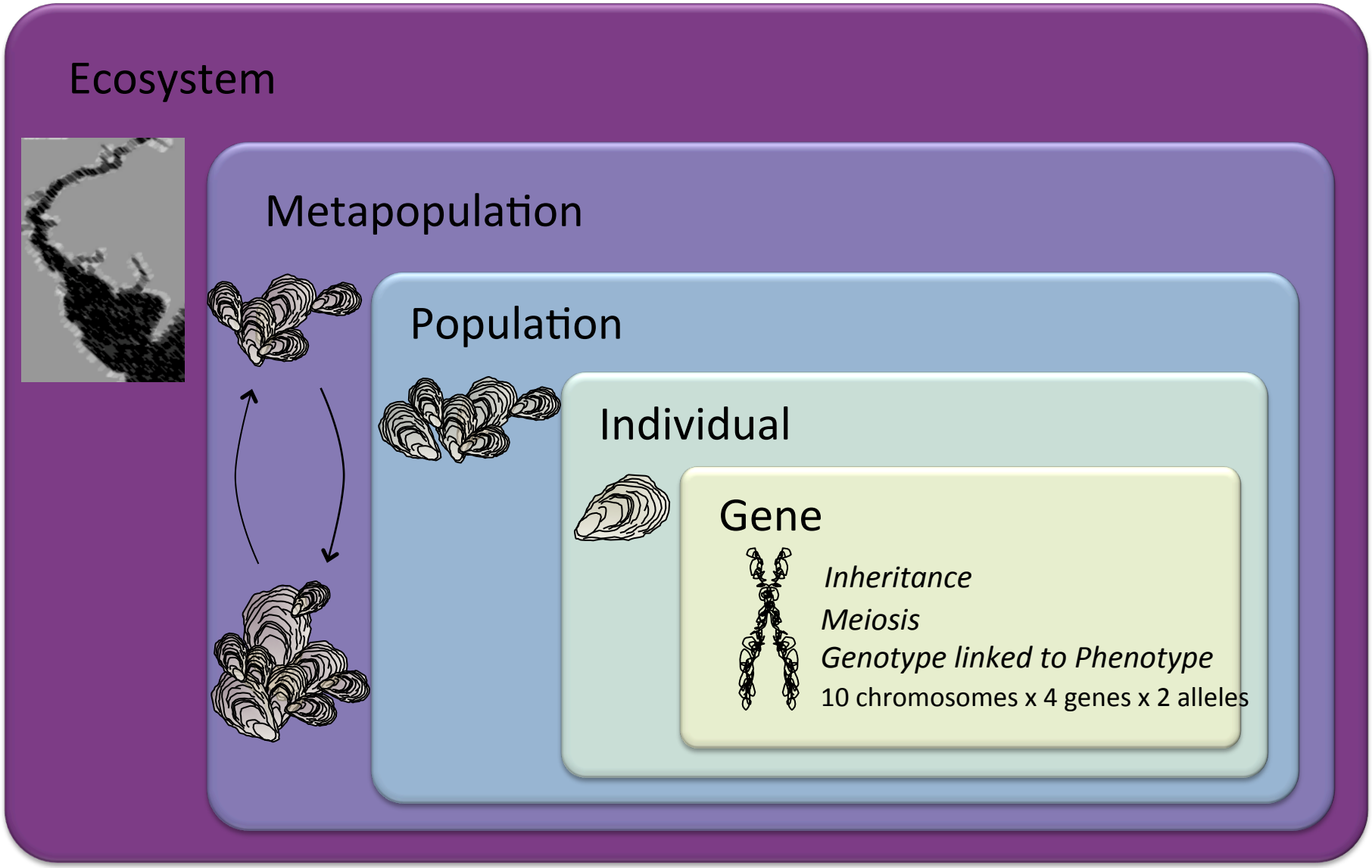
- Marine ecosystems characterized by long dispersal kernels
- 'open populations'
- Challenge = observing, characterizing dispersal
- Fragmented habitats
  - MPAs

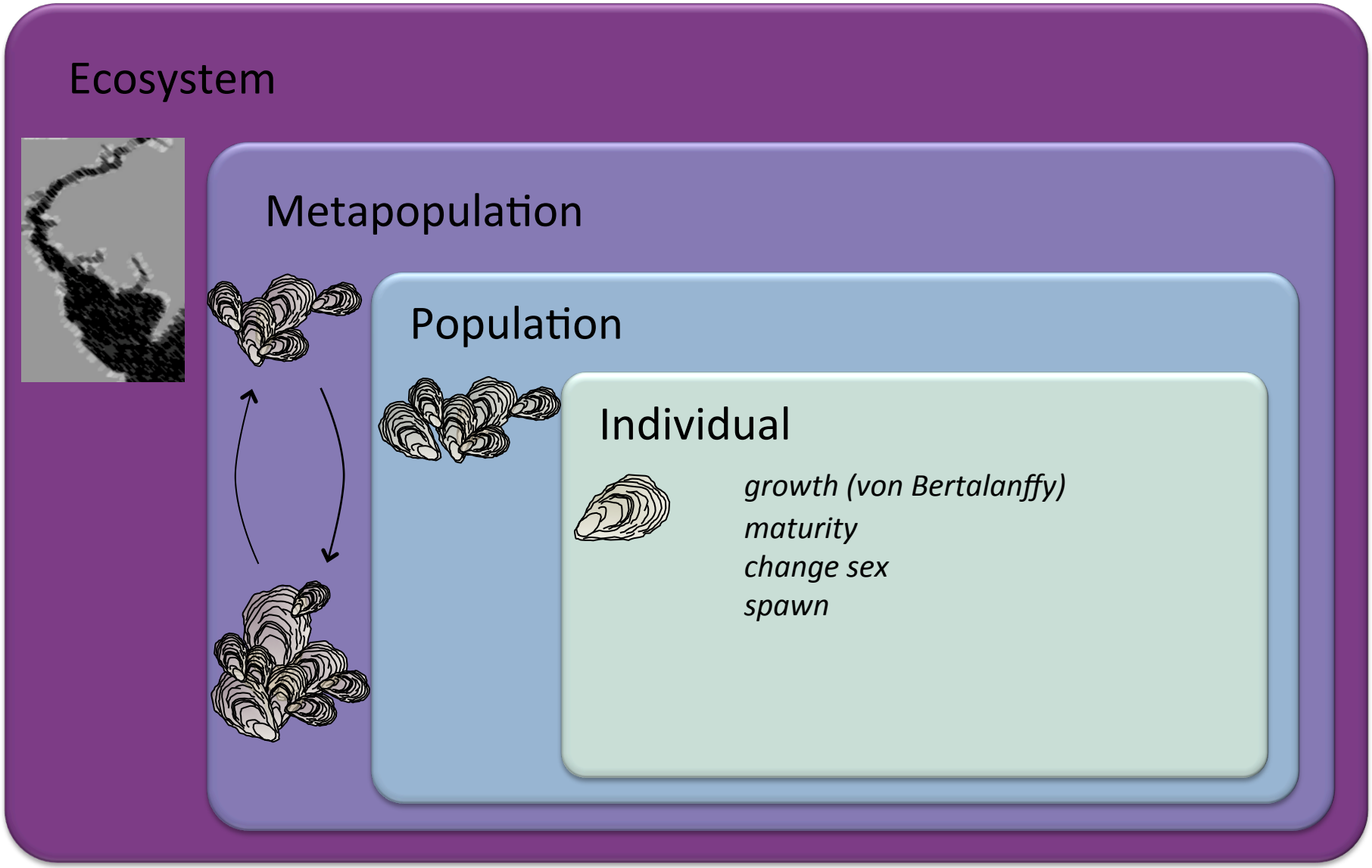
THEORETICAL POPULATION BIOLOGY **29**, 235–261 (1986)

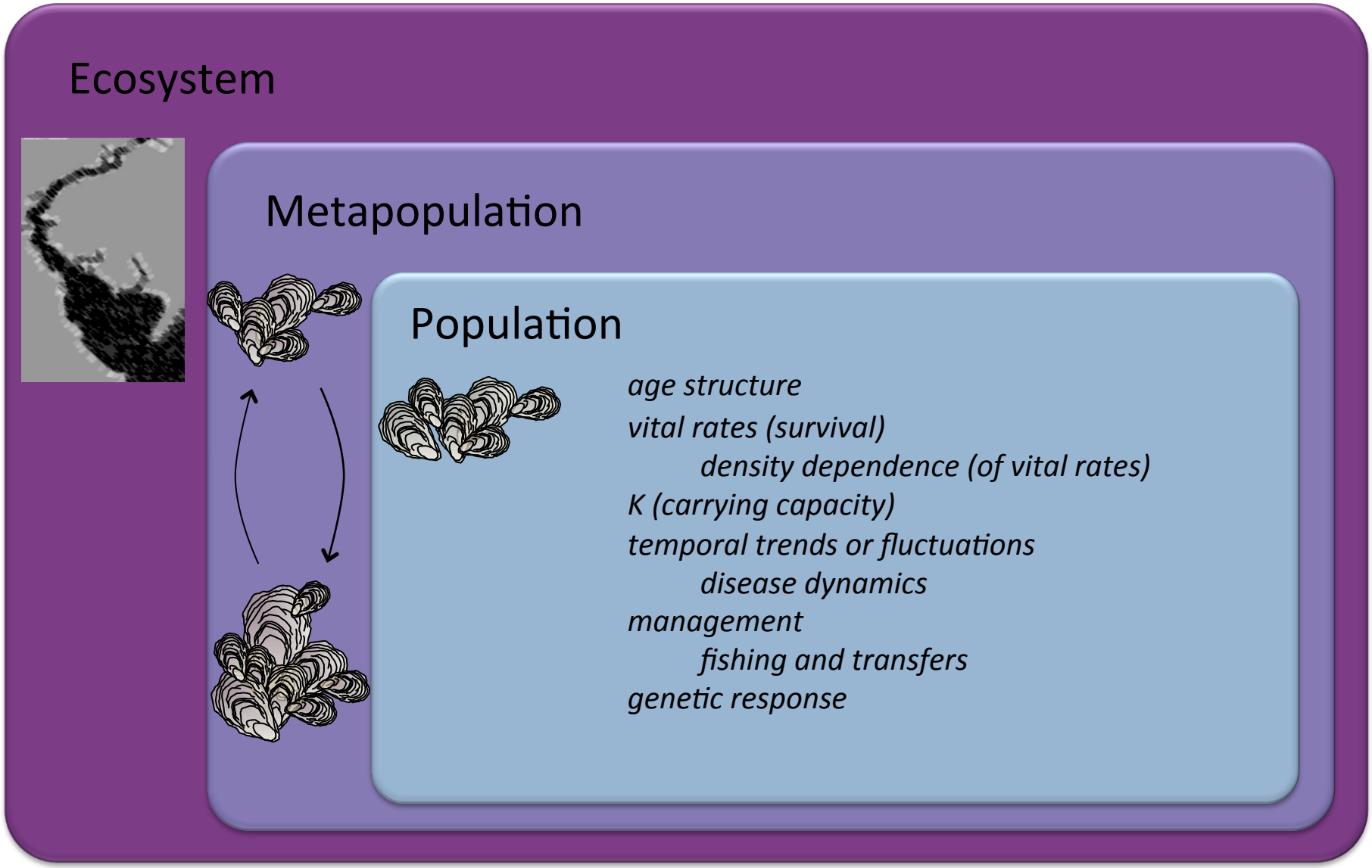
Dynamics of a Metapopulation with Space-Limited Subpopulations

JONATHAN ROUGHGARDEN AND YOH IWASA*


Ecosystem
Metapopulation
Population
Individual
Gene


Ecosystem
Metapopulation
Population
Individual
Gene
Inheritance
Meiosis
Genotype linked to Phenotype
10 chromosomes x 4 genes x 2 alleles

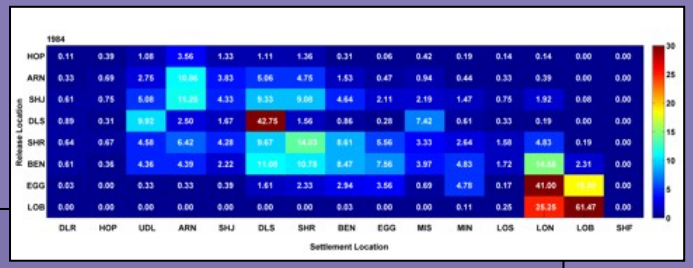

Ecosystem
Metapopulation
Population
Individual
growth (von Bertalanffy)
maturity
change sex
spawn


Ecosystem
Metapopulation
Population
age structure
vital rates (survival)
density dependence (of vital rates)
K (carrying capacity)
temporal trends or fluctuations
disease dynamics
management
fishing and transfers
genetic response

Ecosystem

Metapopulation

larval dispersal
genetic connectivity
spatial variability in vital rates
management
genetic response



Larval Dispersal Defined by coupled biophysical model

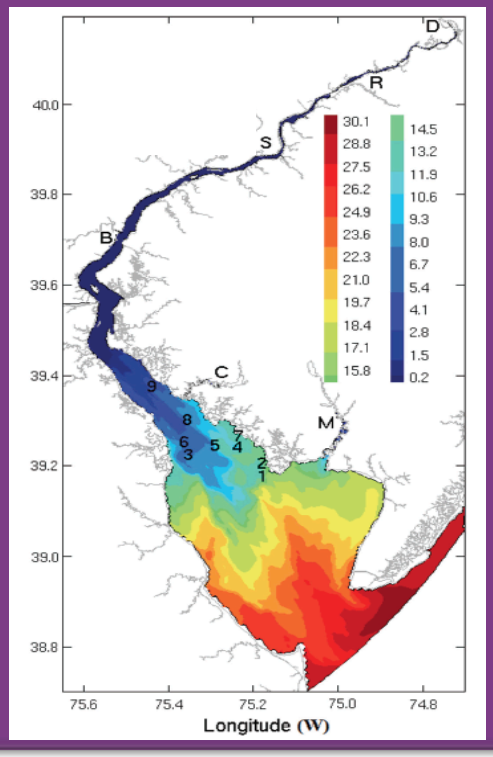
(larval growth-behaviour & ROMS)

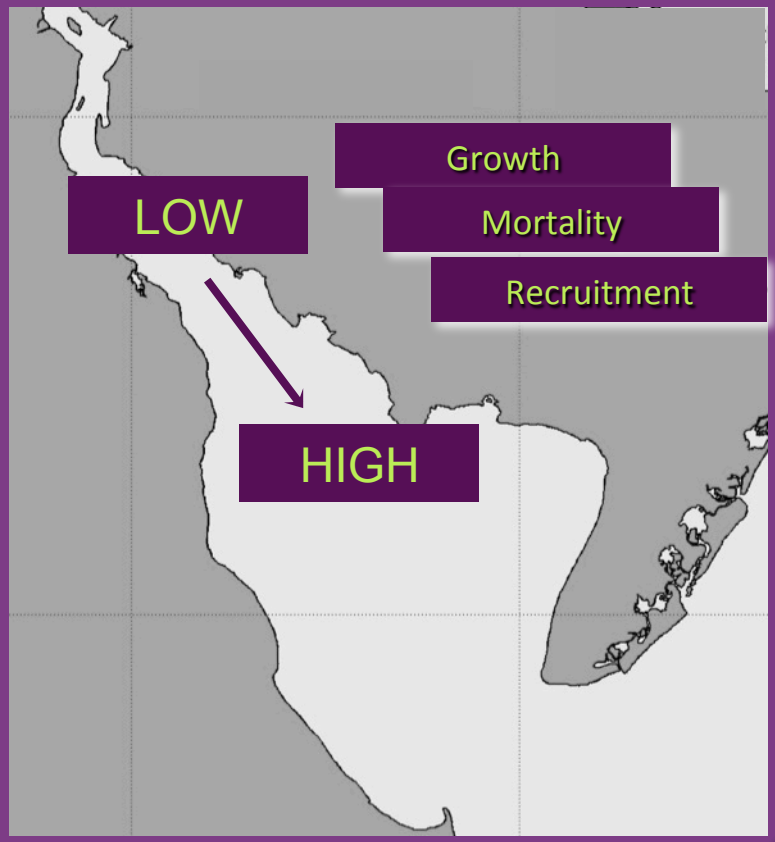
Diego Narváez

Narváez, et al. 2012. Modeling the dispersal of eastern oyster (*Crassostrea virginica*) larvae in Delaware Bay. J. Mar Res. 70: 381-409.

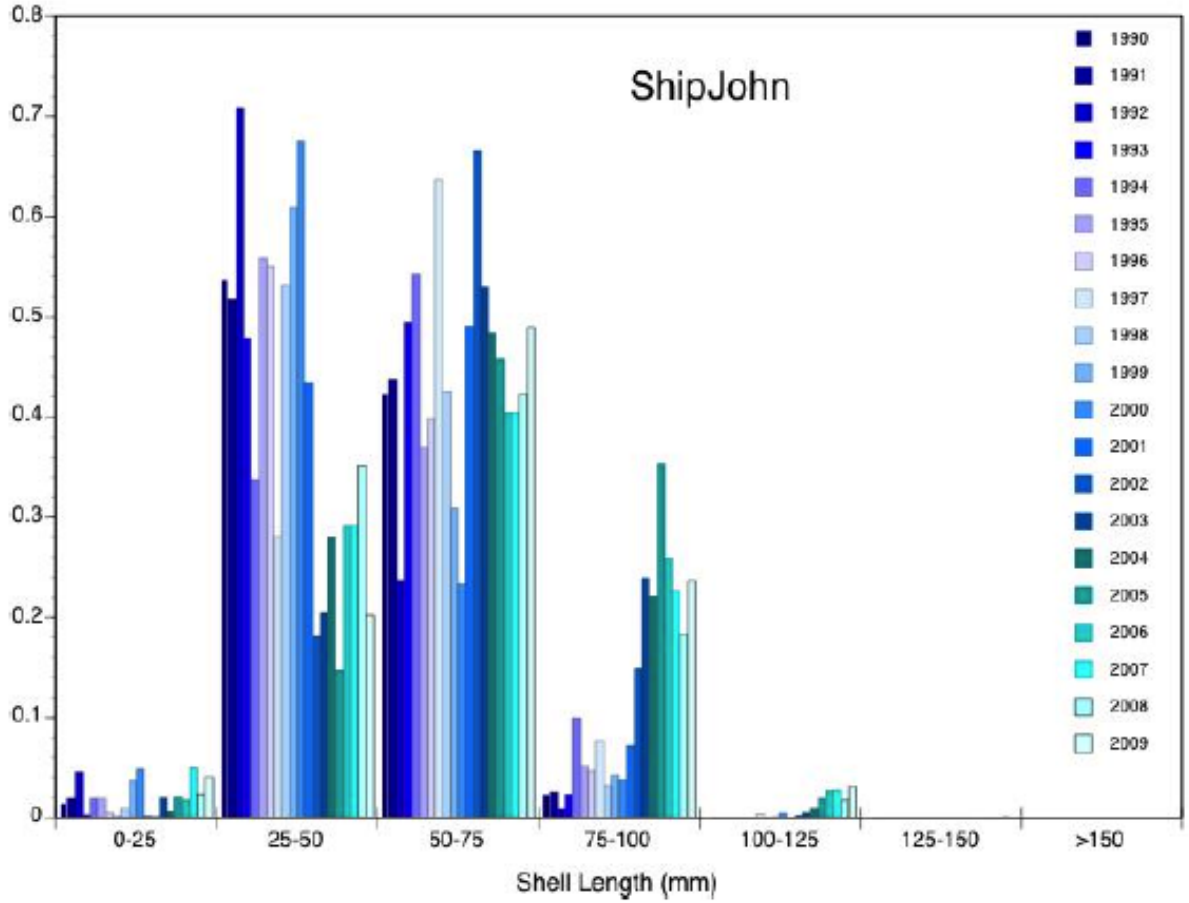
Ecosystem

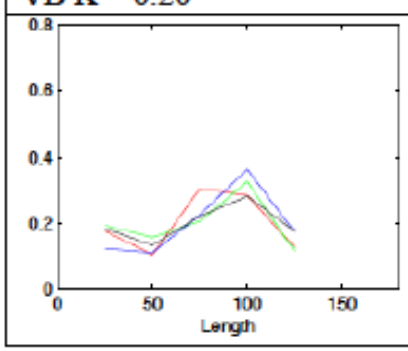
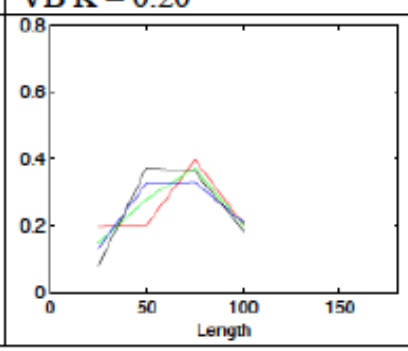
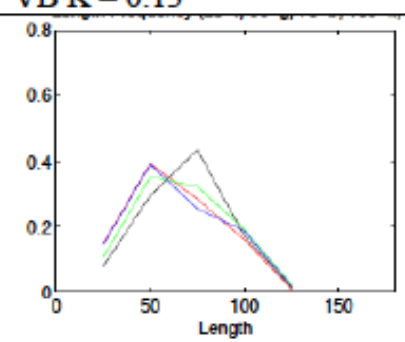
spatially explicit – gradients
genetic and dynamic response to stressors
management
catastophic response





From: Hofmann *et al.*,
Oceanography, 22: 212-231.



Base Case (2000's) L∞ = 125 VB K = 0.20	1990's Simulation via ΔL∞ L∞ = 100 VB K = 0.20	1990's Simulation via ΔK L∞ = 125 VB K = 0.13
		

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Disaster's Aftermath: Assessing Hurricane Irene's Damage

Scientists from some of the areas hardest hit have now had time to evaluate the storm's dramatic geologic effects on their home states

By Andrea Mustain and OurAmazing Planet | October 14, 2011

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1 2 Next >

MINNEAPOLIS — Less than two months after Hurricane Irene barreled up the eastern coastline of the United States, a group of scientists from some of the areas hardest hit presented evidence of the storm's dramatic geological effects on their home states.

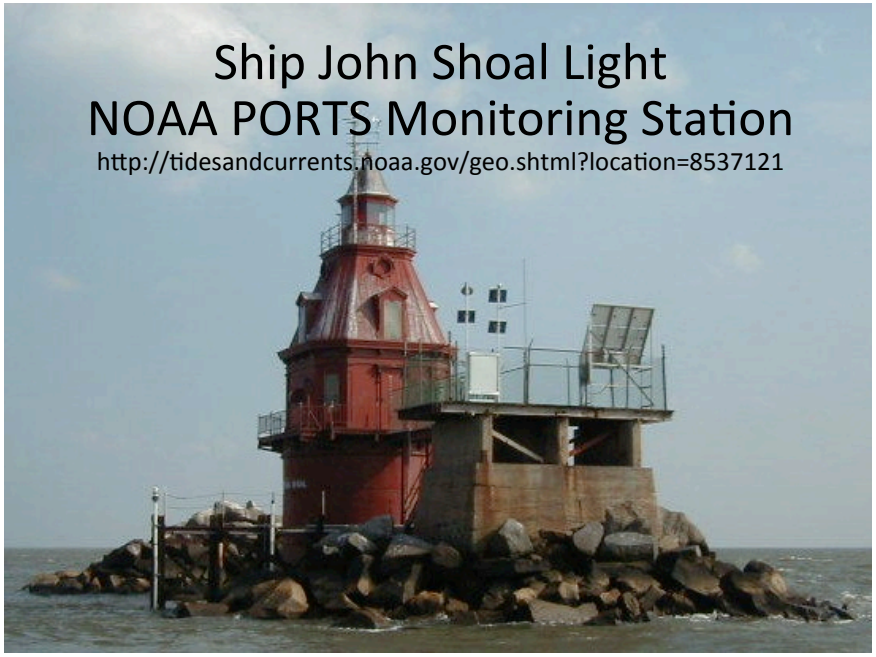
Researchers from Pennsylvania, New Jersey, New York and Vermont took to the podium at a meeting of the Geological Society of America, to discuss what they've learned since the massive storm swept across the Northeast.

EYE FROM THE SKY: Hurricane Irene makes landfall over New York City. For much of New England, the extreme damage was still to come. *Image: NASA/NOAA GOES Project*

The numbers that are emerging, not

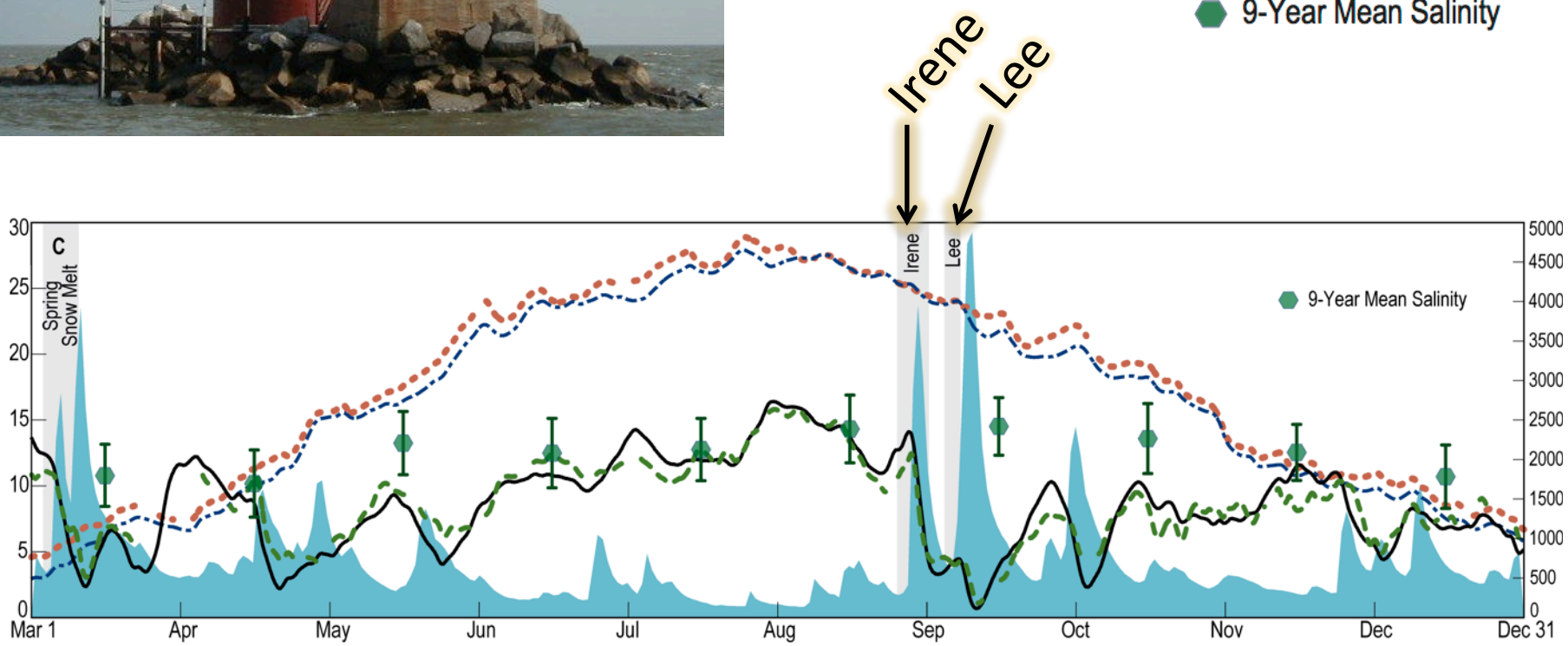
- "we got a year's worth of precipitation in those two months."
- "Some streams… saw peak levels that were 300% higher than high-water records"
  - Joshua Galster, Montclair State University
- "The flood was so massive it pushed all the salt water out into the ocean"
  - Douglas A. Burns, U.S. Geological Survey

http://www.scientificamerican.com/article.cfm?id=hurricane-east-coast-damage



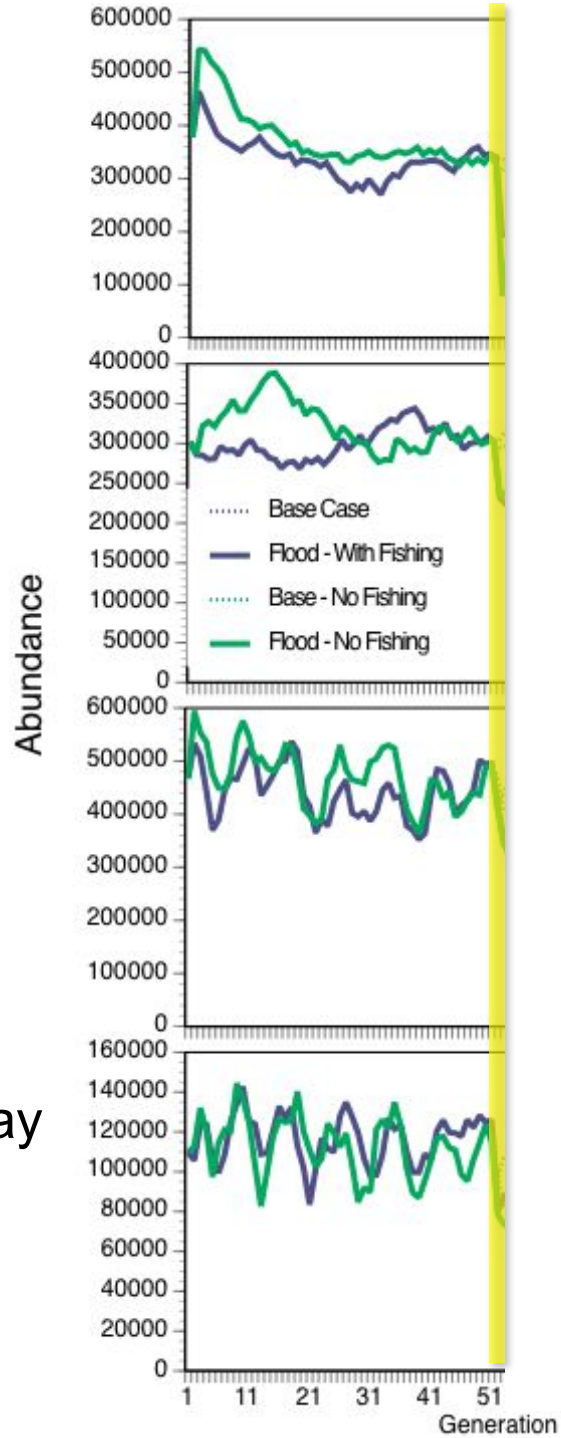
Physical Model:
ROMS

Regional Oceanographic Modeling System



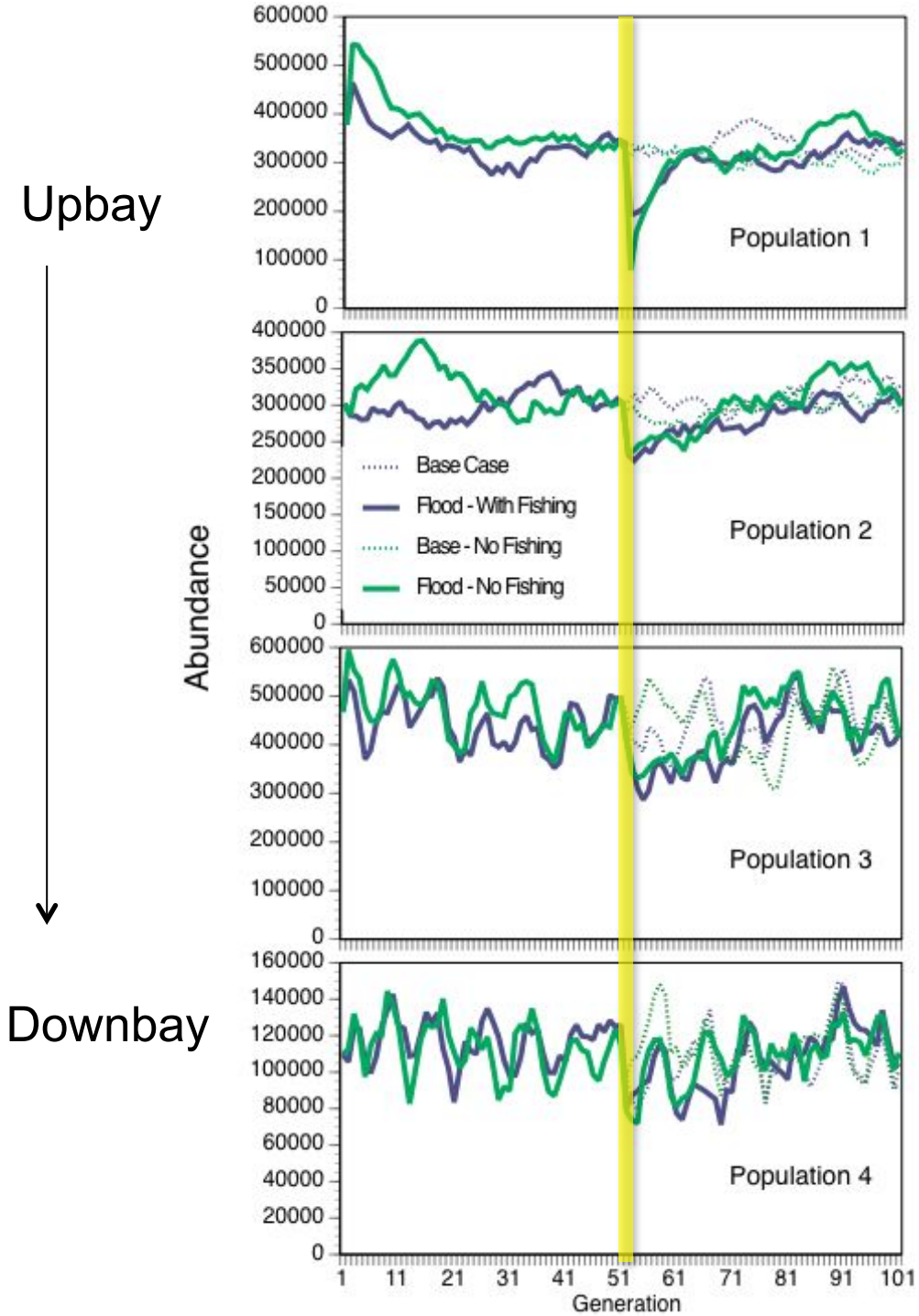
Munroe, D. et al. Estuarine, Coastal and Shelf Science. 135:209-219.
DOI: 10.1016/j.ecss.2013.10.011

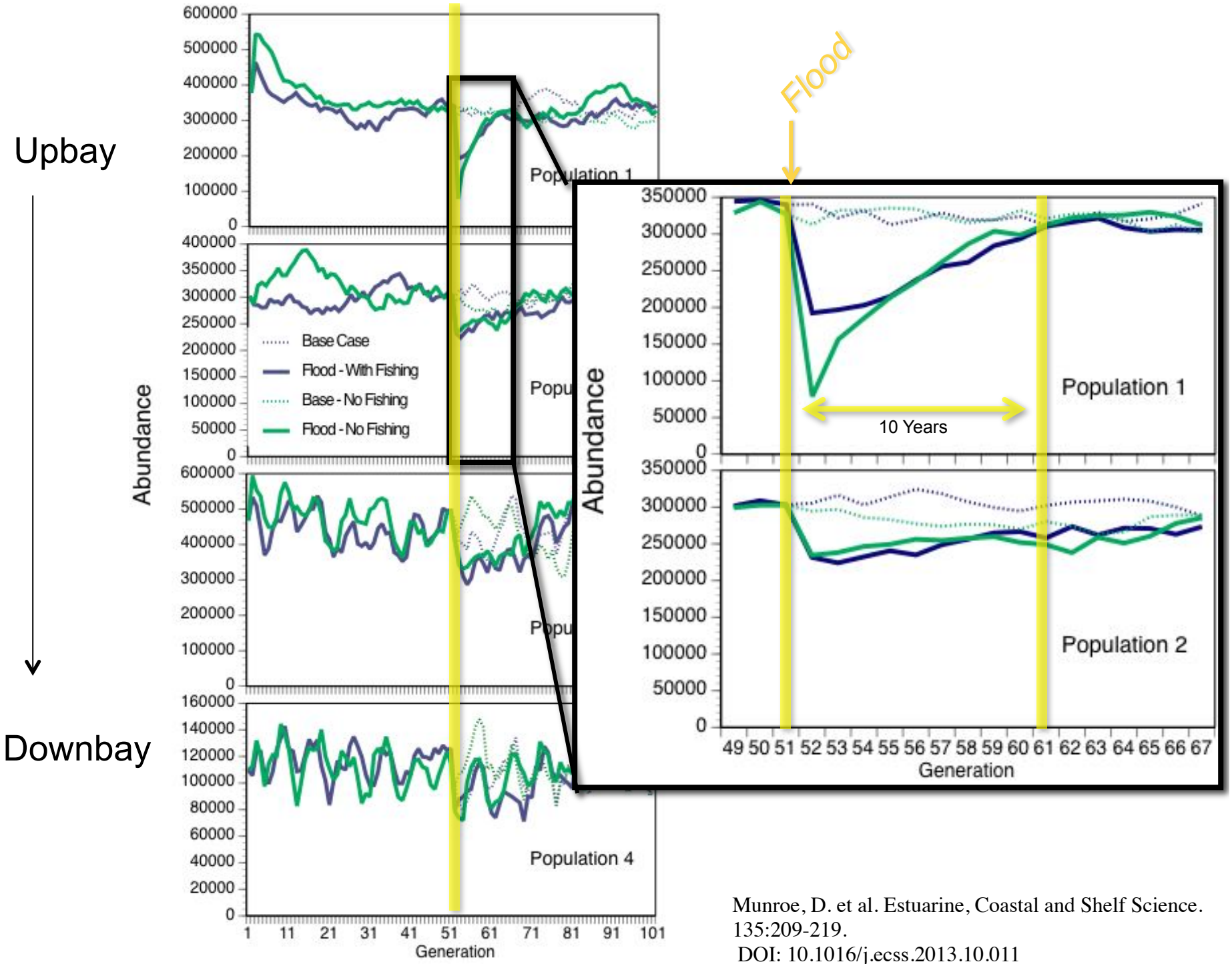
Upbay



Downbay

?


Upbay
Downbay
Abundance
Population 1
Population 2
Population 3
Population 4
Base Case
Flood - With Fishing
Base - No Fishing
Flood - No Fishing
Generation
600000
500000
400000
300000
200000
100000
0
400000
350000
300000
250000
200000
150000
100000
50000
0
600000
500000
400000
300000
200000
100000
0
160000
140000
120000
100000
80000
60000
40000
20000
0
1
11
21
31
41
51
61
71
81
91
101



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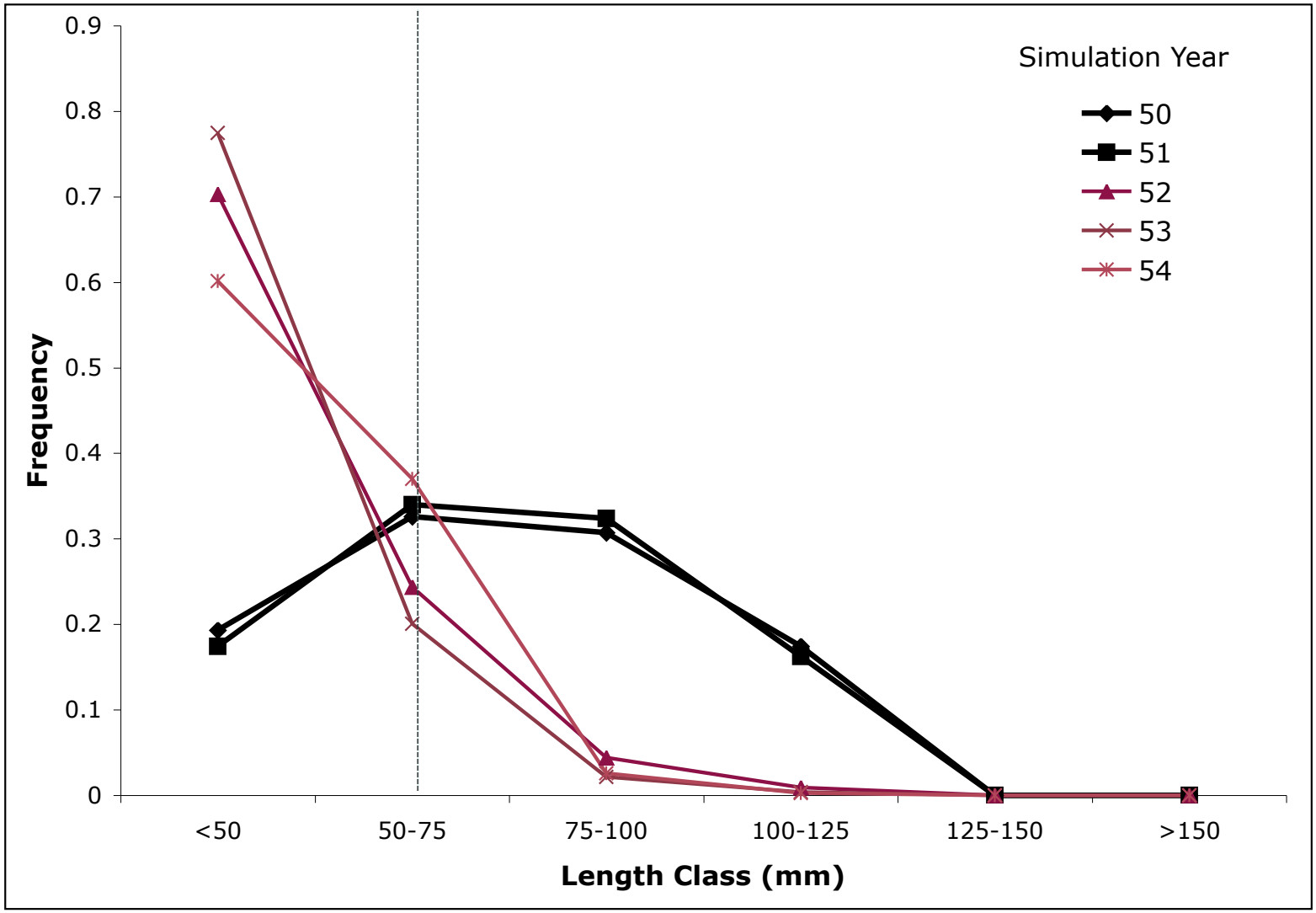
Population 1 - Post-Flood Simulated Length Frequencies



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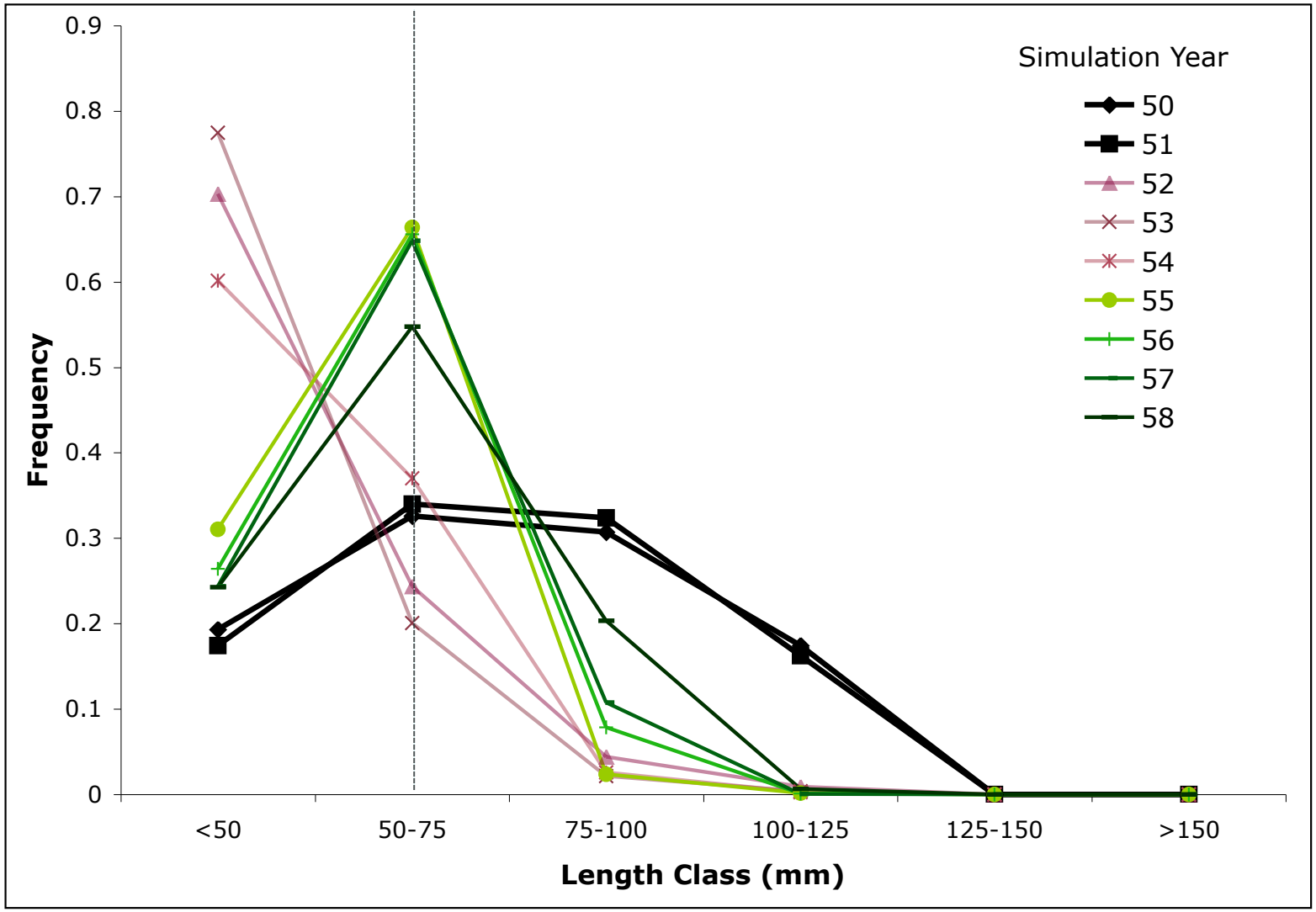

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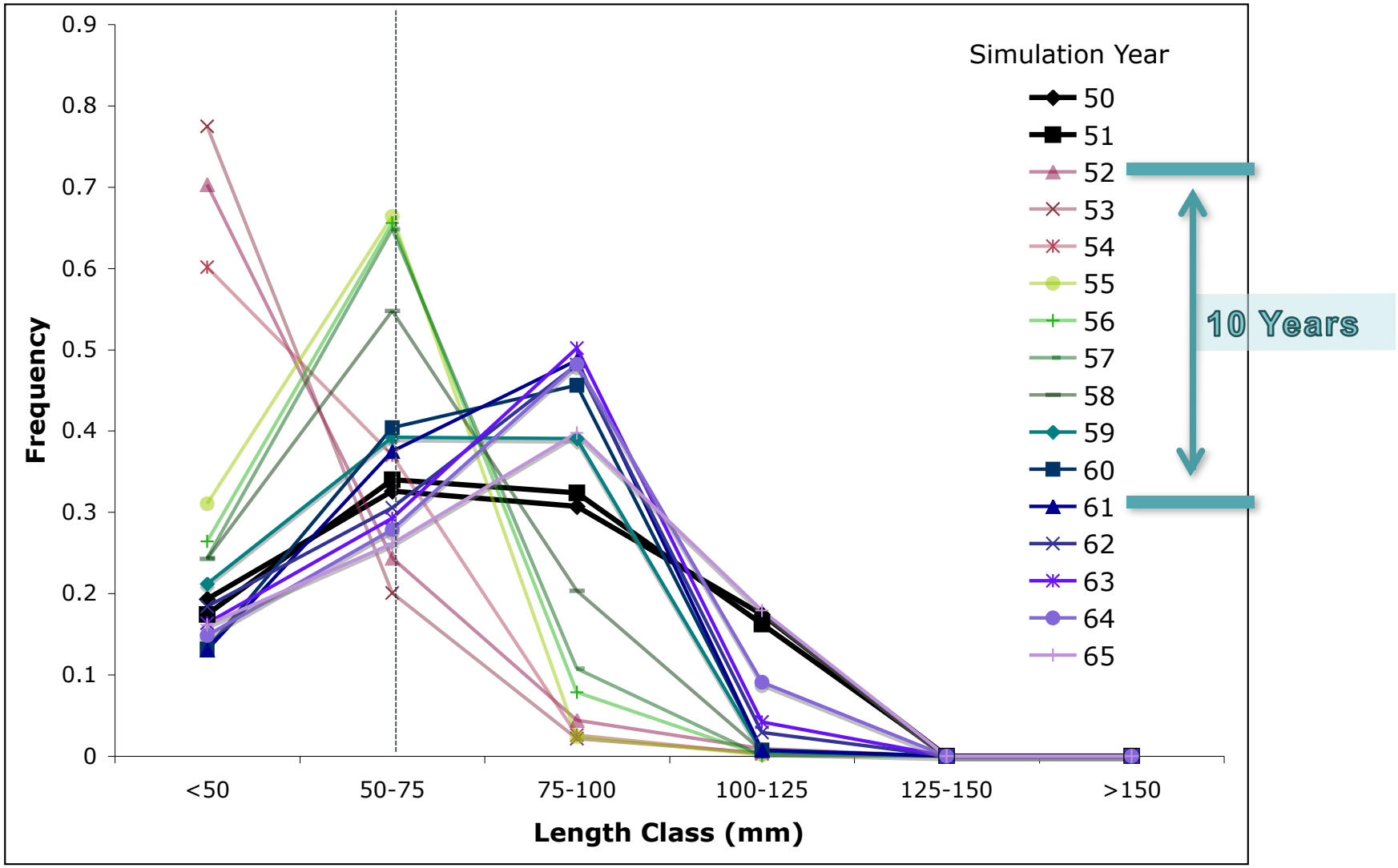

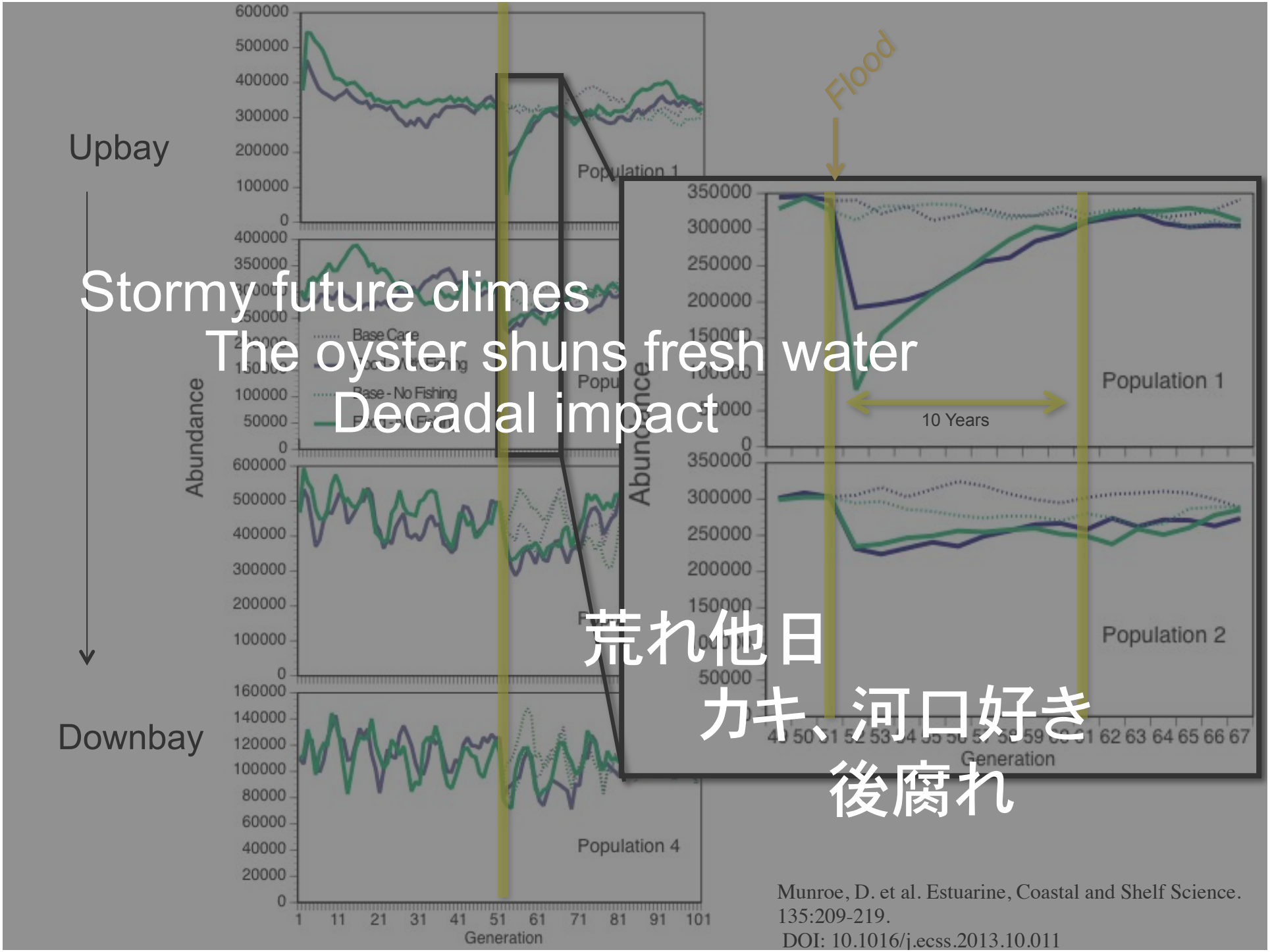

Munroe, D. et al. Estuarine, Coastal and Shelf Science. 135:209-219.
DOI: 10.1016/j.ecss.2013.10.011

Vol. 393: 1–12, 2009
doi: 10.3354/meps08287

MARINE ECOLOGY PROGRESS SERIES
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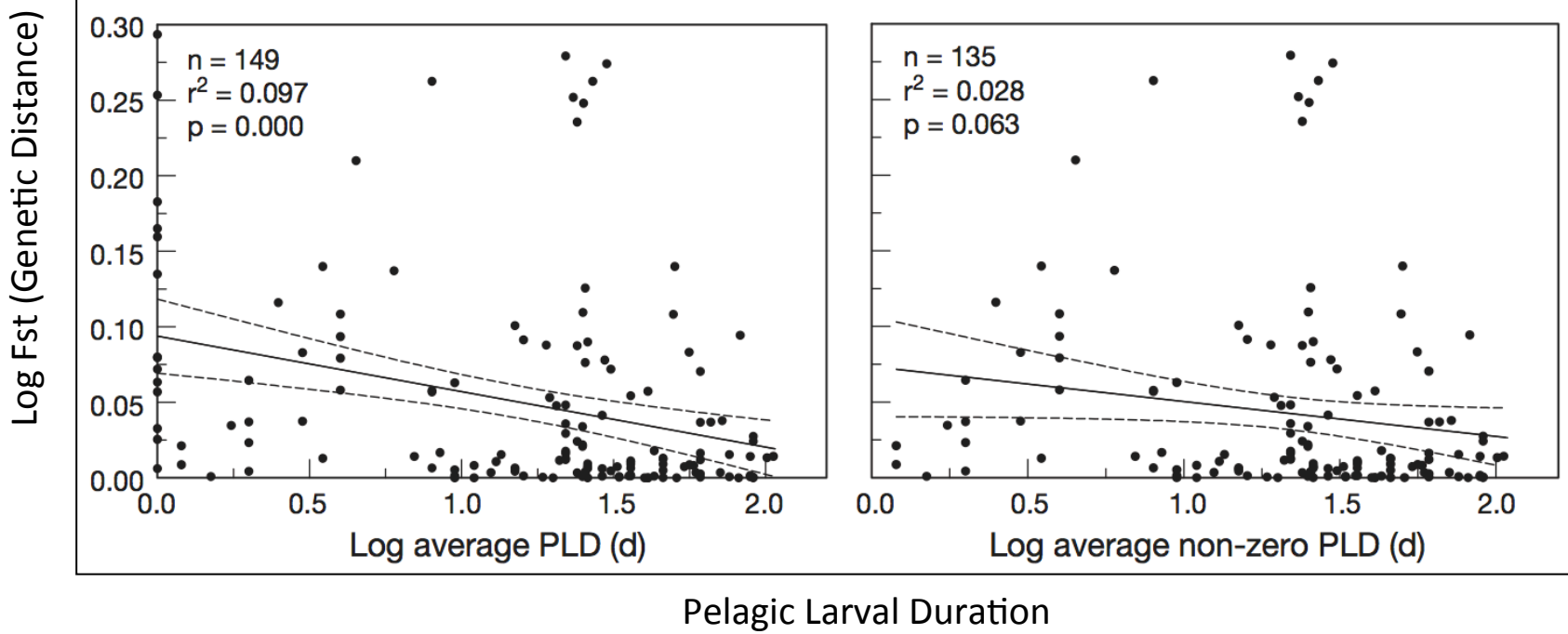
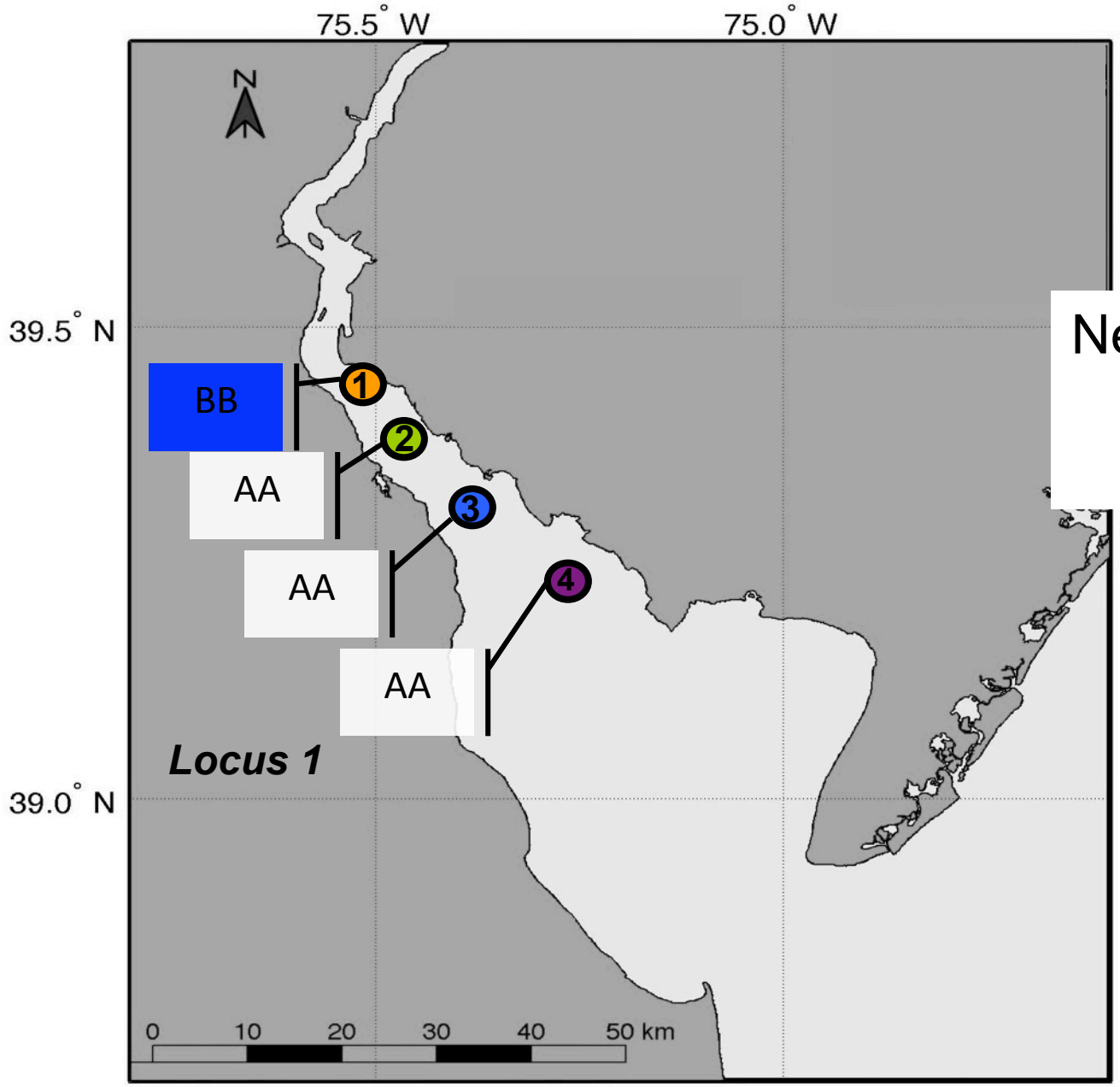
FEATURE ARTICLE

Population genetics, larval dispersal, and connectivity in marine systems

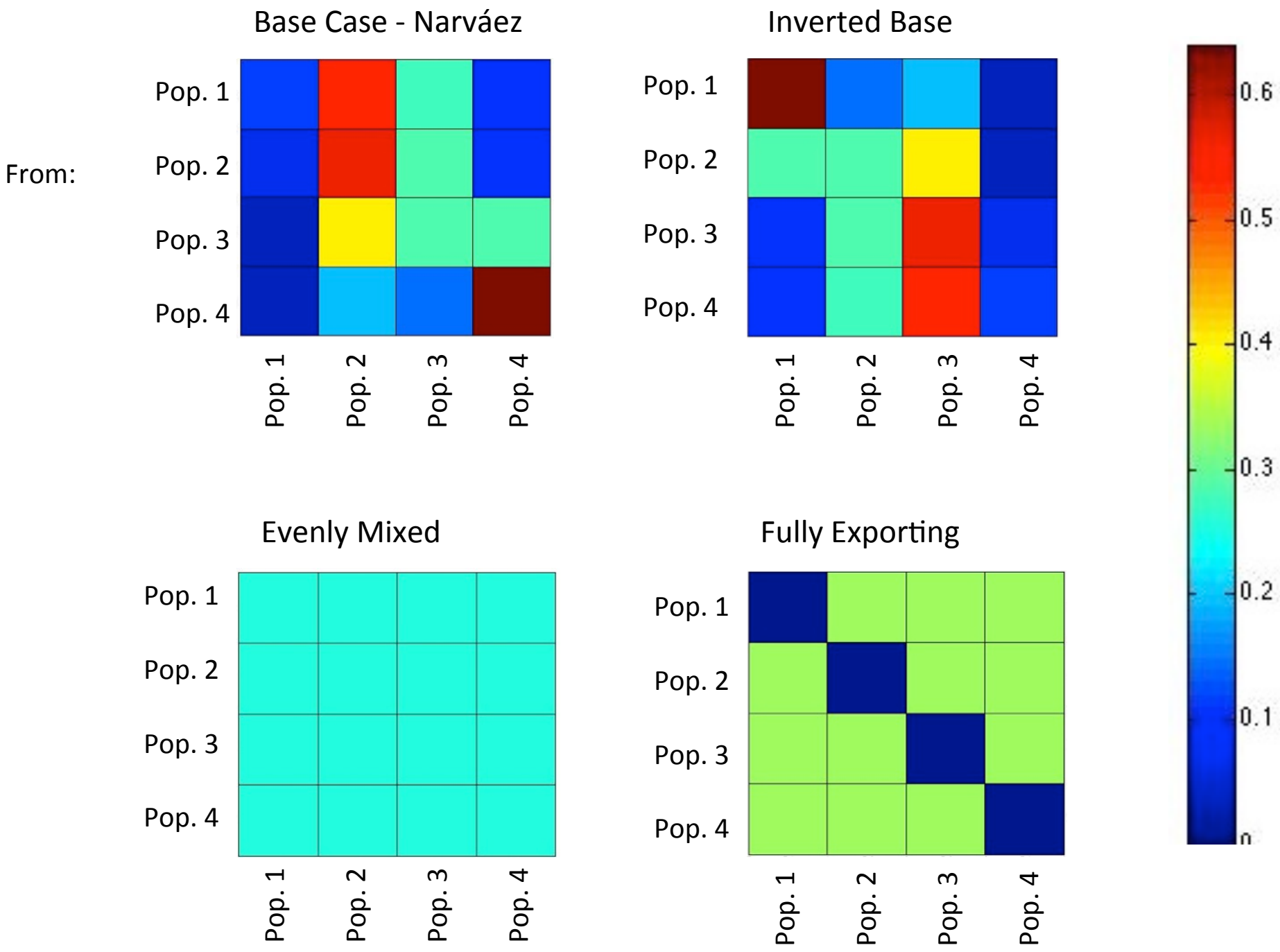
Kimberley Weersing[1,2,*], Robert J. Toonen[2]



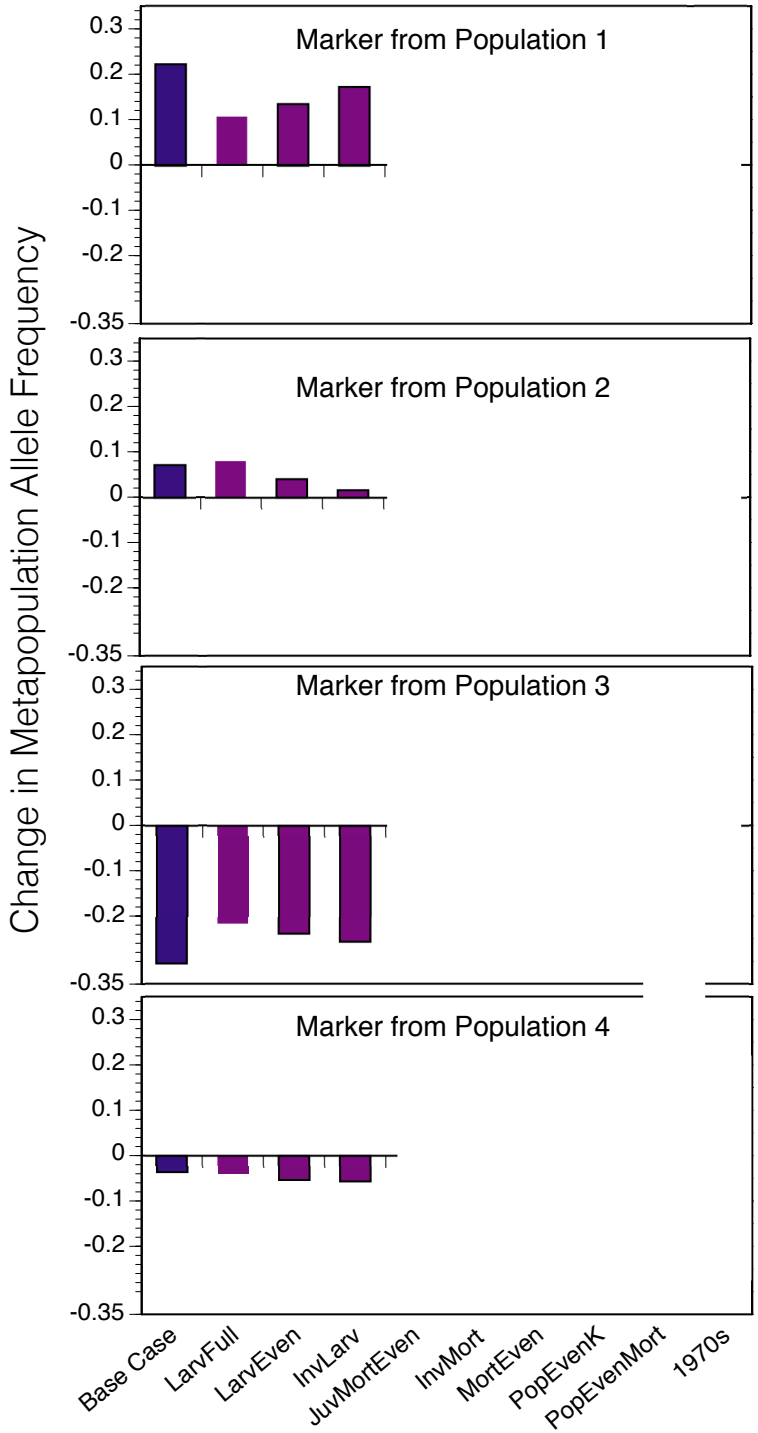


Neutral Marker Alleles

Used to track genetic connectivity over time

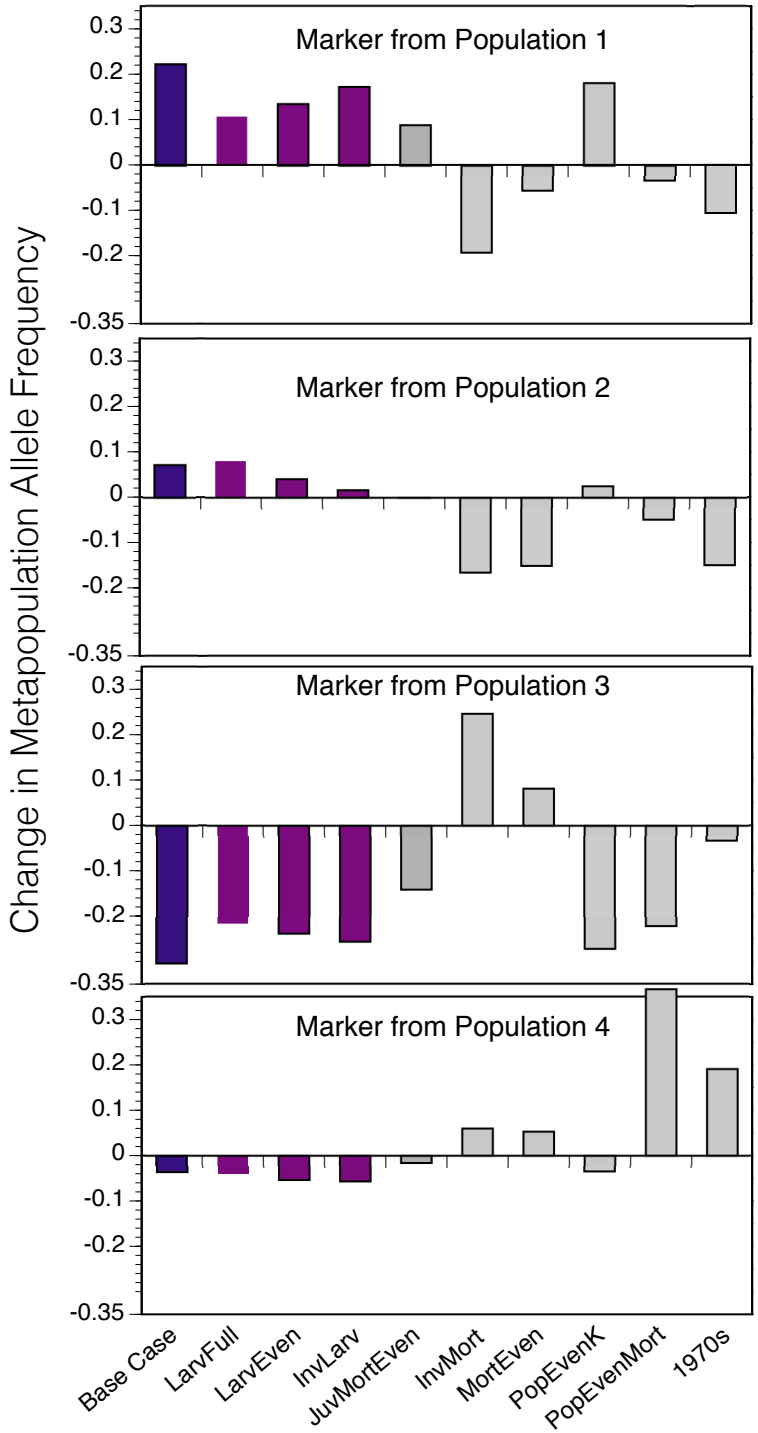

Base Case - Narváez
Inverted Base
Evenly Mixed
Fully Exporting
From:
Pop. 1
Pop. 2
Pop. 3
Pop. 4
0.6
0.5
0.4
0.3
0.2
0.1
0

Is larval dispersal or post-settlement processes more important to genetic connectivity?



Munroe, D.et al. 2012 Journal of Marine Research. 70: 441-467.

Is larval dispersal or post-settlement processes more important to genetic connectivity?



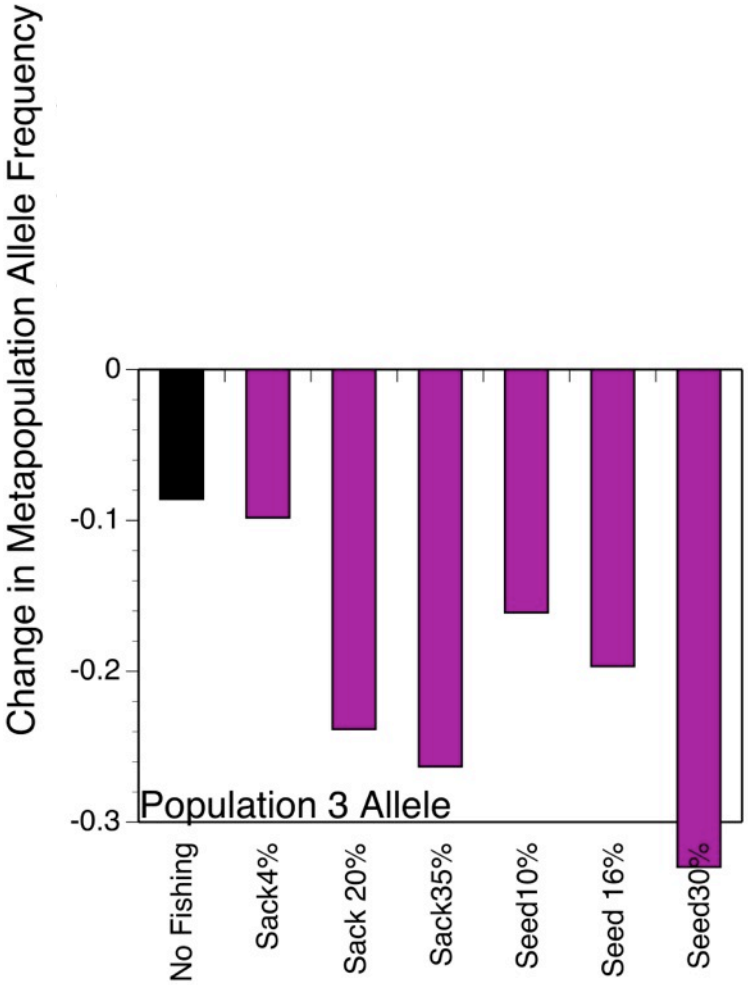
Connectivity changes due to changing

larval dispersal ~ 1 to 4%

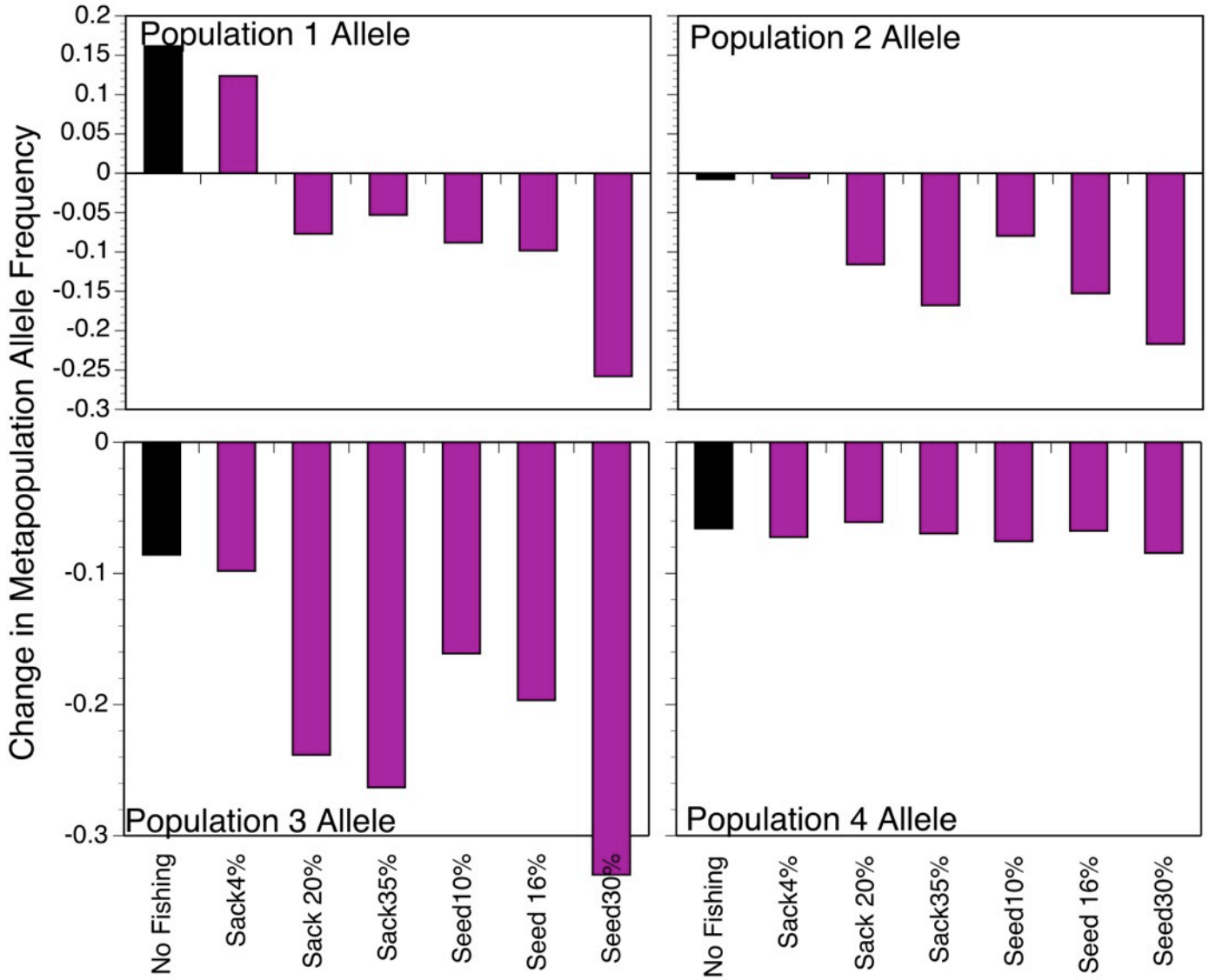
post-settlement processes ~ 14-25%

Munroe,.et al. 2012 Journal of Marine Research. 70: 441-467.

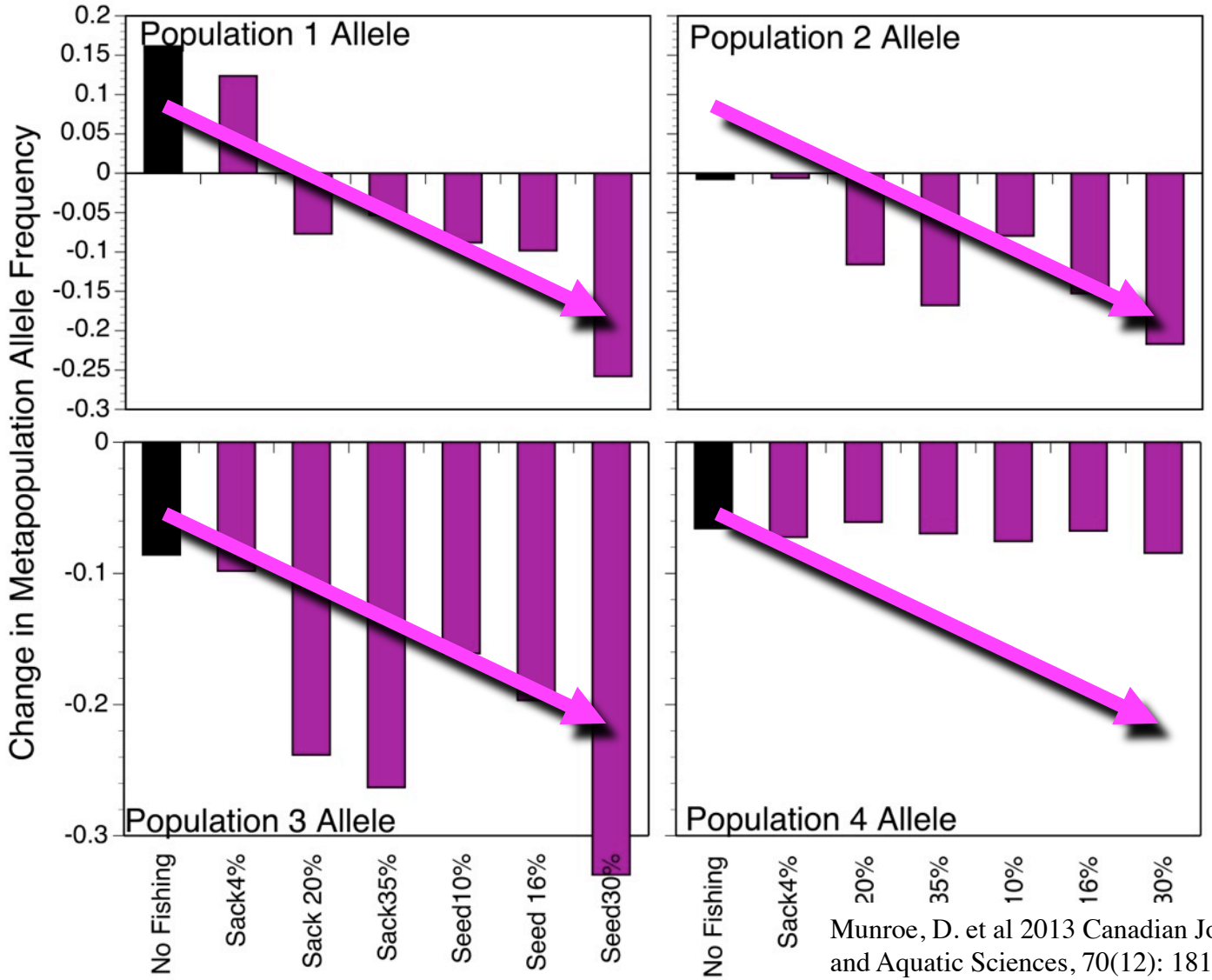
How do fisheries influence genetic connectivity?



How do fisheries influence genetic connectivity?

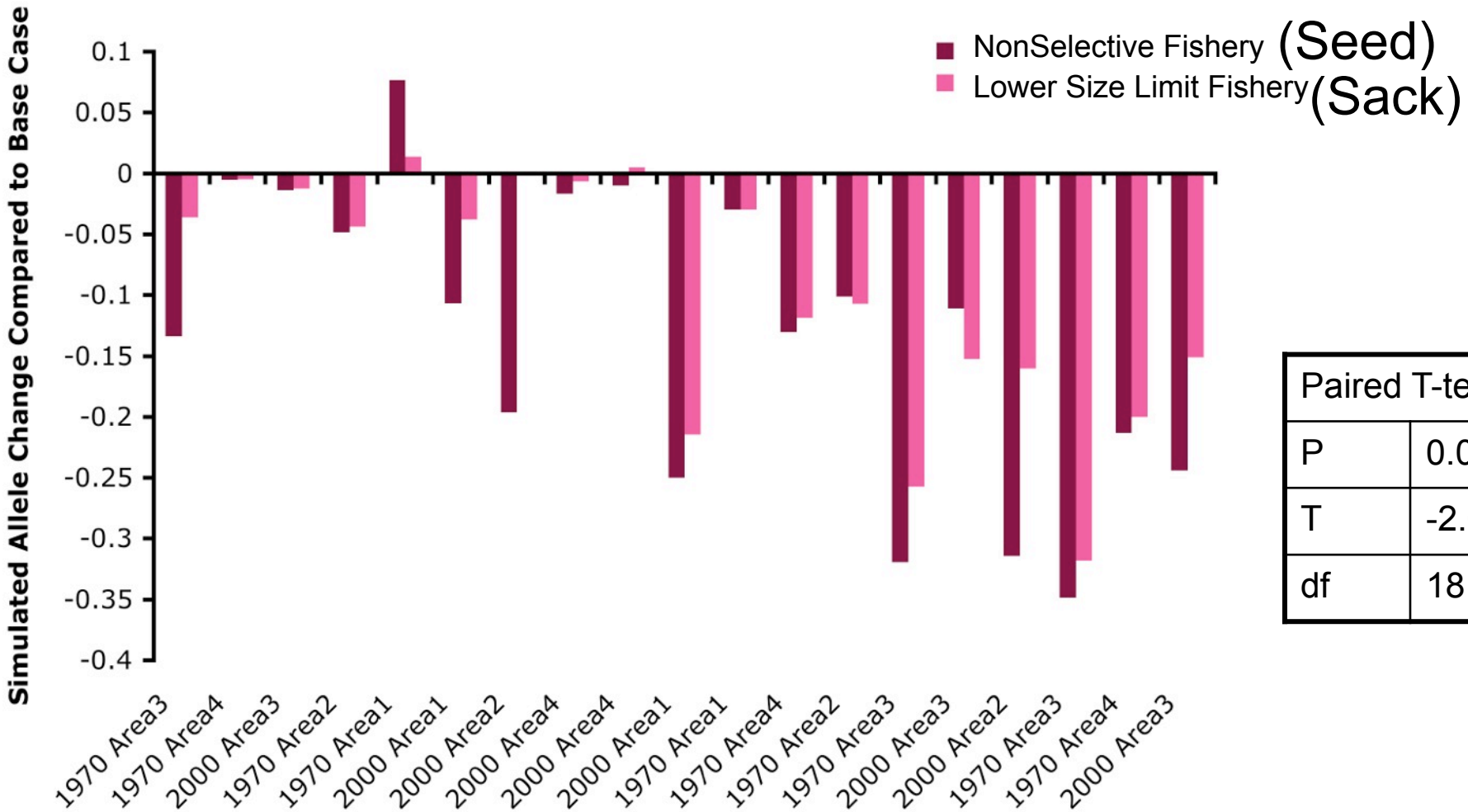


How do fisheries influence genetic connectivity?



Munroe, D. et al 2013 Canadian Journal of Fisheries and Aquatic Sciences, 70(12): 1813-1828, DOI: 10.1139/cjfas-2013-0089

How do fisheries influence genetic connectivity?

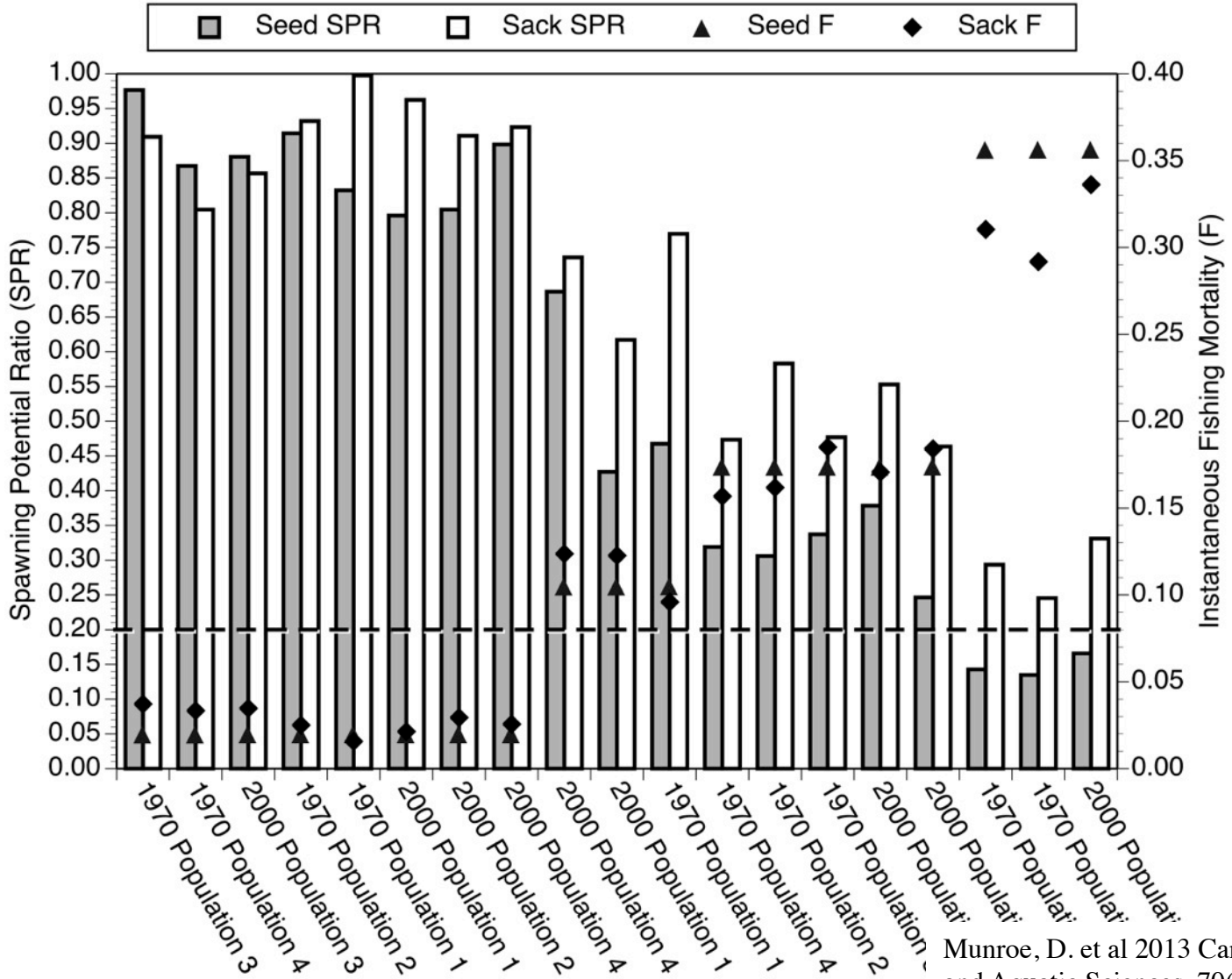


Paired T-test	
P	0.025
T	-2.09
df	18

NonSelective < Size Selective Fishery
allele change versus Base Case
on average 3.5 % lower allele frequency

Munroe, D. et al 2013 Canadian Journal of Fisheries and Aquatic Sciences, 70(12): 1813-1828, DOI: 10.1139/cjfas-2013-0089

How do fisheries influence genetic connectivity?

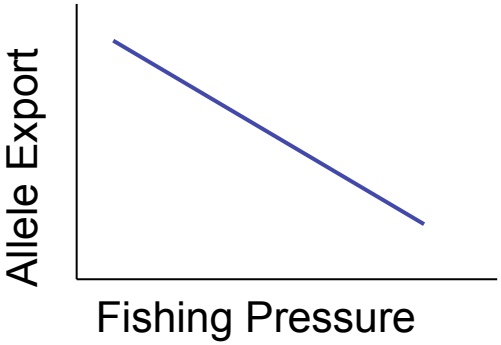


Munroe, D. et al 2013 Canadian Journal of Fisheries and Aquatic Sciences, 70(12): 1813-1828, DOI: 10.1139/cjfas-2013-0089

How do fisheries influence genetic connectivity?

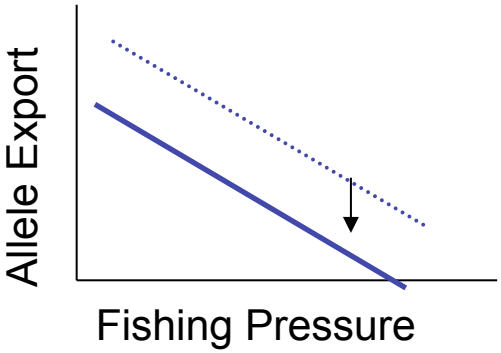
Increasing fishing decreases allele export

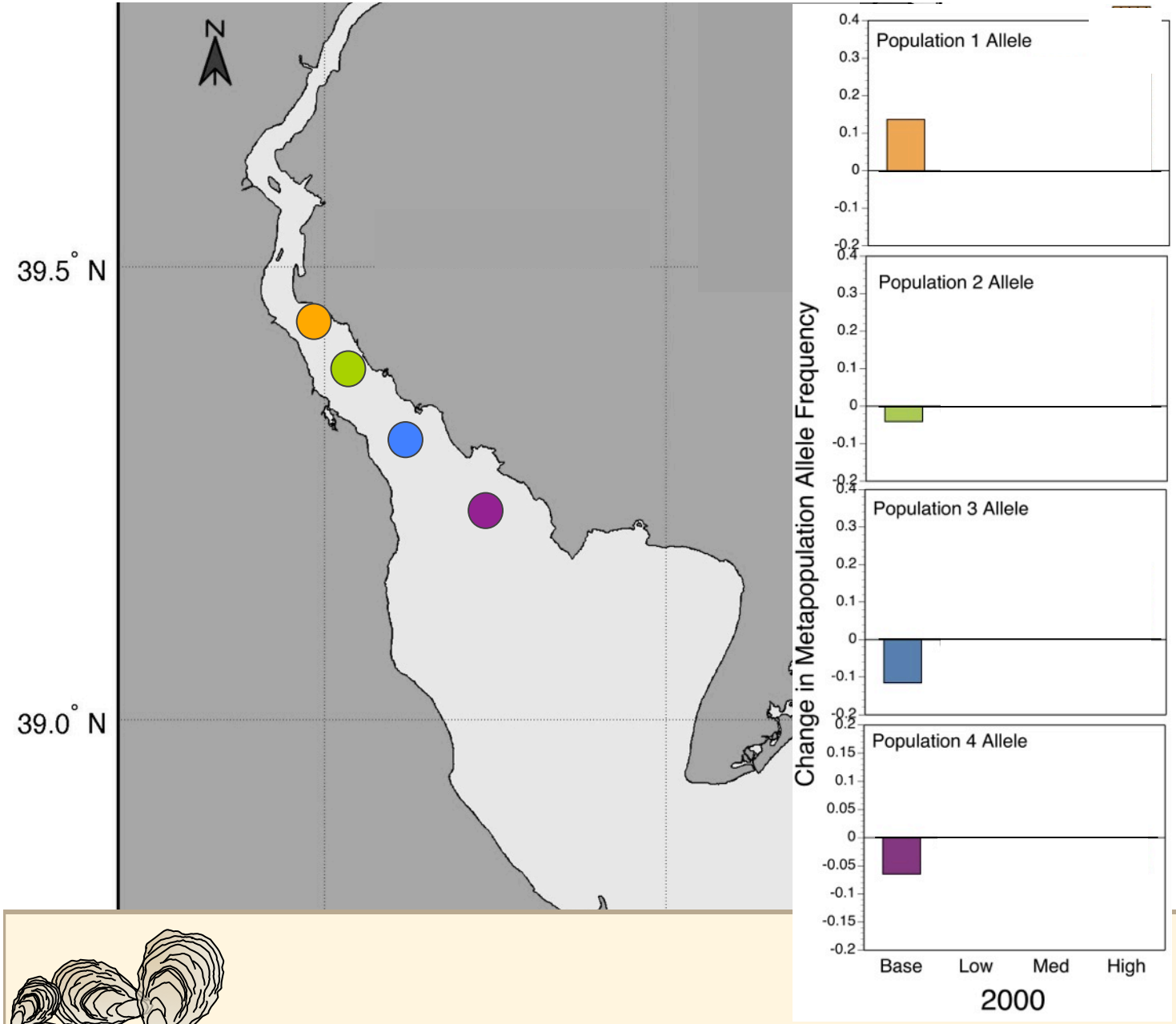
- True for both fishery types



Non-selective fisheries lead to a greater decrease in allele export

- On average, 3.5% lower

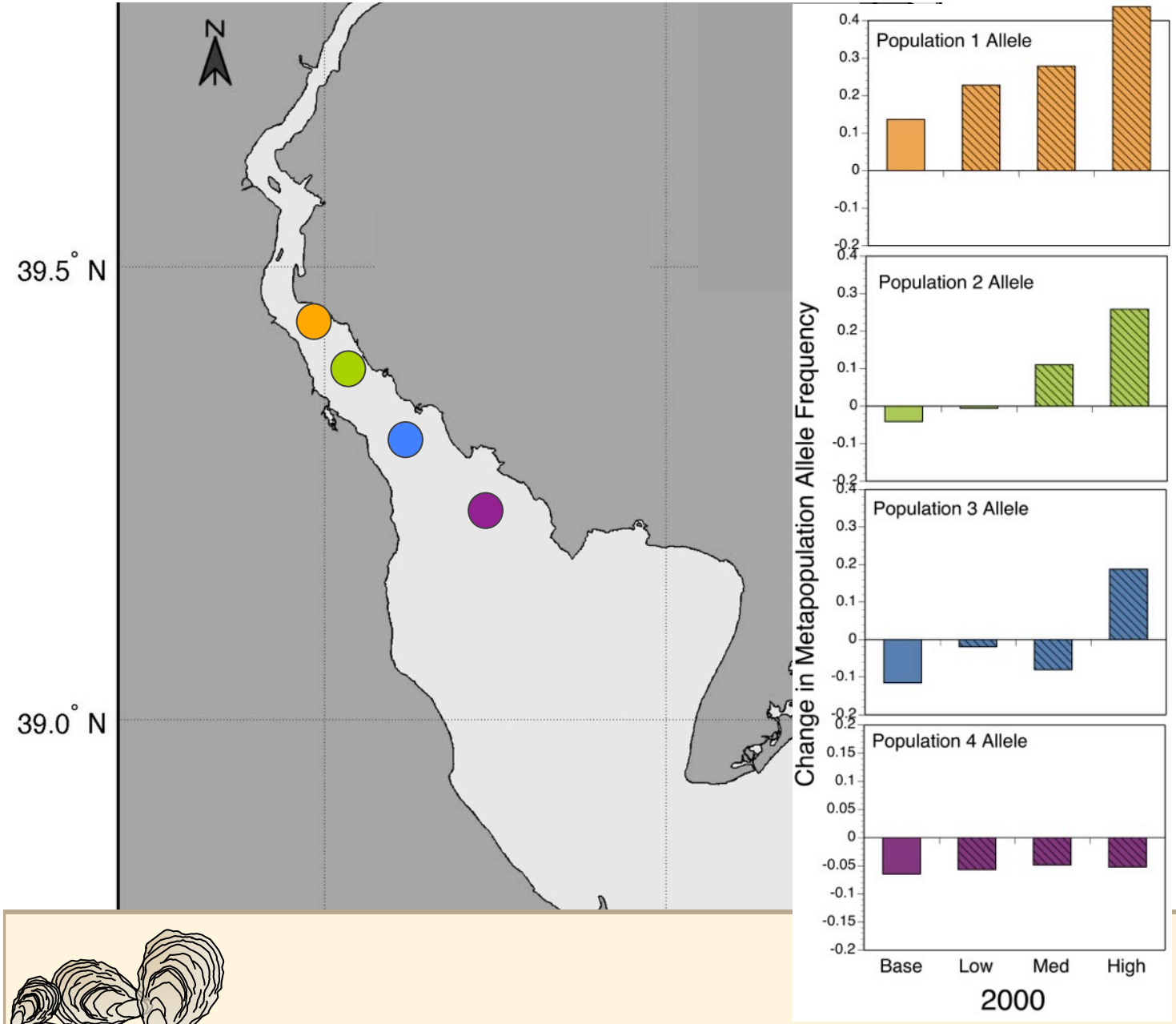




Shifts in source:sink dynamics

What role do MPAs play in genetic connectivity?

Munroe, et al. 2014. Aquatic Conservation. *In Press*. DOI: 10.1002/aqc.2400

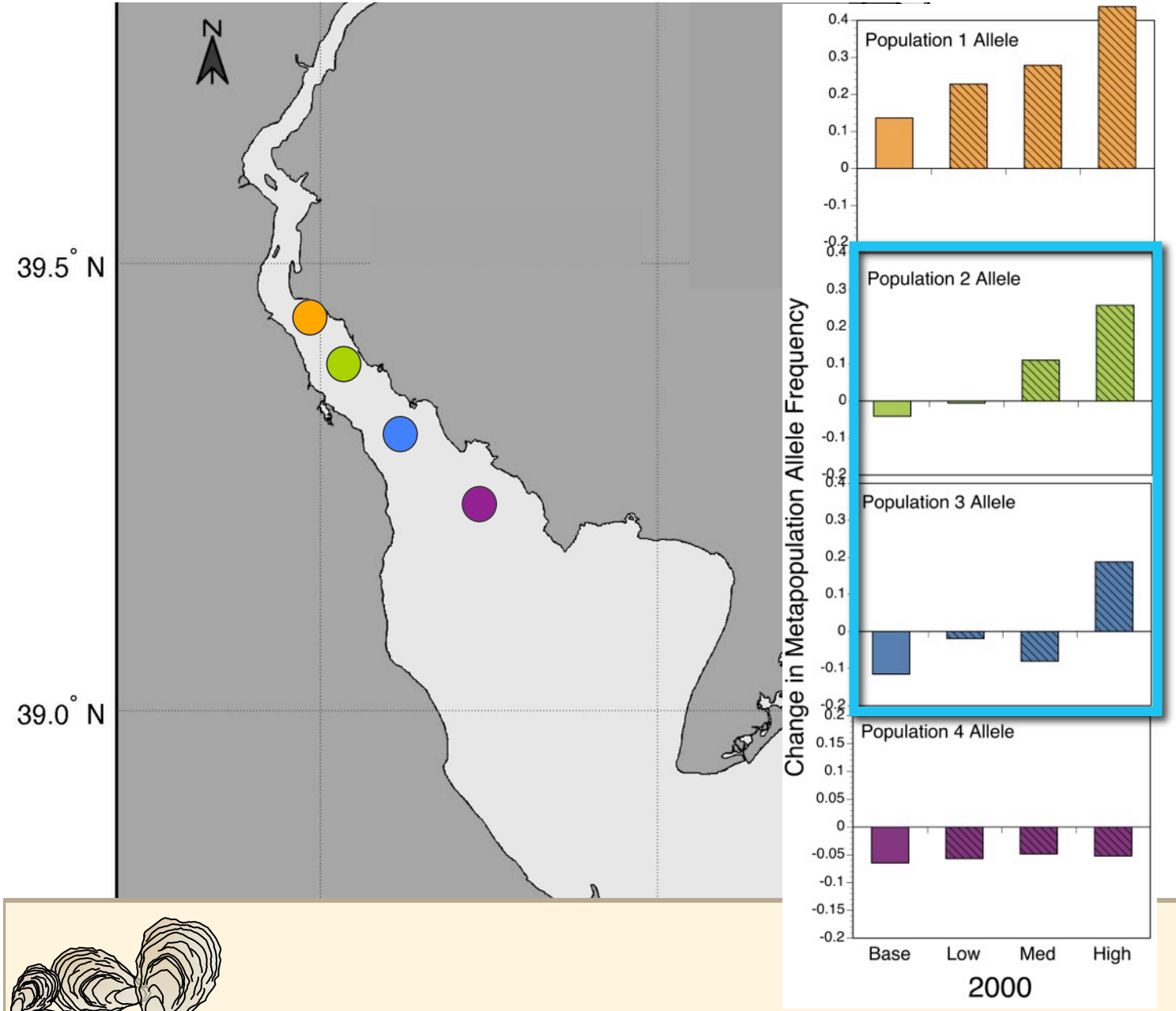


MPAs:

Increasing export of allele with surrounding fishing pressure

What role do MPAs play in genetic connectivity?

Munroe et al., 2014. Aquatic Conservation 24: 645-666.
DOI: 10.1002/aqc.2400



MPAs:

Can alter source:sink locations

What role do MPAs play in genetic connectivity?

Munroe et al., 2013. Aquatic Conservation 24: 645-666.
DOI: 10.1002/aqc.2400

Genotype Linked to Phenotype

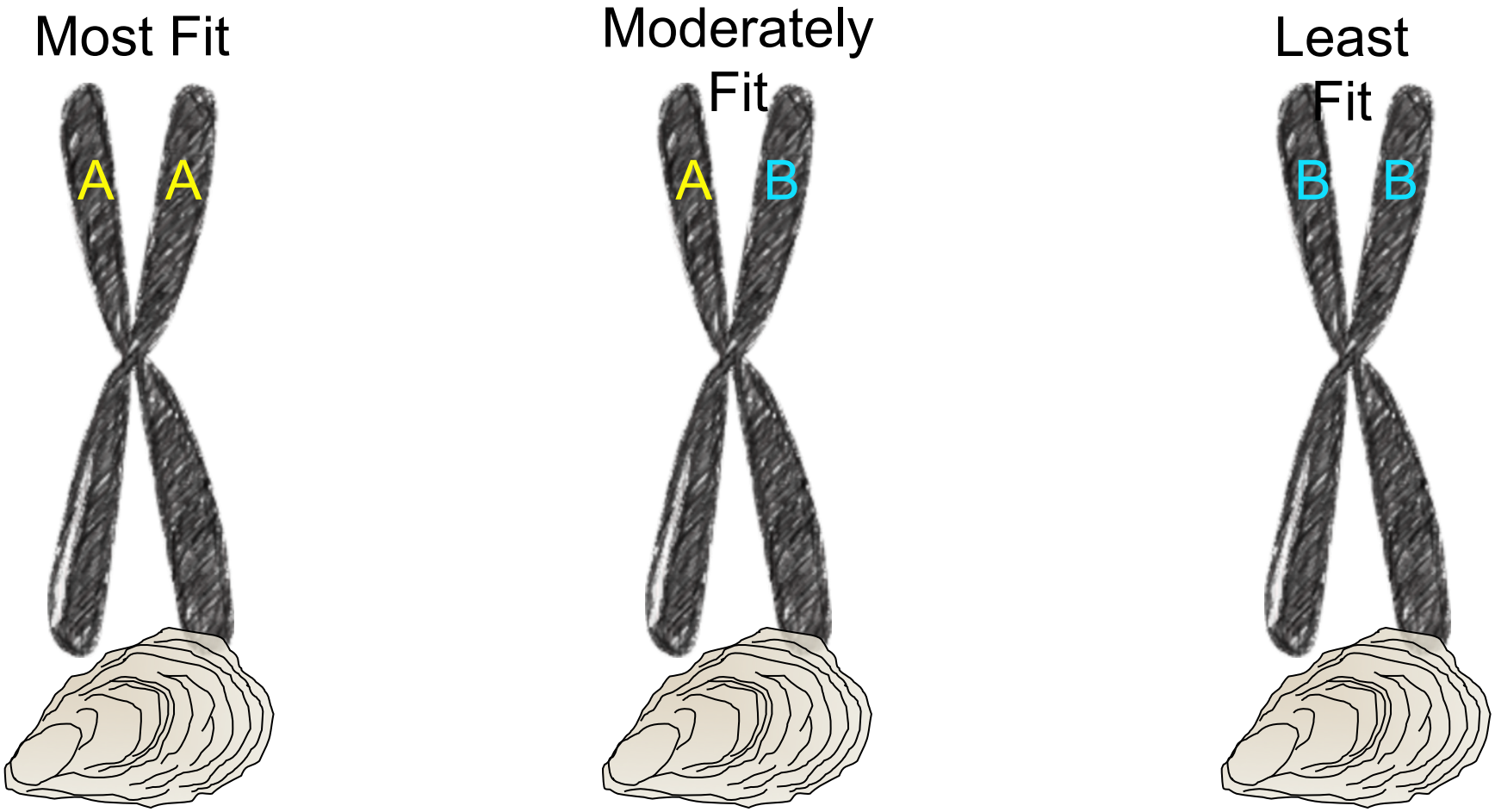
Most Fit

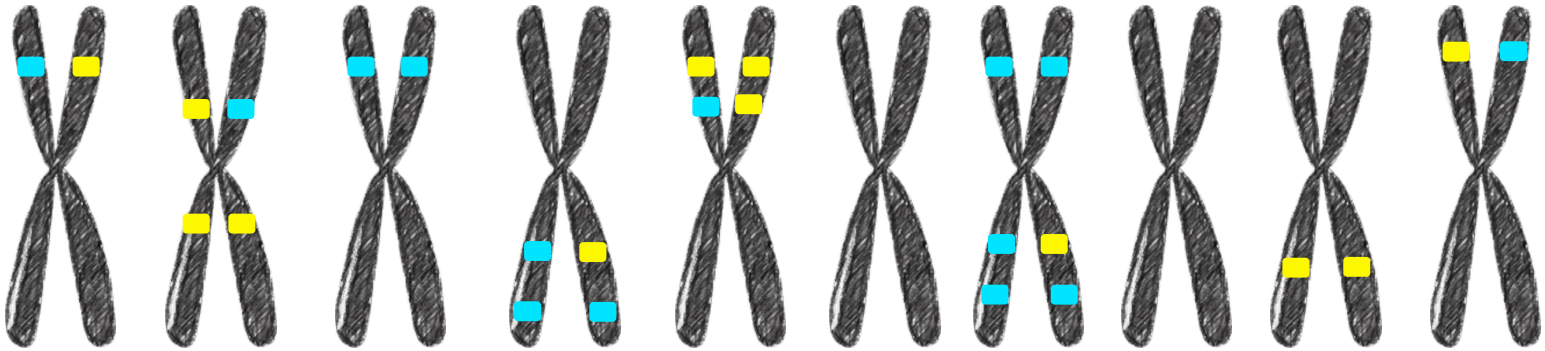
Genotype Linked to Phenotype

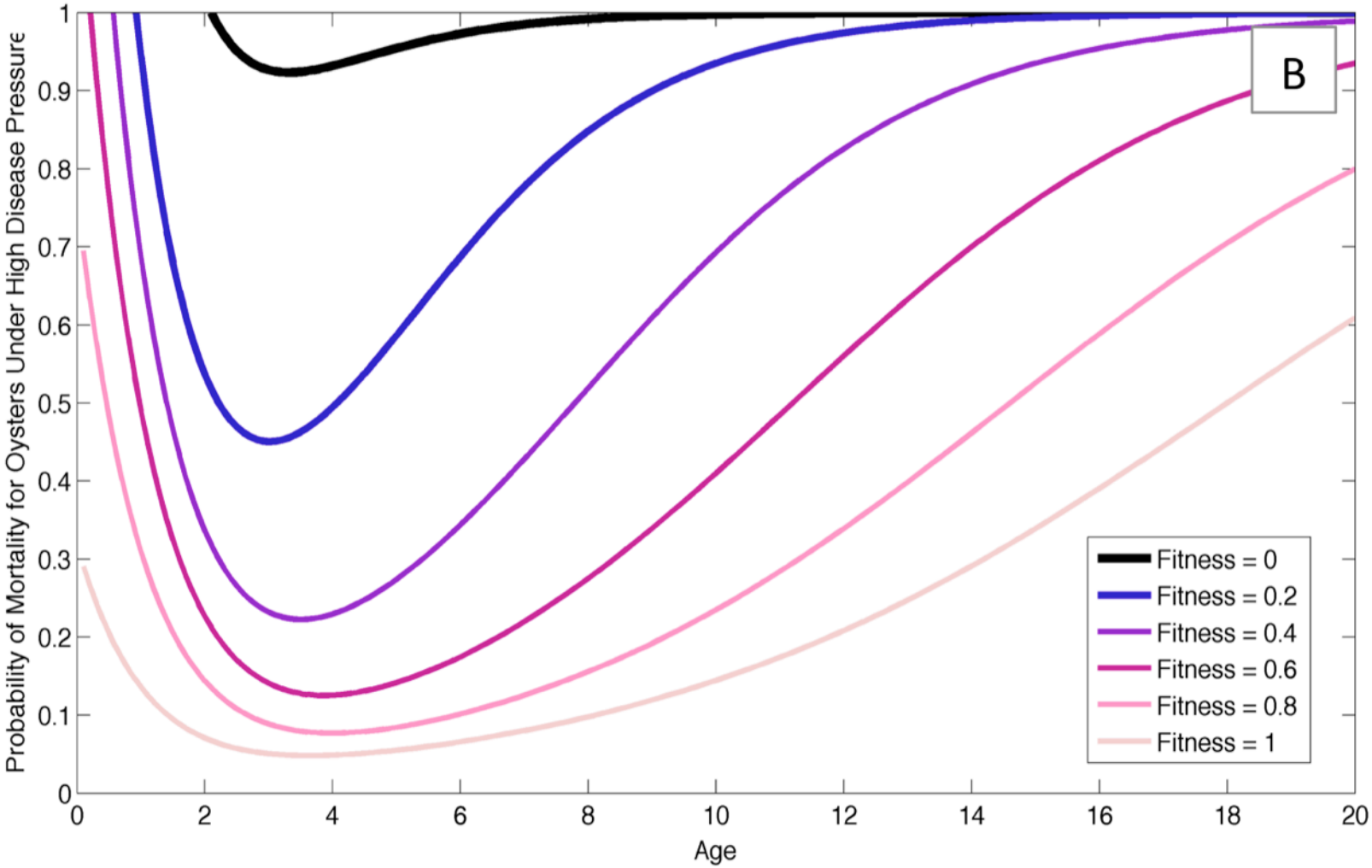
Most Fit

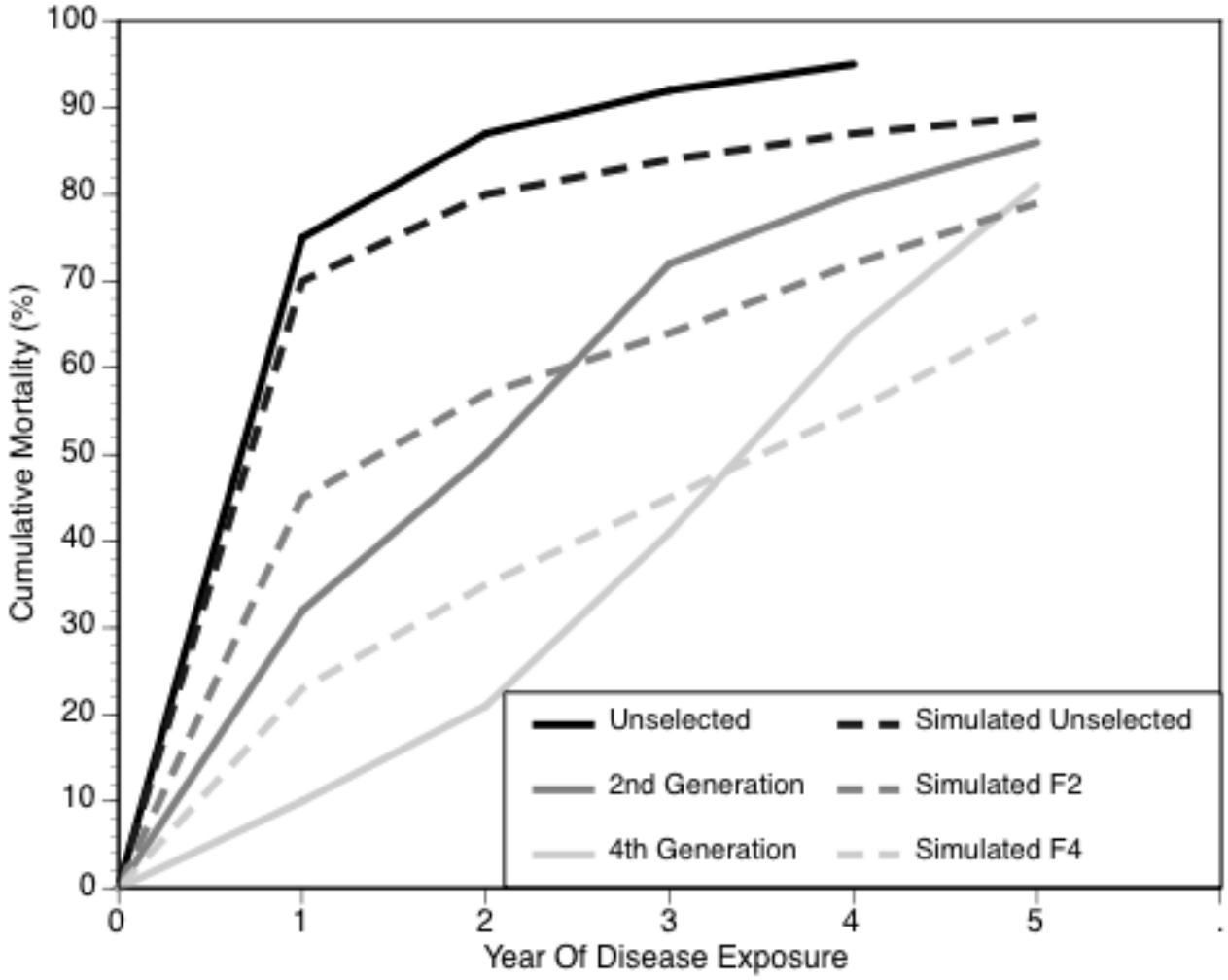
Moderately Fit

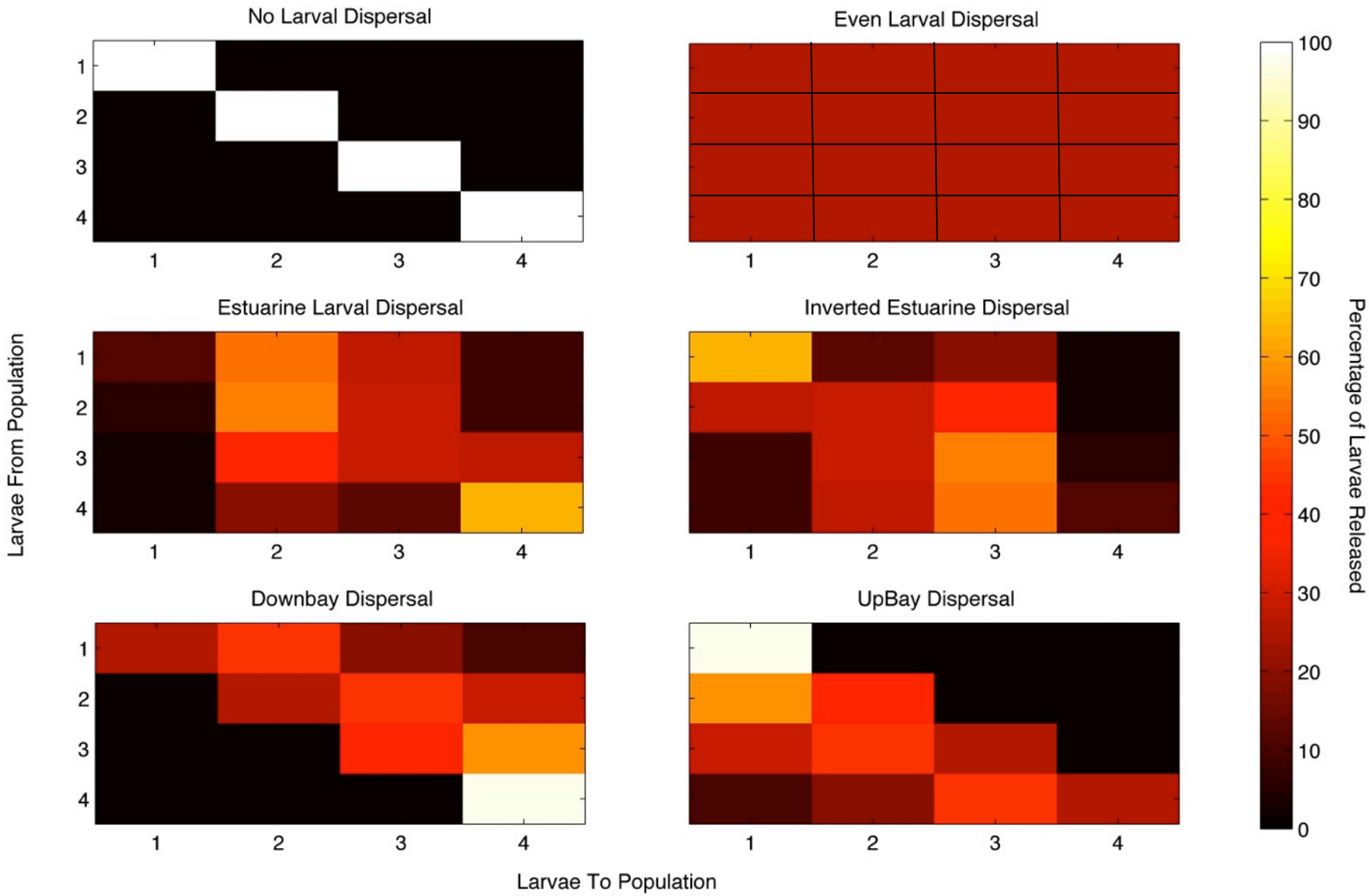
Genotype Linked to Phenotype



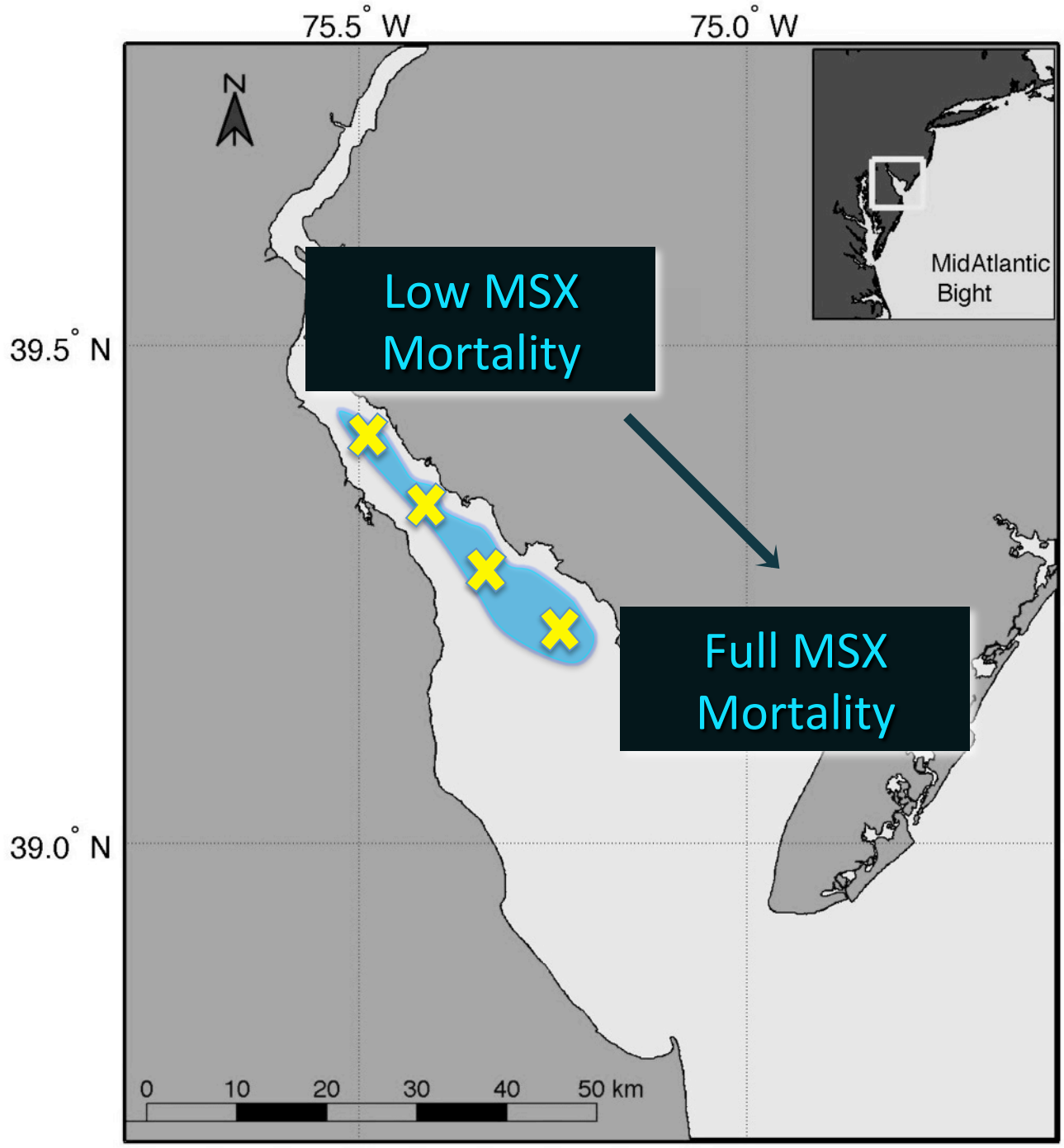


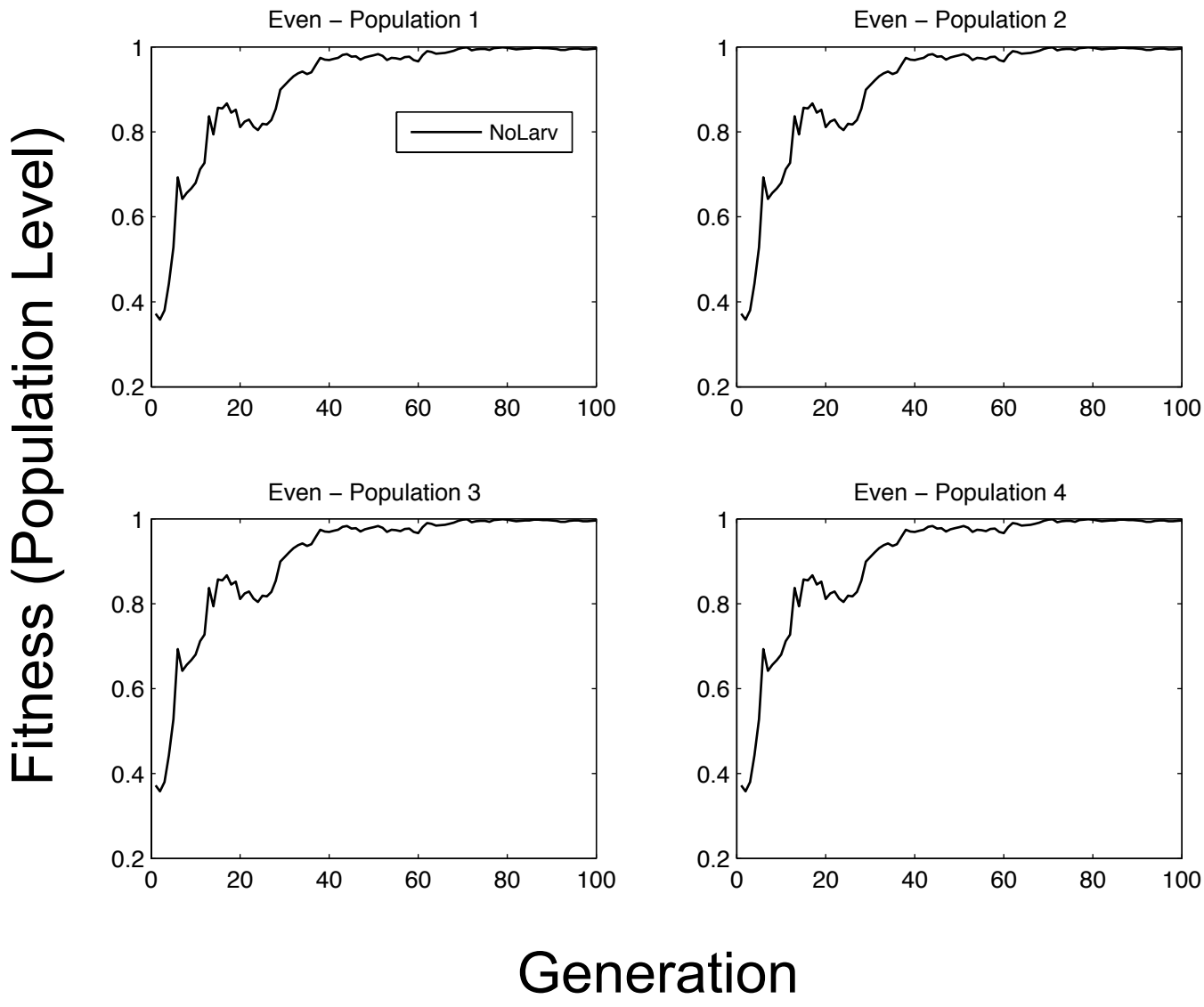

B
Probability of Mortality for Oysters Under High Disease Pressure
Age
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
2
4
6
8
10
12
14
16
18
20
Fitness = 0
Fitness = 0.2
Fitness = 0.4
Fitness = 0.6
Fitness = 0.8
Fitness = 1

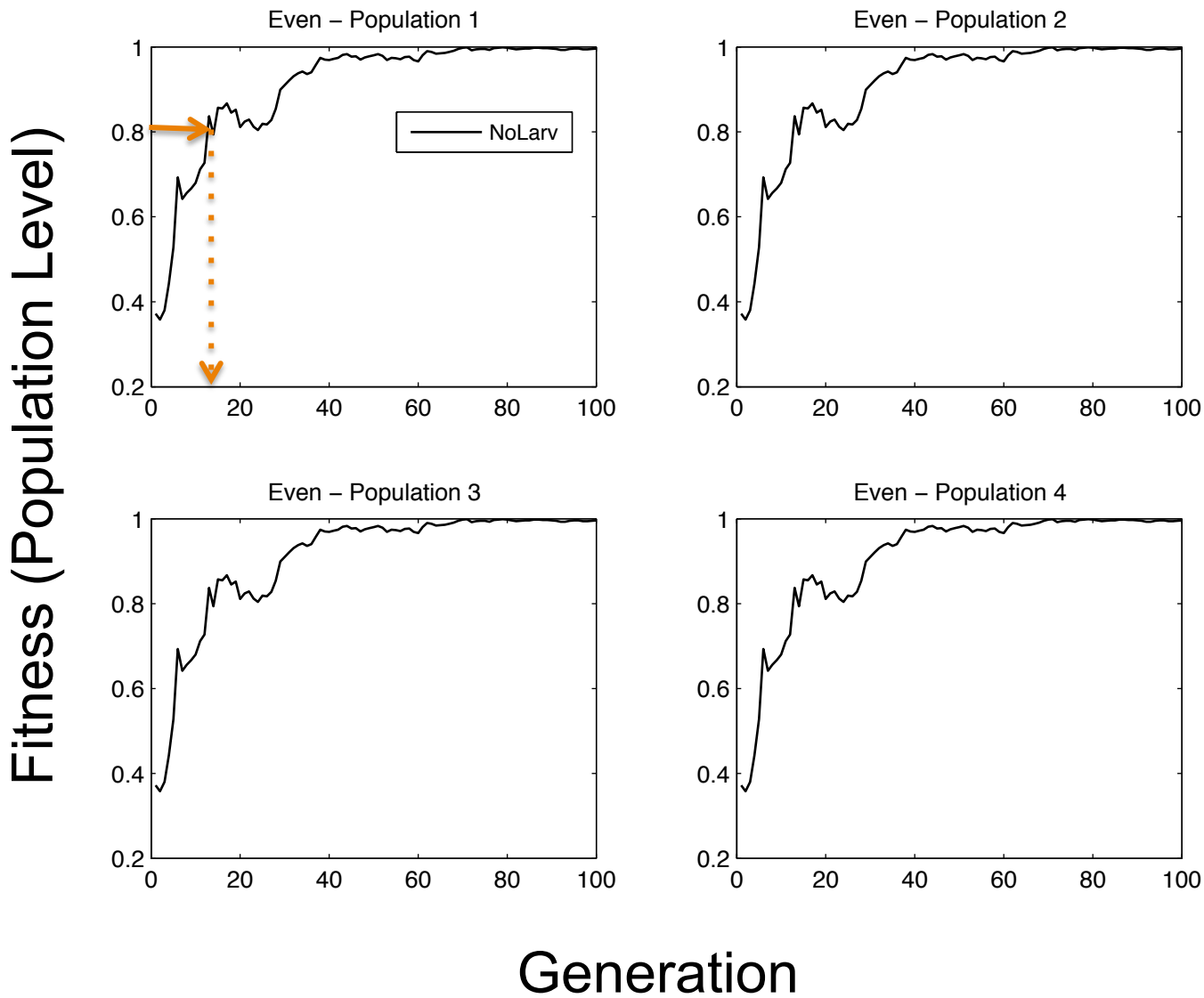

Cumulative Mortality (%)
100
90
80
70
60
50
40
30
20
10
0
0
1
2
3
4
5
Year Of Disease Exposure
Unselected
Simulated Unselected
2nd Generation
Simulated F2
4th Generation
Simulated F4

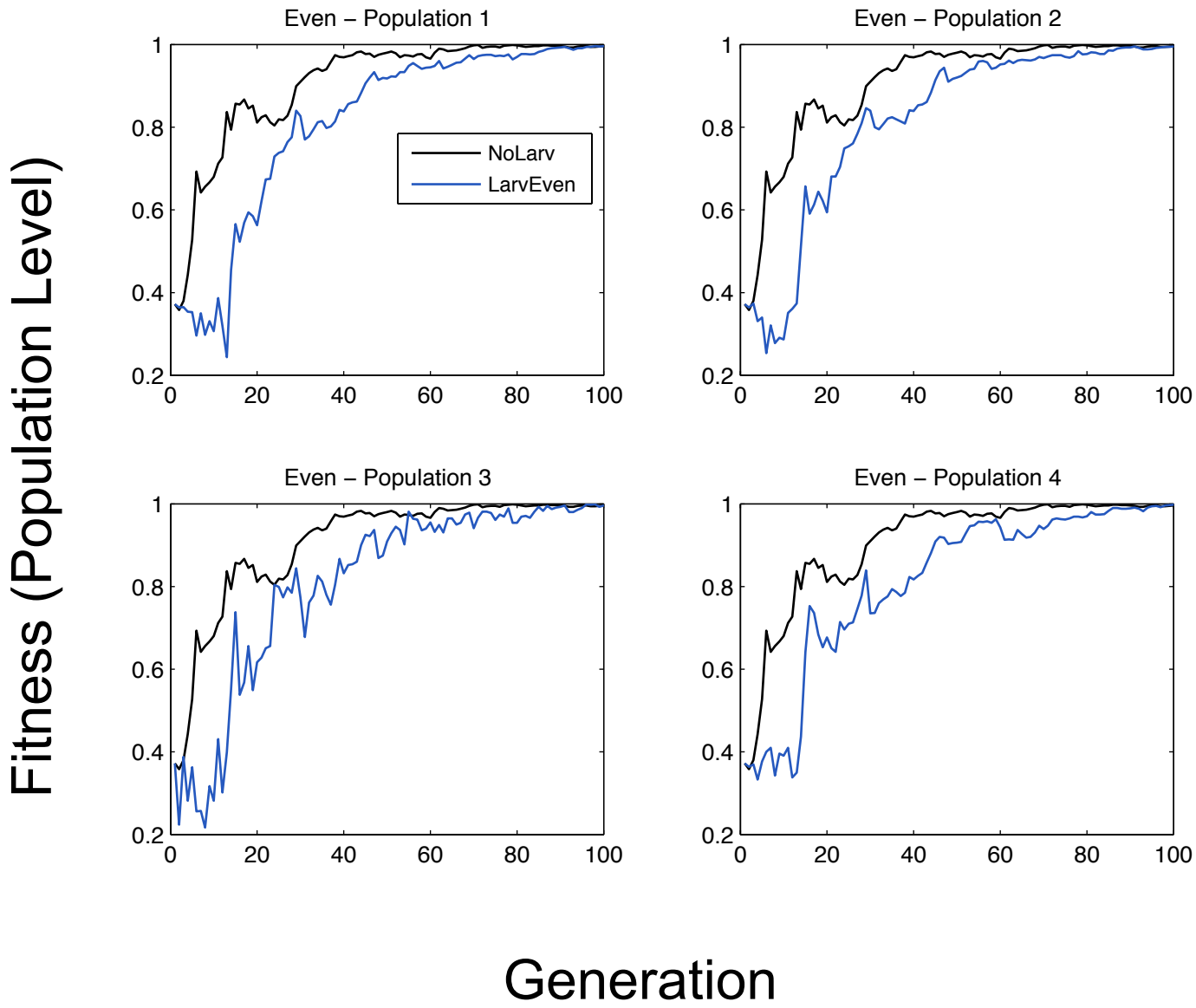

No Larval Dispersal
Even Larval Dispersal
Estuarine Larval Dispersal
Inverted Estuarine Dispersal
Downbay Dispersal
UpBay Dispersal
Larvae From Population
Larvae To Population
Percentage of Larvae Released
1
2
3
4
0
10
20
30
40
50
60
70
80
90
100

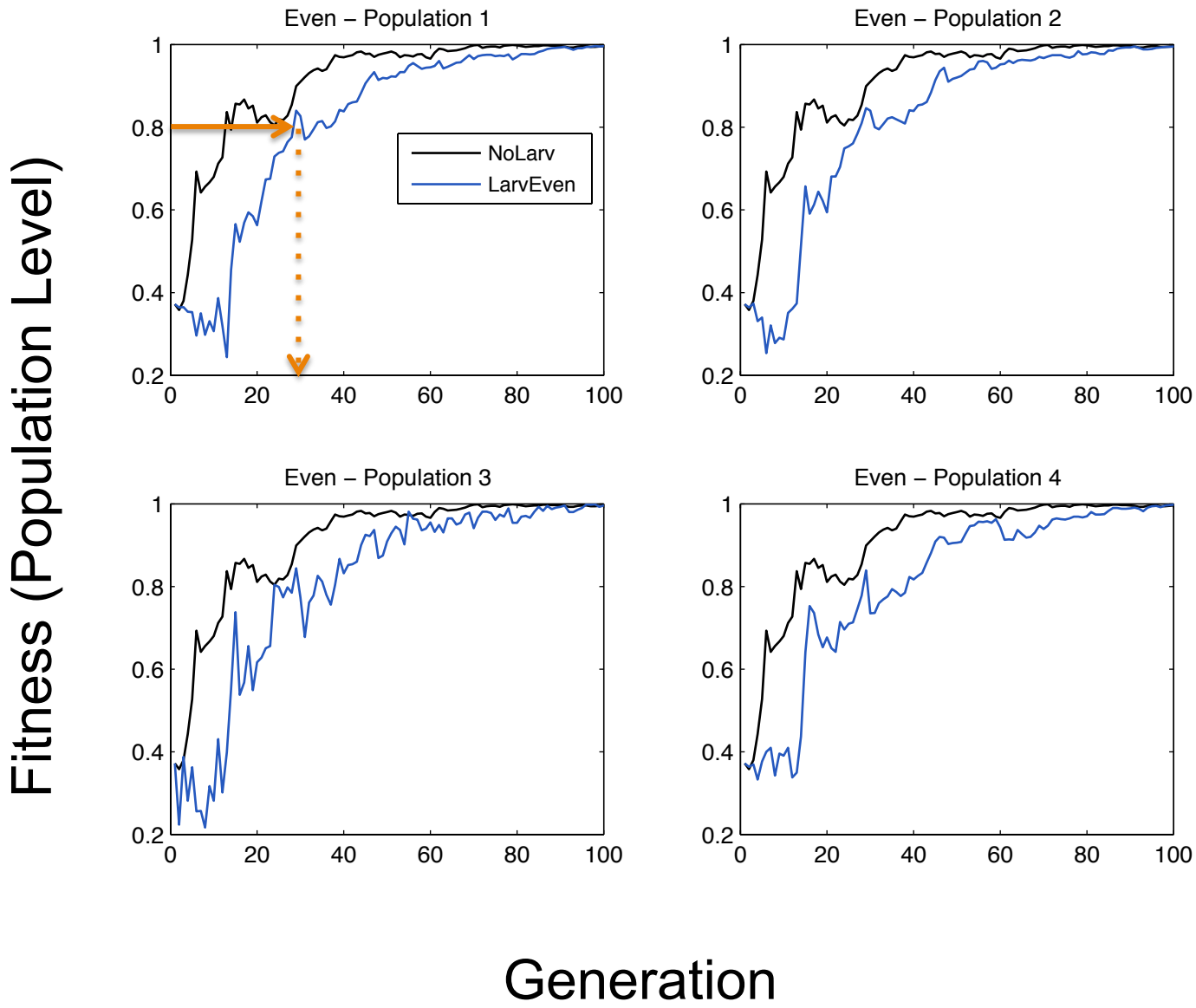
No Gradient in MSX Mortality

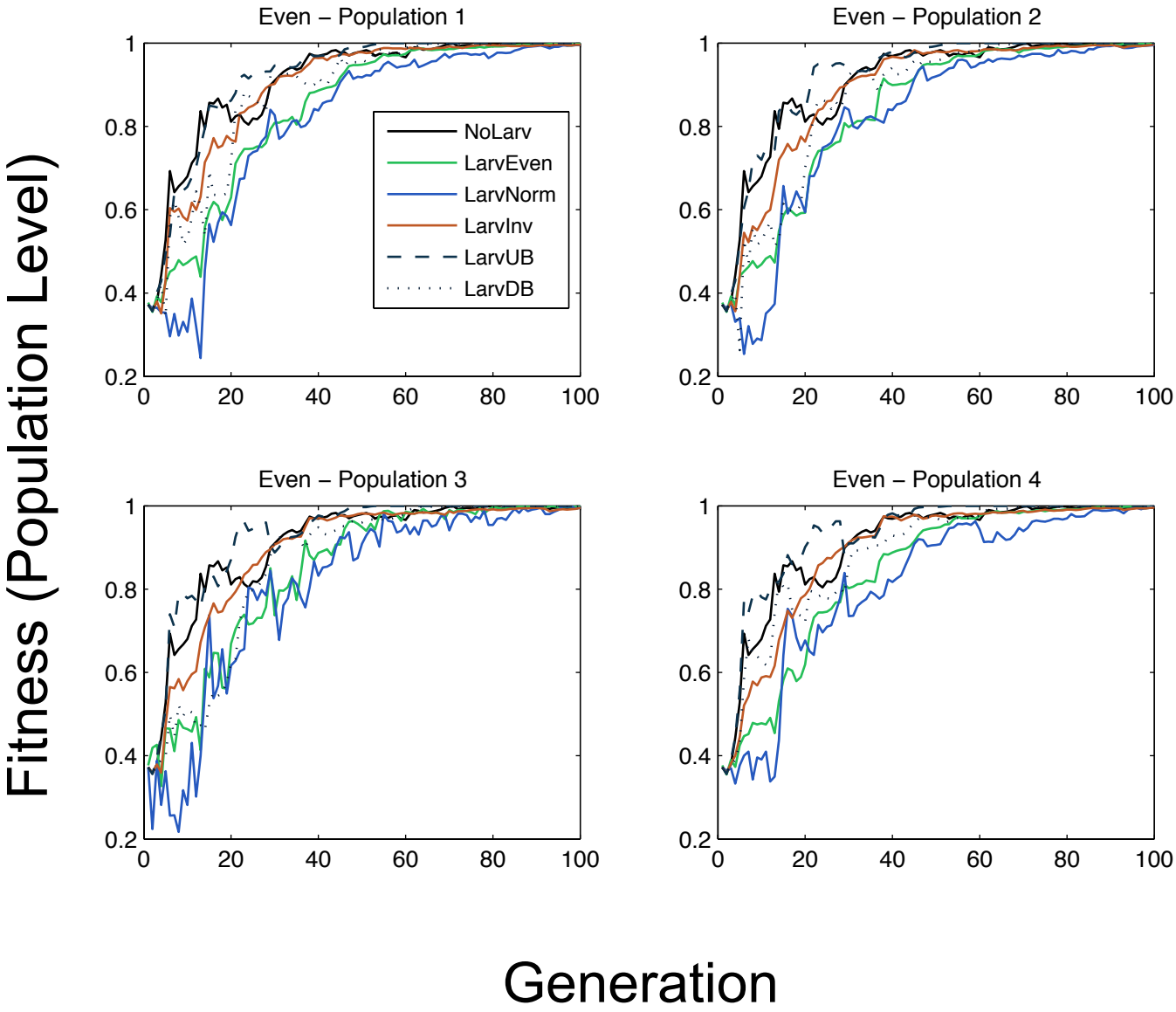


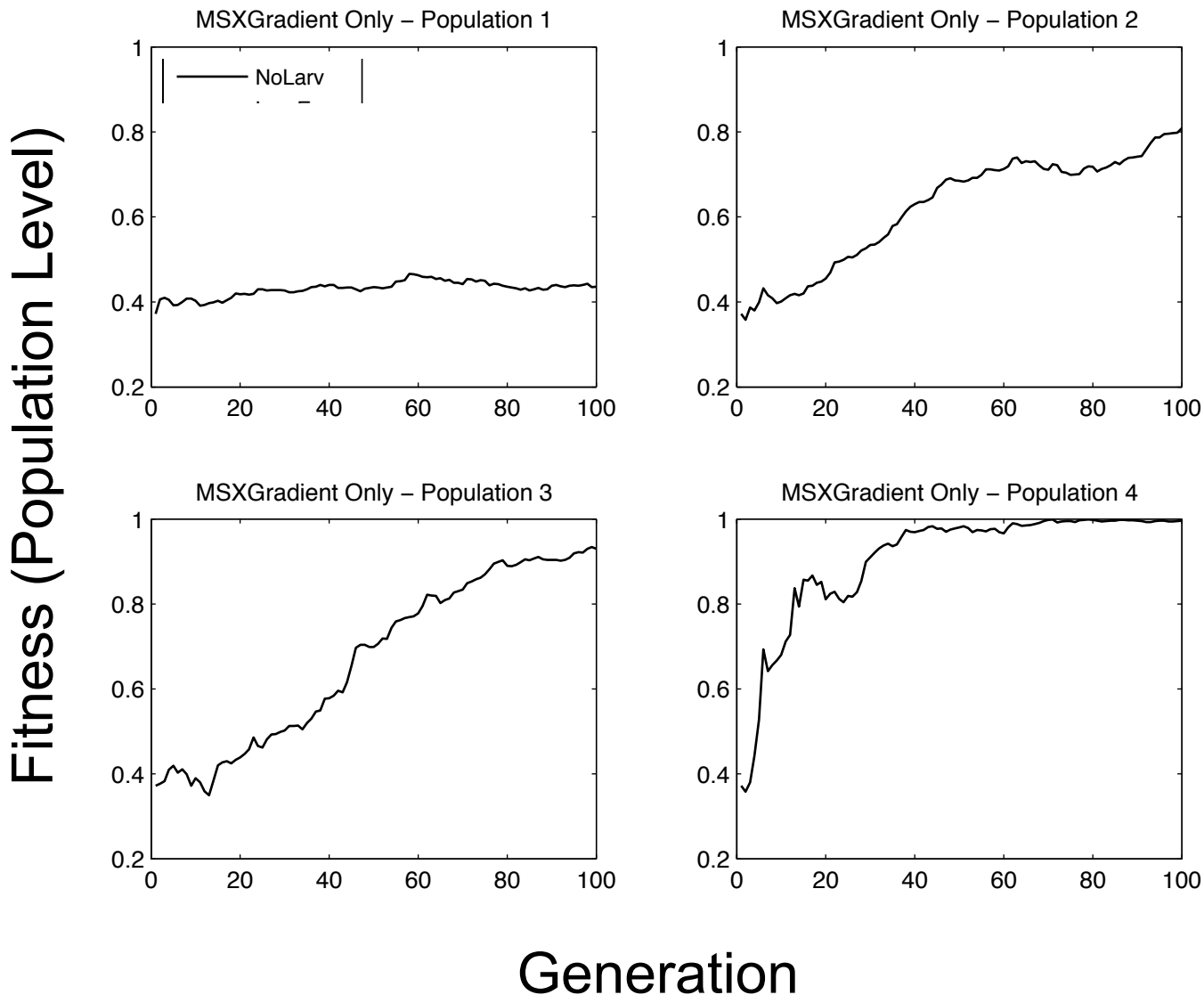

Even – Population 1
Even – Population 2
Even – Population 3
Even – Population 4
NoLarv
Fitness (Population Level)
Generation
1
0.8
0.6
0.4
0.2
0
20
40
60
80
100

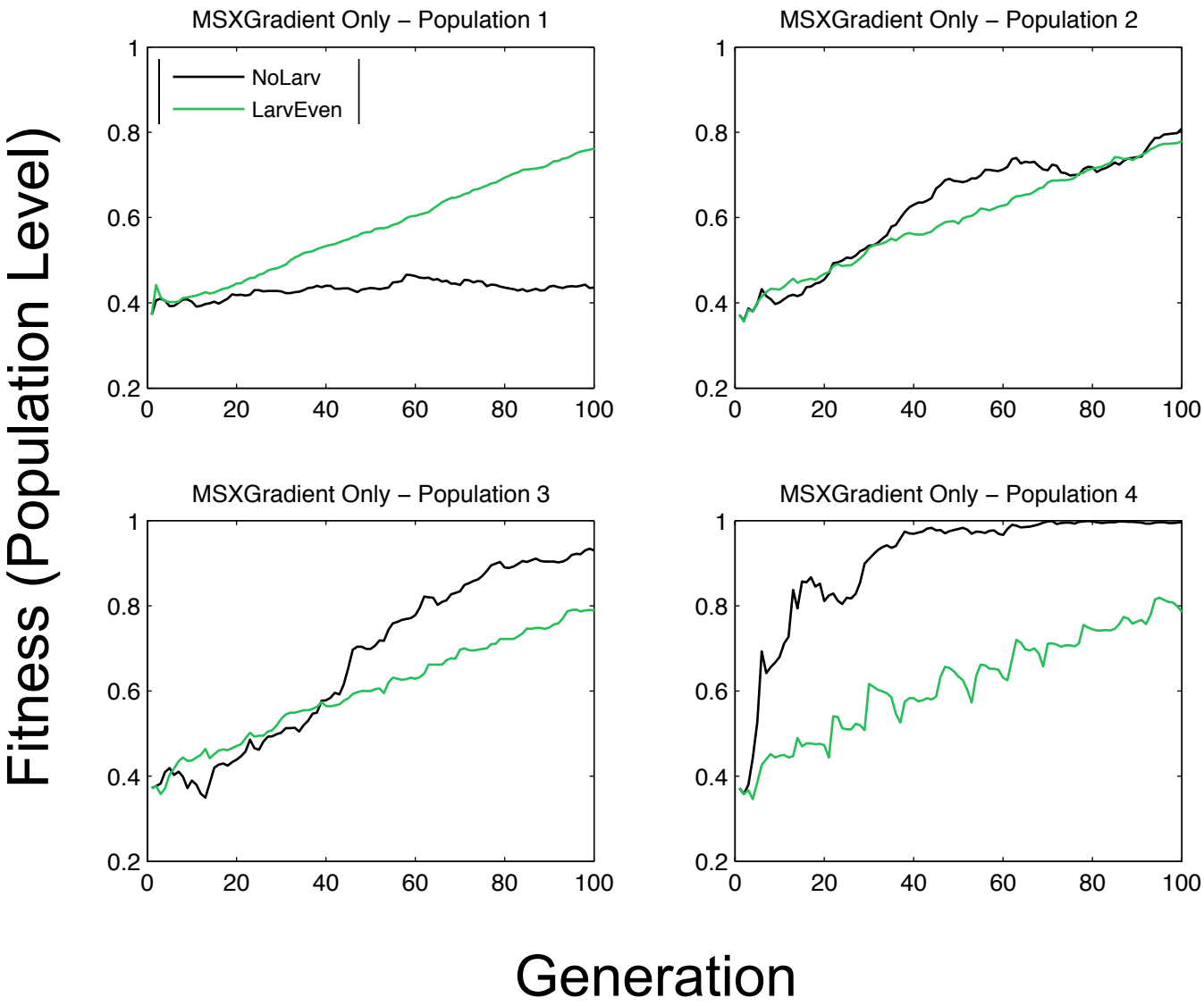

Even – Population 1
Even – Population 2
Even – Population 3
Even – Population 4
NoLarv
Fitness (Population Level)
Generation
0.2
0.4
0.6
0.8
1
0
20
40
60
80
100

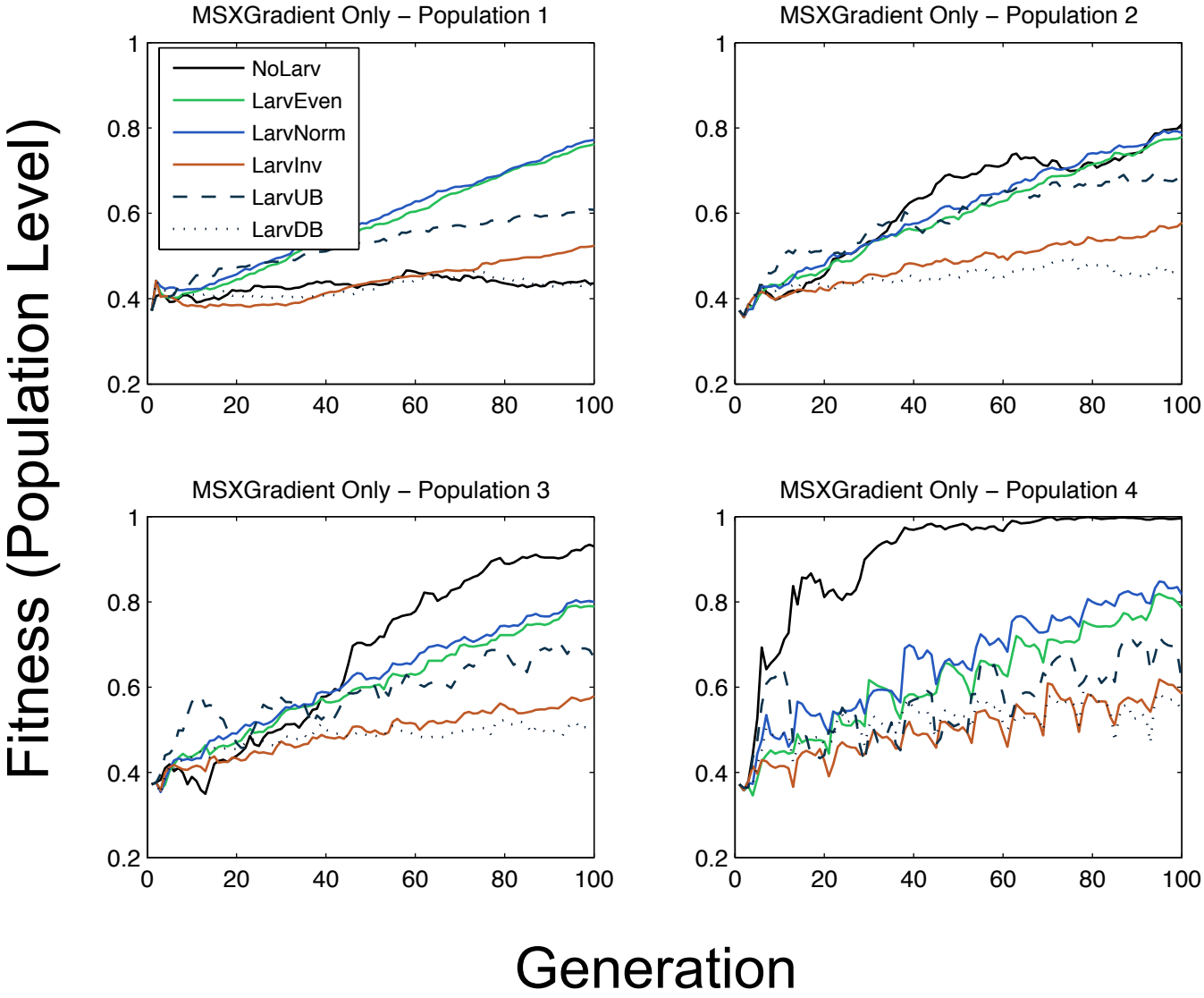

Even – Population 1
Even – Population 2
Even – Population 3
Even – Population 4
NoLarv
LarvEven
Fitness (Population Level)
Generation
0.2
0.4
0.6
0.8
1
0
20
40
60
80
100

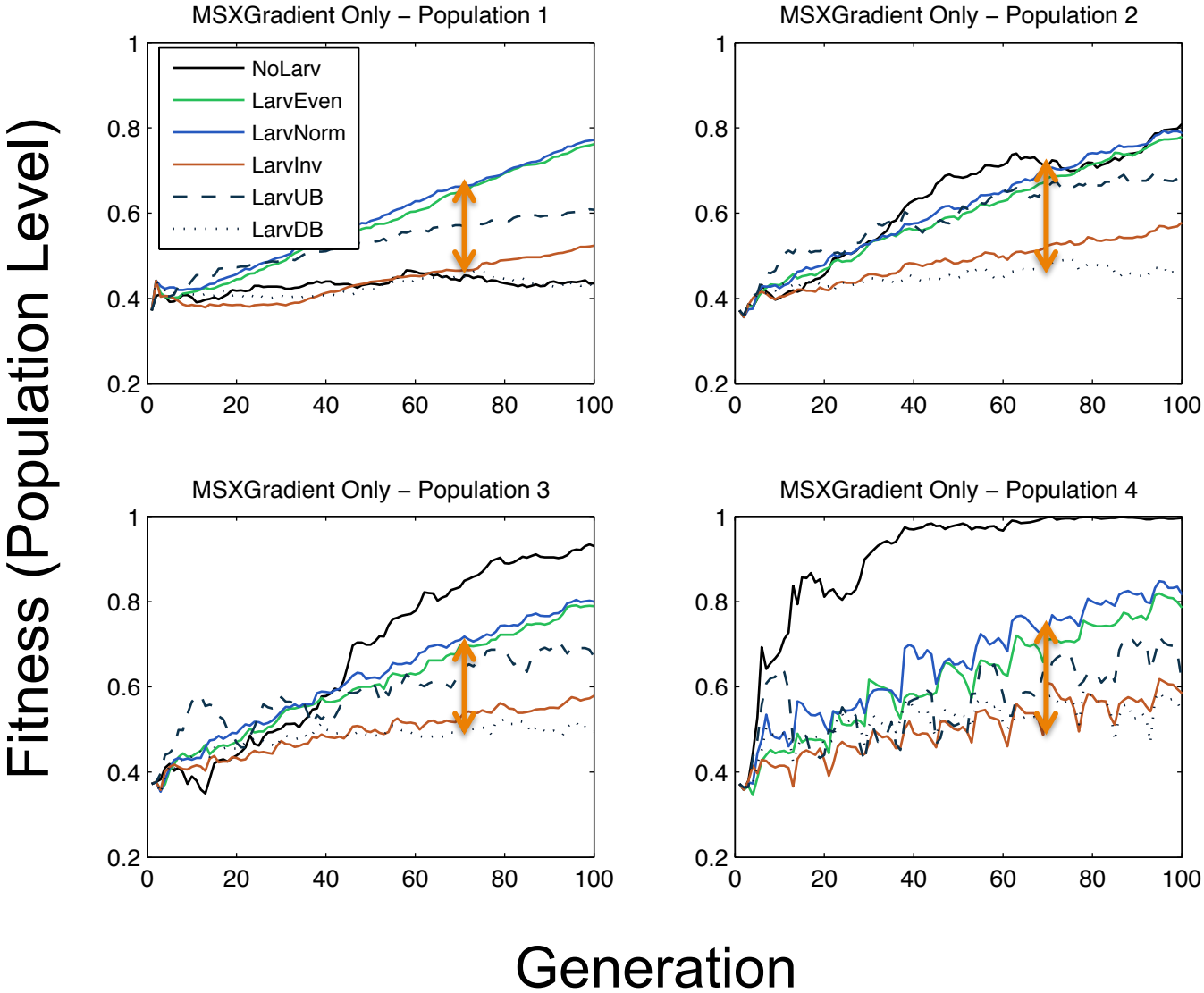

Even – Population 1
Even – Population 2
Even – Population 3
Even – Population 4
NoLarv
LarvEven
Fitness (Population Level)
Generation
0.2
0.4
0.6
0.8
1
0
20
40
60
80
100

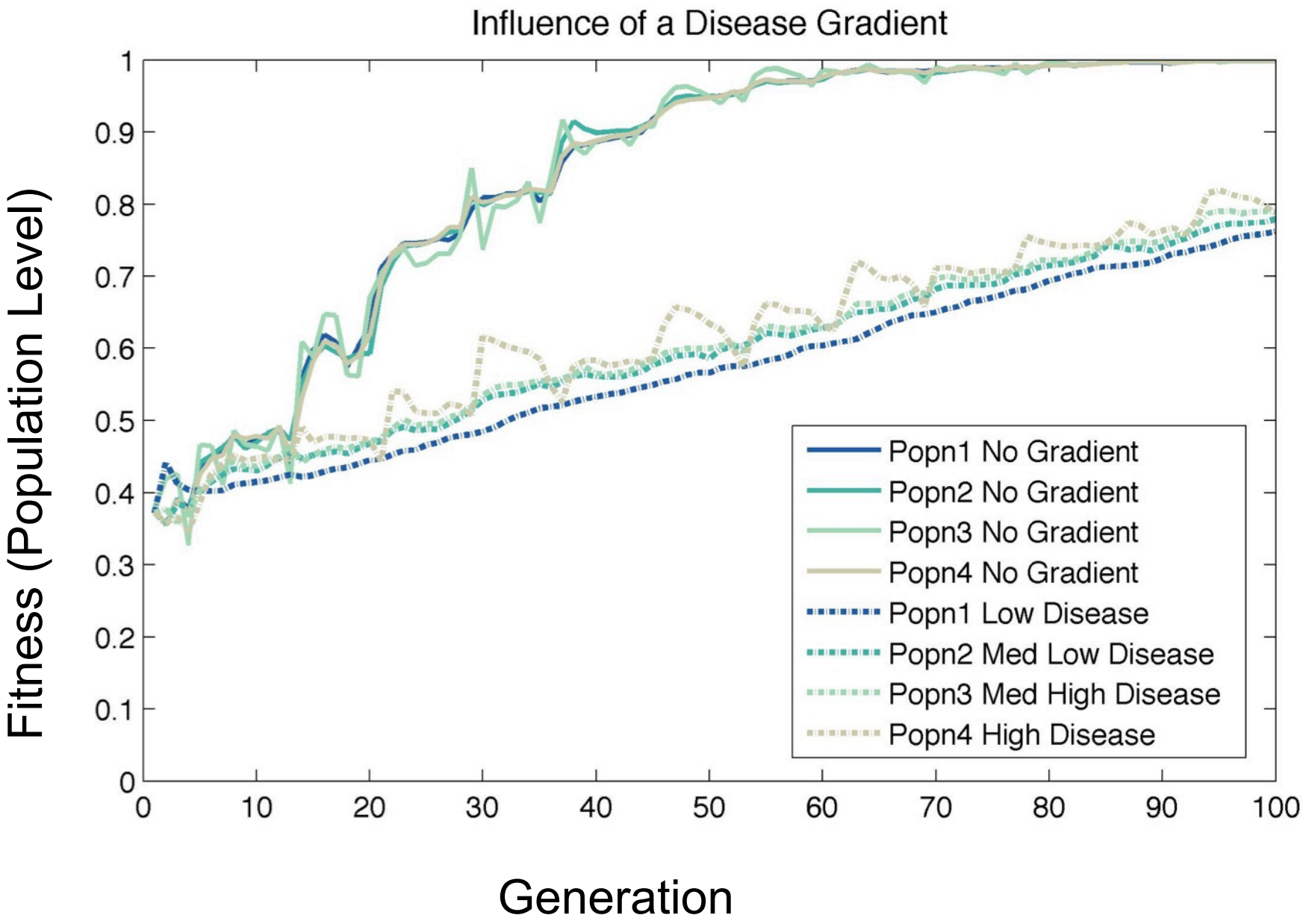

Even – Population 1
Even – Population 2
Even – Population 3
Even – Population 4
NoLarv
LarvEven
LarvNorm
LarvInv
LarvUB
LarvDB
Fitness (Population Level)
Generation
0.2
0.4
0.6
0.8
1
0
20
40
60
80
100

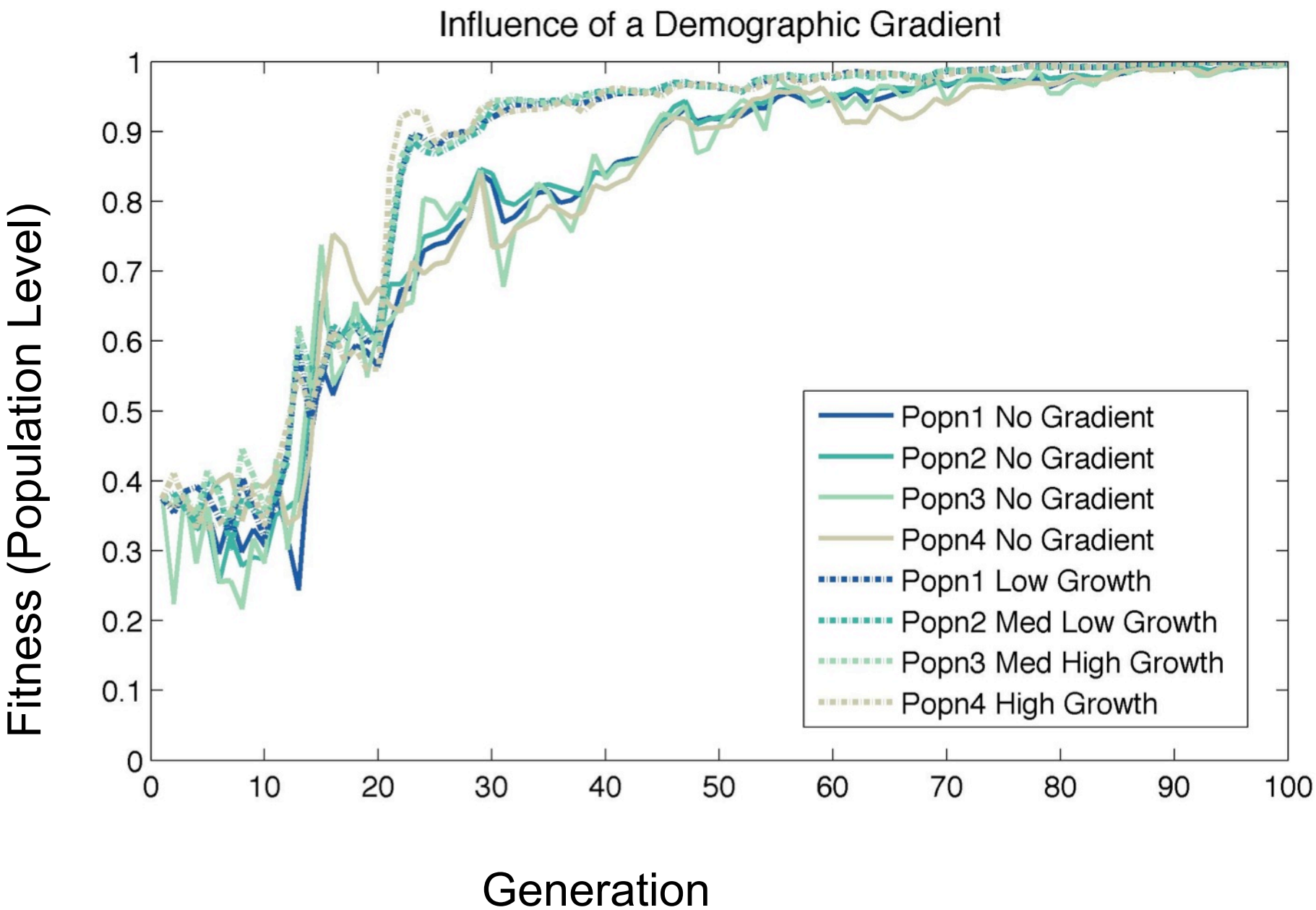

MSXGradient Only – Population 1
MSXGradient Only – Population 2
MSXGradient Only – Population 3
MSXGradient Only – Population 4
NoLarv
Fitness (Population Level)
Generation
0.2
0.4
0.6
0.8
1
0
20
40
60
80
100

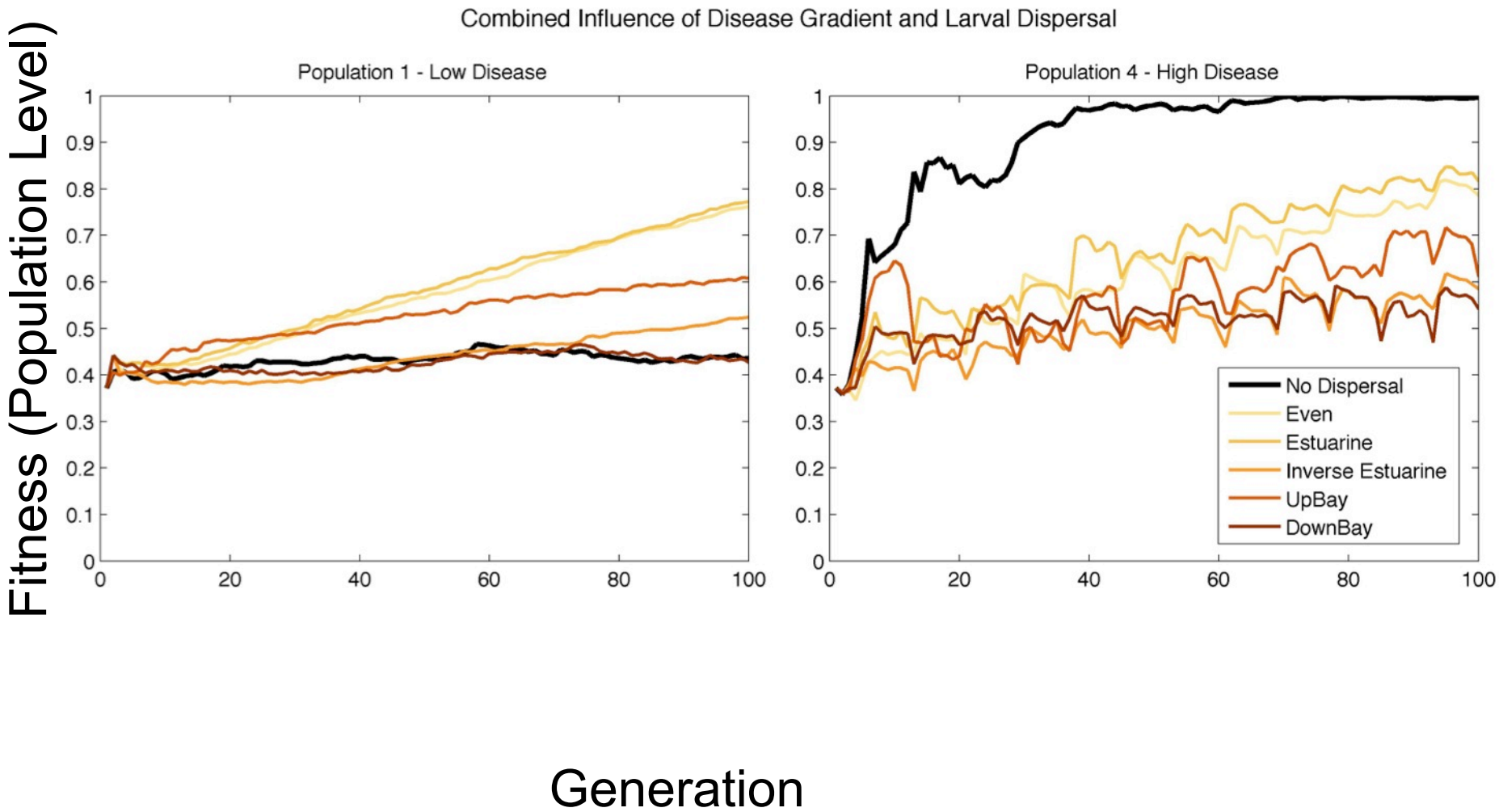

MSXGradient Only – Population 1
MSXGradient Only – Population 2
MSXGradient Only – Population 3
MSXGradient Only – Population 4
NoLarv
LarvEven
Fitness (Population Level)
Generation
0.2
0.4
0.6
0.8
1
0
20
40
60
80
100

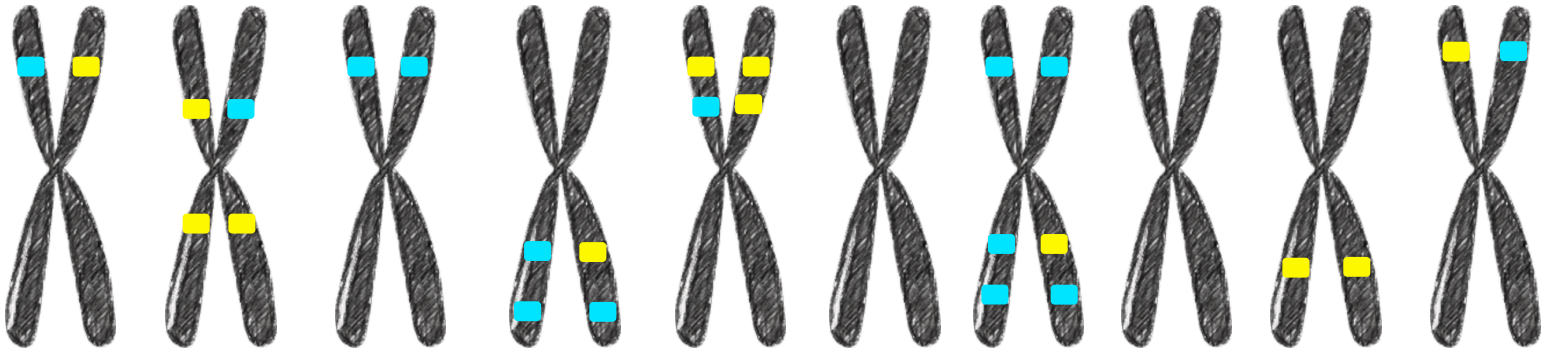

MSXGradient Only – Population 1
MSXGradient Only – Population 2
MSXGradient Only – Population 3
MSXGradient Only – Population 4
NoLarv
LarvEven
LarvNorm
LarvInv
LarvUB
LarvDB
Fitness (Population Level)
Generation
0.2
0.4
0.6
0.8
1
0
20
40
60
80
100


MSXGradient Only – Population 1
MSXGradient Only – Population 2
MSXGradient Only – Population 3
MSXGradient Only – Population 4
NoLarv
LarvEven
LarvNorm
LarvInv
LarvUB
LarvDB
Fitness (Population Level)
Generation
0.2
0.4
0.6
0.8
1
0
20
40
60
80
100


Influence of a Disease Gradient
Fitness (Population Level)
Generation
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
10
20
30
40
50
60
70
80
90
100
Popn1 No Gradient
Popn2 No Gradient
Popn3 No Gradient
Popn4 No Gradient
Popn1 Low Disease
Popn2 Med Low Disease
Popn3 Med High Disease
Popn4 High Disease


Influence of a Demographic Gradient
Fitness (Population Level)
Generation
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
10
20
30
40
50
60
70
80
90
100
Popn1 No Gradient
Popn2 No Gradient
Popn3 No Gradient
Popn4 No Gradient
Popn1 Low Growth
Popn2 Med Low Growth
Popn3 Med High Growth
Popn4 High Growth


Combined Influence of Disease Gradient and Larval Dispersal
Population 1 - Low Disease
Population 4 - High Disease
Fitness (Population Level)
Generation
No Dispersal
Even
Estuarine
Inverse Estuarine
UpBay
DownBay

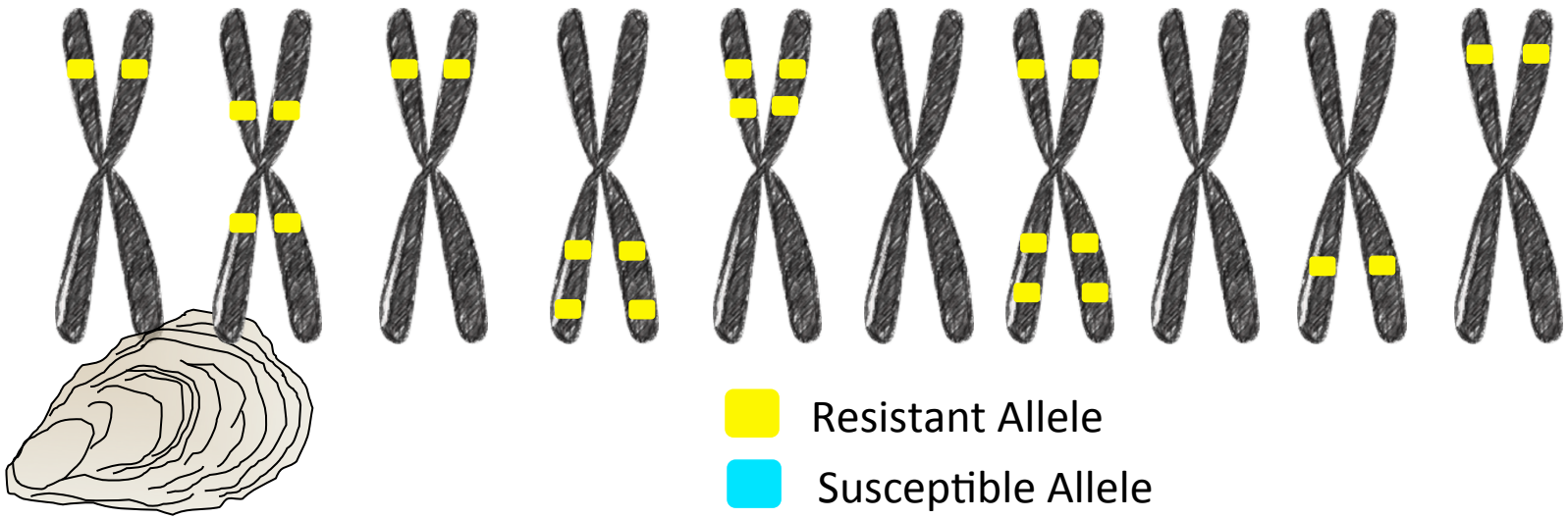


Larval dispersal

- tends to slow evolution
- Adds uncertainty

Spatial Variation in Disease

- Slows fast evolvers, speeds slow evolvers
- Inhibits metapopulation resistance



Metapopulation approaches are useful for disease modeling:

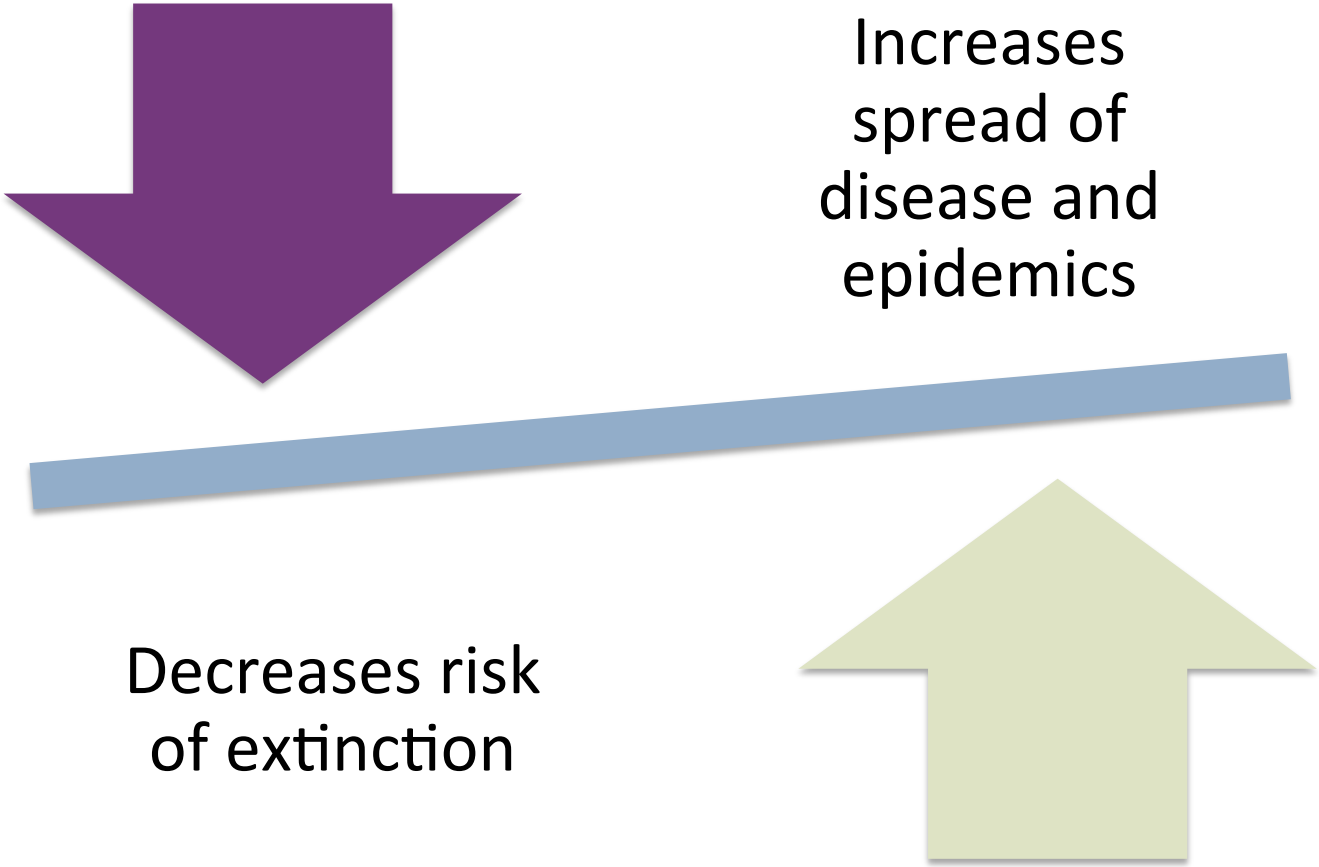
- Allows inclusion of transmission dynamics relative to animal movement
- Allows mitigation and mangement strategies (quarantine etc) to be explored
- Better represents overall metapopulation responses in evolution of resistance and possible extinctions

However, metapopulation disease models have been developed for terrestrial systems.

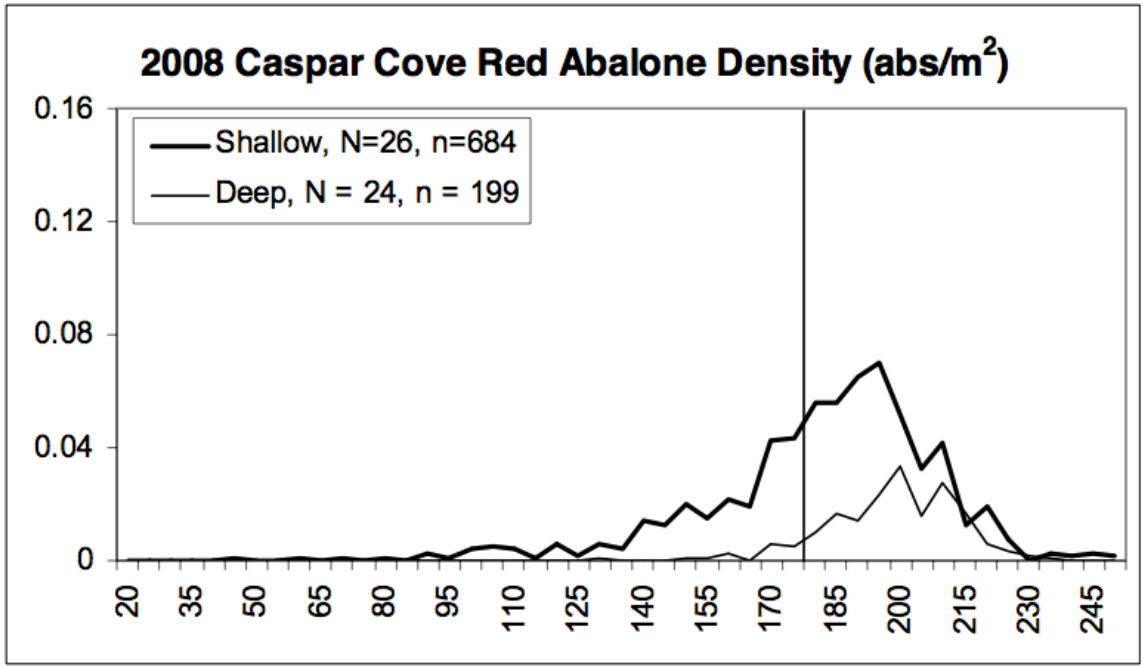
Have limited applicability in marine ecosystems because:

- hosts are often sessile (many invertebrates)
- disease agents may be dispersed more widely and rapidly in water than on land
- pathogens may survive well outside of the host in marine conditions
- terrestrial systems tend to have habitat that is highly fragmented

Increasing Dispersal



Data Matters



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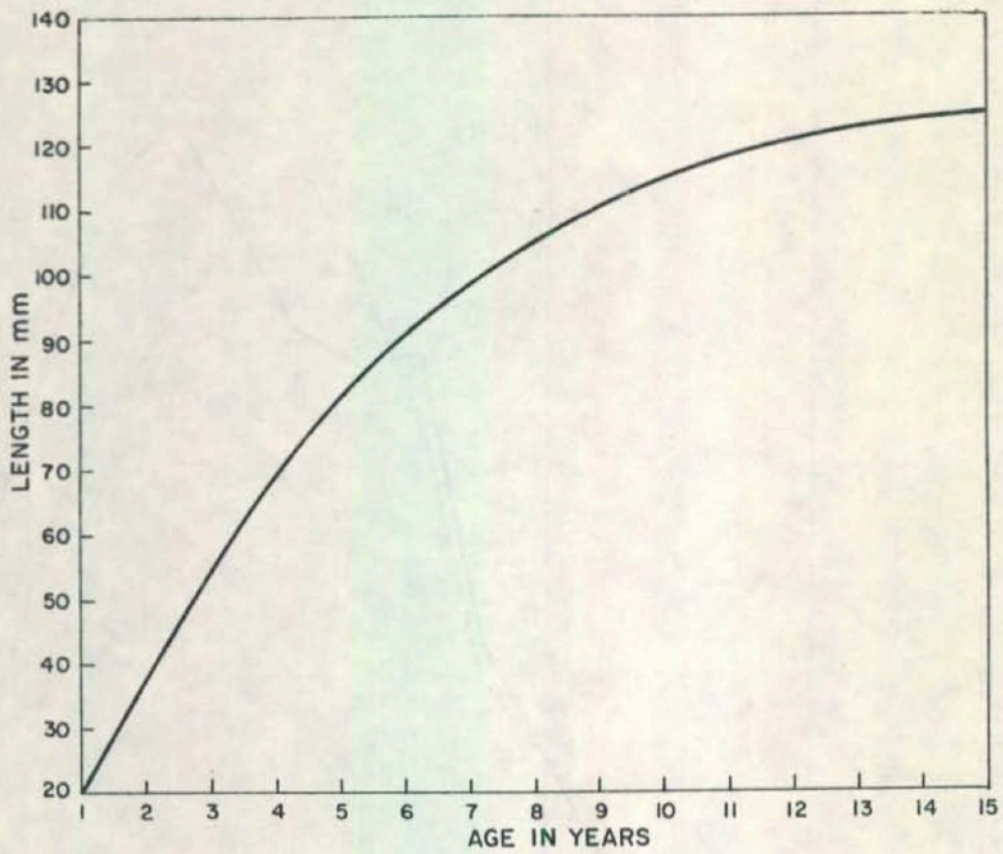
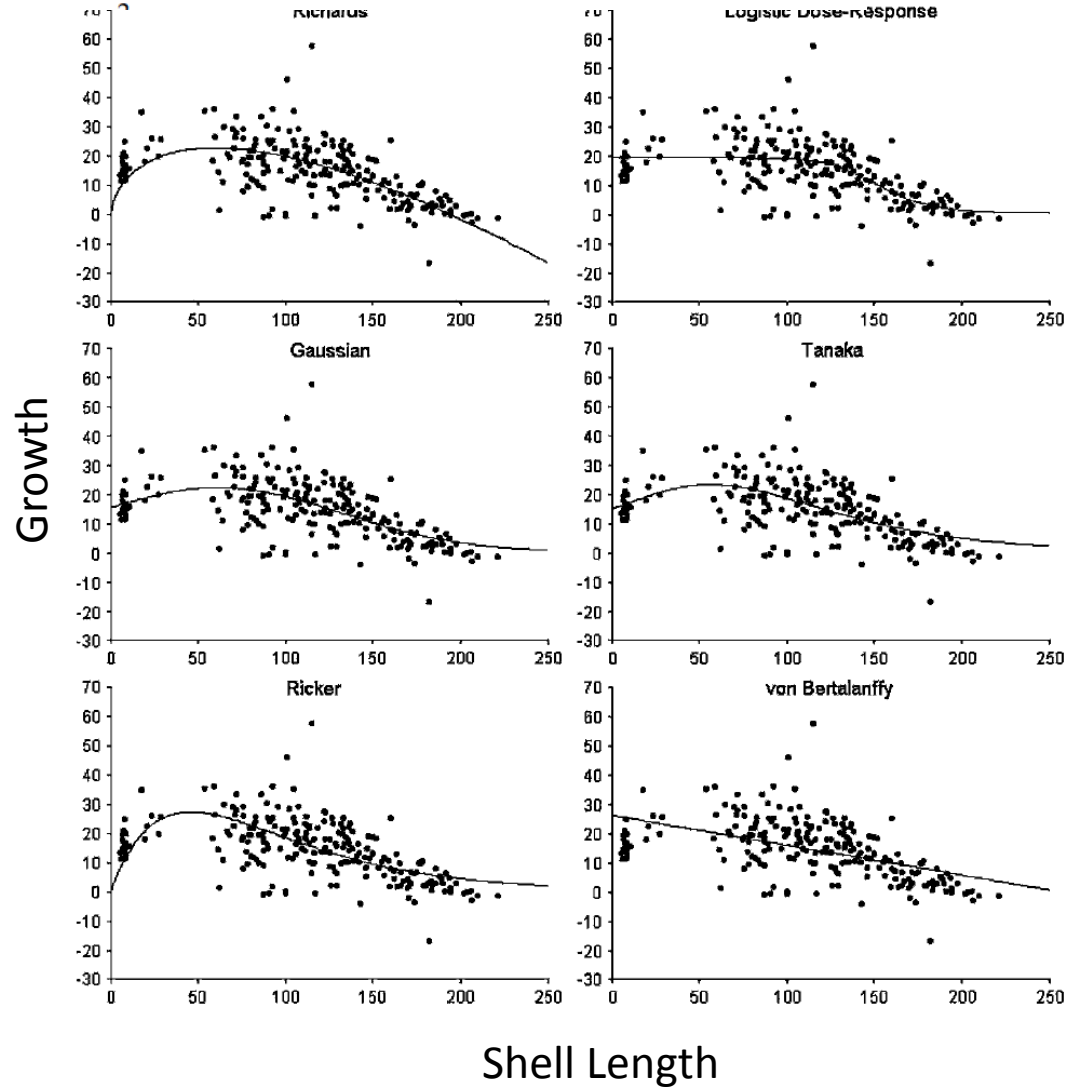


Fig. 4. Suggested growth curve for H. kamtschatkana.

http://www.dfo-mpo.gc.ca/Library/26748.pdf

Journal of Shellfish Research, Vol. 26, No. 3, 719–727, 2007.

MODELING GROWTH AND MORTALITY OF RED ABALONE (*HALIOTIS RUFESCENS*) IN NORTHERN CALIFORNIA

LAURA ROGERS-BENNETT,[1,2]* DONALD W. ROGERS[3] AND STEVEN A. SCHULTZ[4]