Eco-evolutionary dynamics, Part B

Sylvie Oddou-Muratorio

Contents

Part 1 : Concepts related to eco-evolutionary dynamics

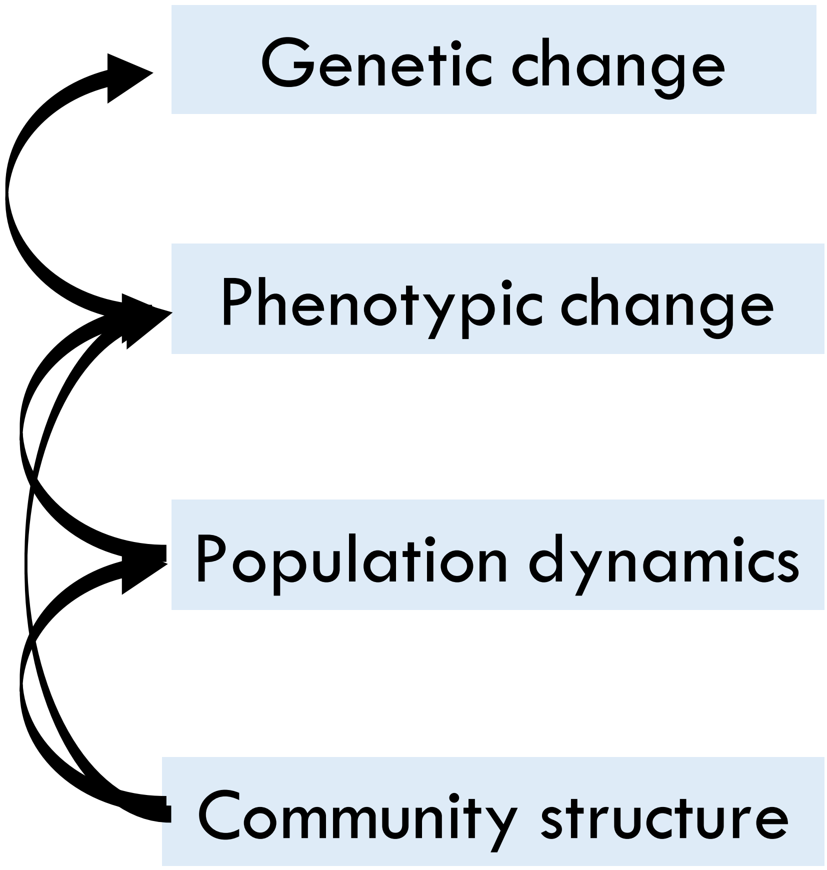
From Hendry, A. P. (2017). Eco-evolutionary Dynamics. Princeton University Press.

+ Course of David Claessen (Institut de Biologie de l'ENS)

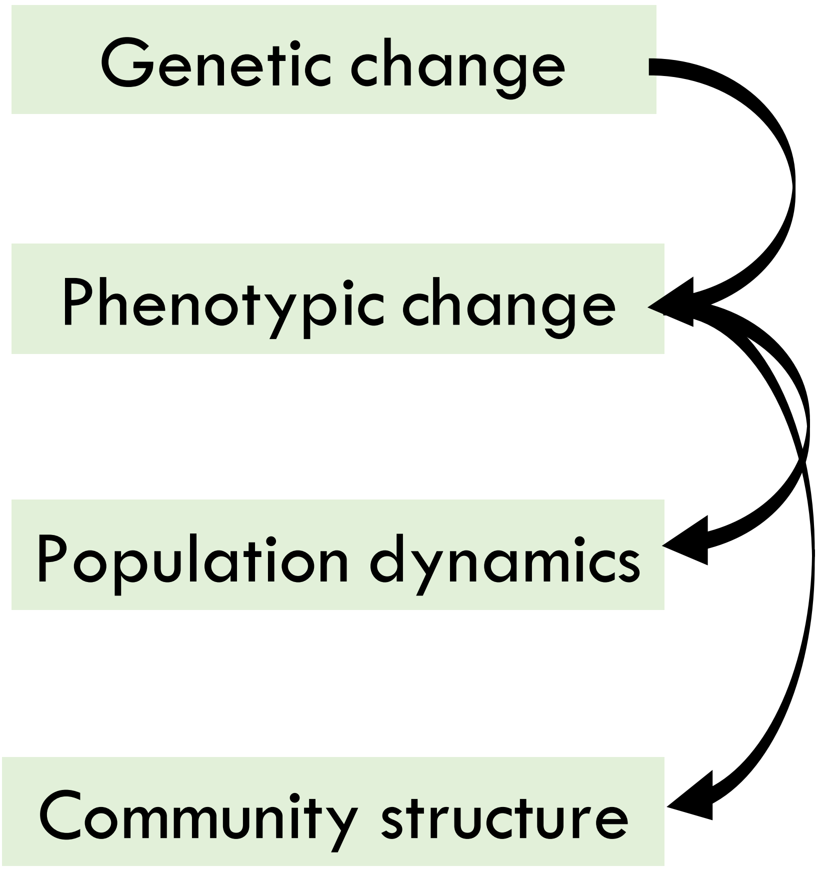
- Feedbacks between ecological and evolutionary processes
- Selection (types of selection, how to measure selection, selection in nature)
- Adaptation (response to selection, how to measure evolutionary change, adaptive landscapes)
- Population dynamics (relation between maladaptation and population decline)
- Genetics, genomics and plasticity

Eco-evolutionary feedbacks

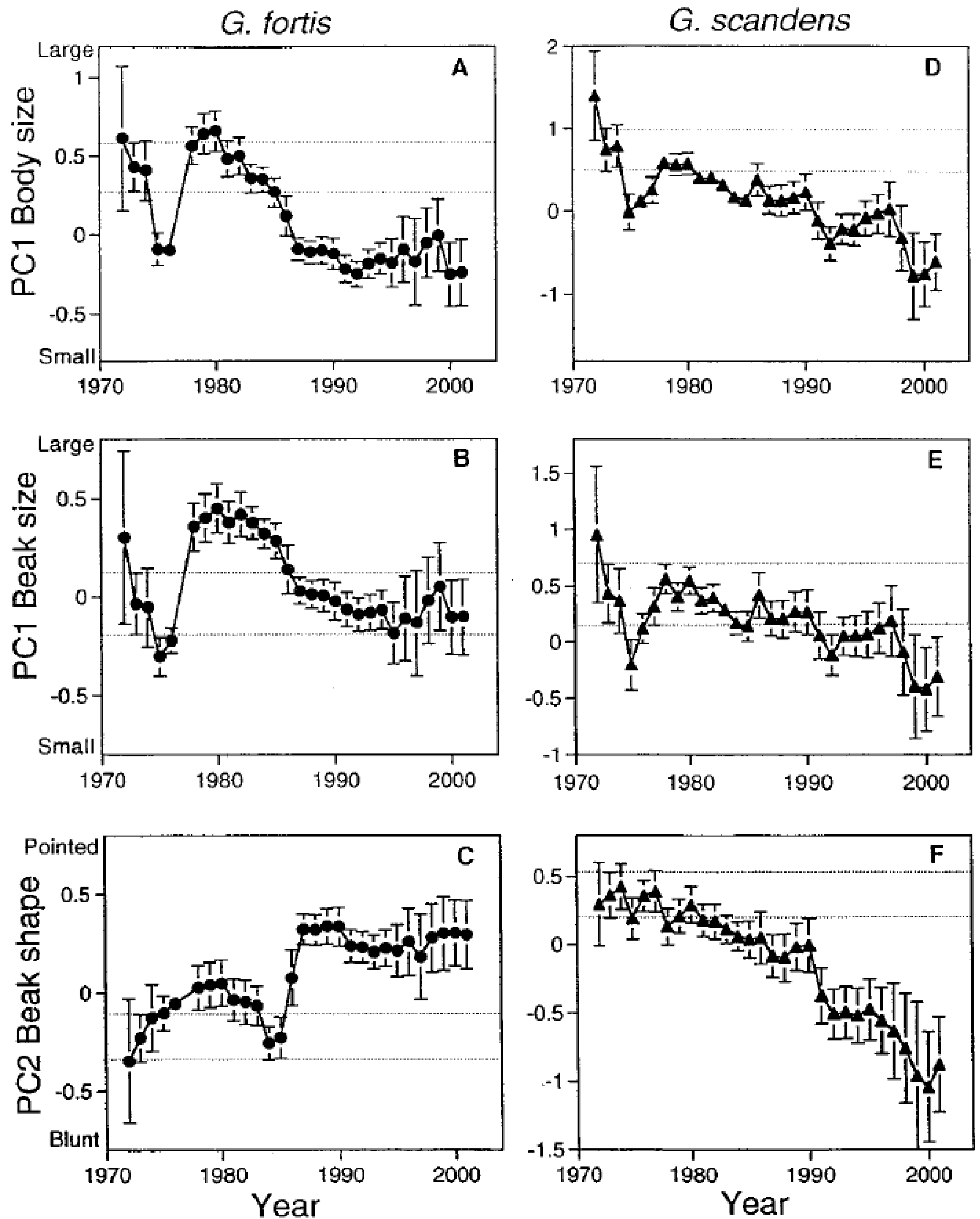
eco-to-evo



evo-to-eco



Example: evolution of adaptive traits in finches



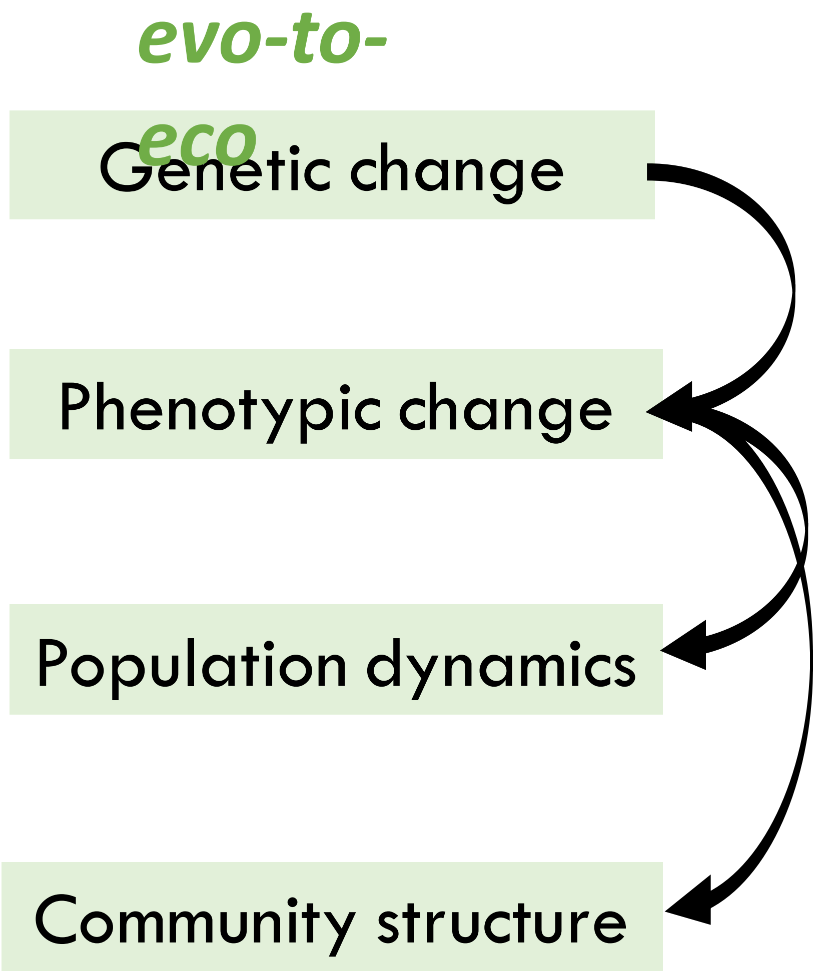
Geospiza fortis (medium ground finch) *Geospiza scandens (cactus finch)*

- Study in medium ground finches during two drought periods on Galapagos

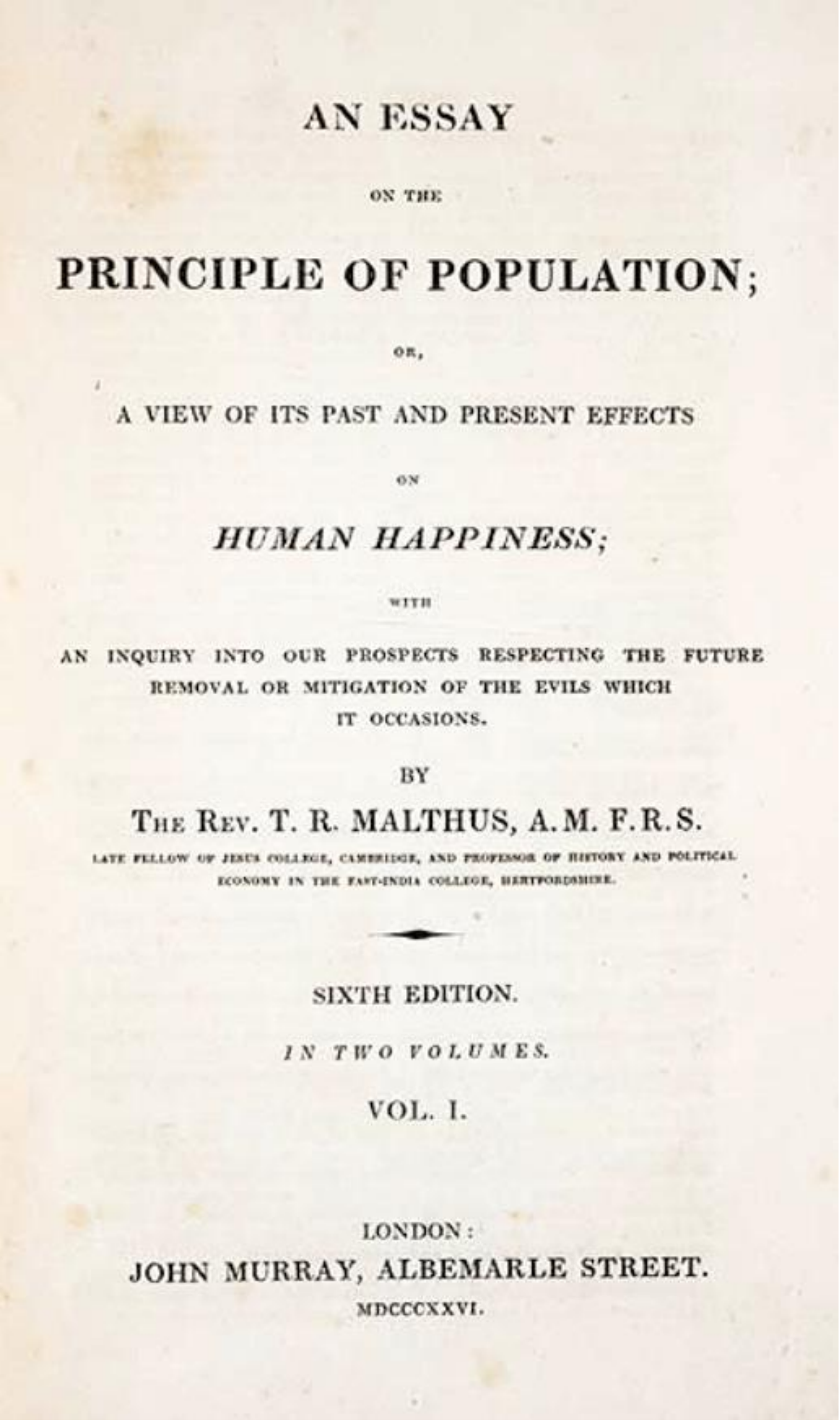
- Illustration of how an ecological change (seed size, drought) drives evolutionary change .

(Grant & Grant, 1995; Grant & Grant, 2002)

Population dynamics



- When might evolution influence population dynamics ? → the struggle for existence
- How to detect evolutionary effects on population dynamics ?
- “Eco-evolutionary population dynamics in nature”


AN ESSAY

ON THE

PRINCIPLE OF POPULATION;

OR,

A VIEW OF ITS PAST AND PRESENT EFFECTS

ON

HUMAN HAPPINESS;

WITH

AN INQUIRY INTO OUR PROSPECTS RESPECTING THE FUTURE REMOVAL OR MITIGATION OF THE EVILS WHICH IT OCCASIONS.

BY

THE REV. T. R. MALTHUS, A.M. F.R.S.

LATE FELLOW OF JESUS COLLEGE, CAMBRIDGE, AND PROFESSOR OF HISTORY AND POLITICAL ECONOMY IN THE EAST-INDIA COLLEGE, HERTFORDSHIRE.

SIXTH EDITION.

IN TWO VOLUMES.

VOL. I.

LONDON:

JOHN MURRAY, ALBEMARLE STREET.

MDCCCXXVI.

The struggle for existence

Thomas Malthus
1766-1834

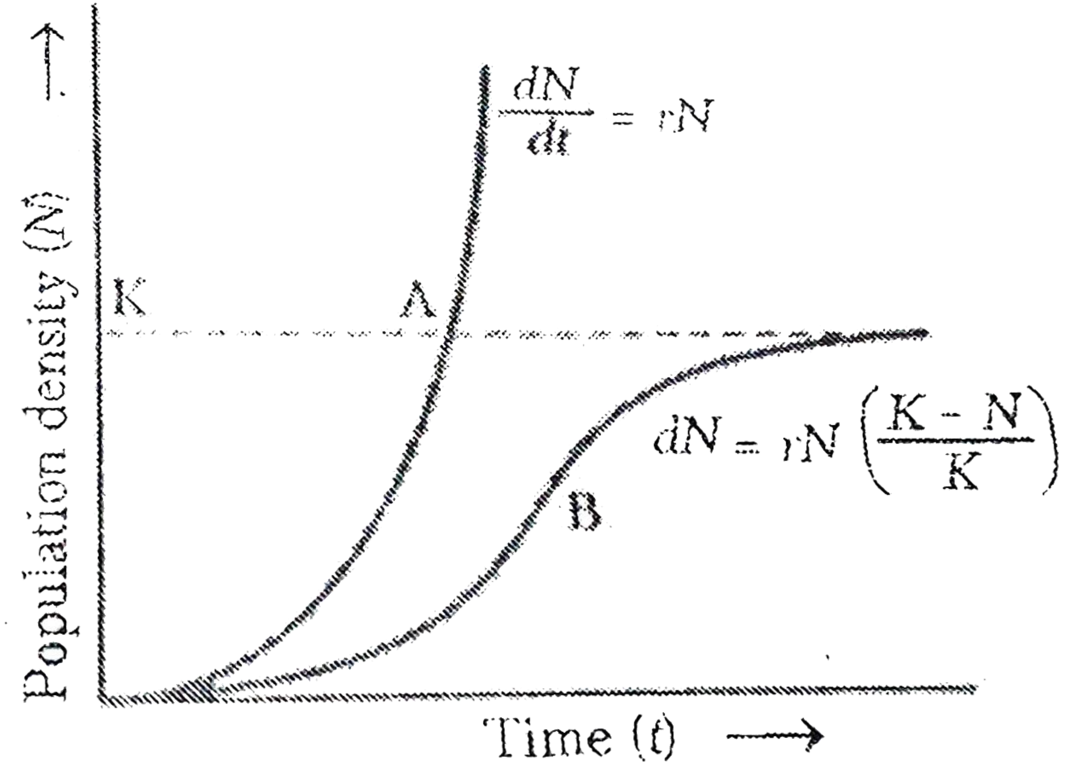
- The increase of population is necessarily limited by the means of subsistence
- The population does invariably increase when the means of subsistence increase
- The superior power of population is repressed, and the actual population kept equal to the means of subsistence, by misery and vice

Dia from David Claessen

The struggle for existence

Pierre-François Verhulst 1804-1849

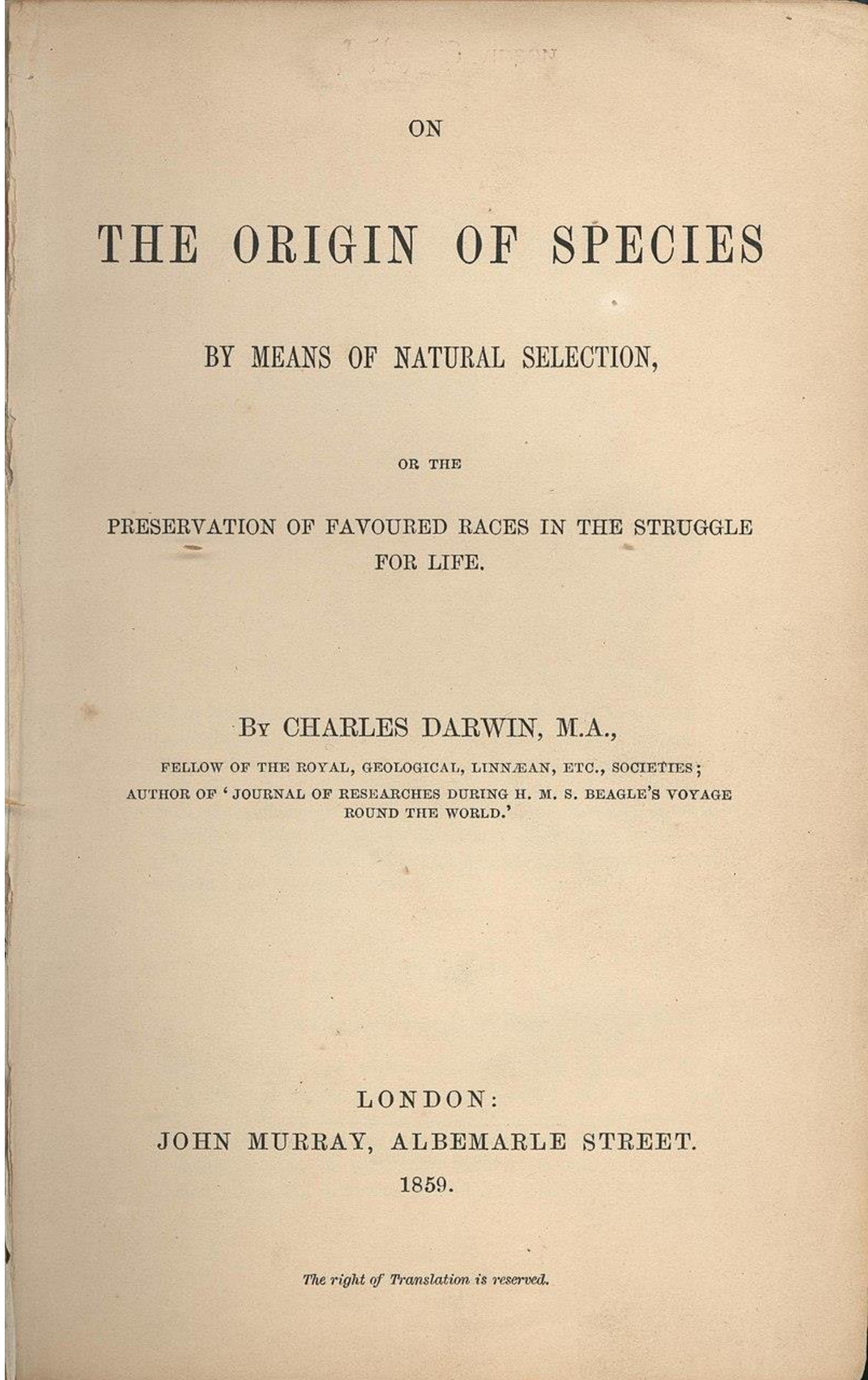
A non-exponential model to describe the evolution of human and animal populations



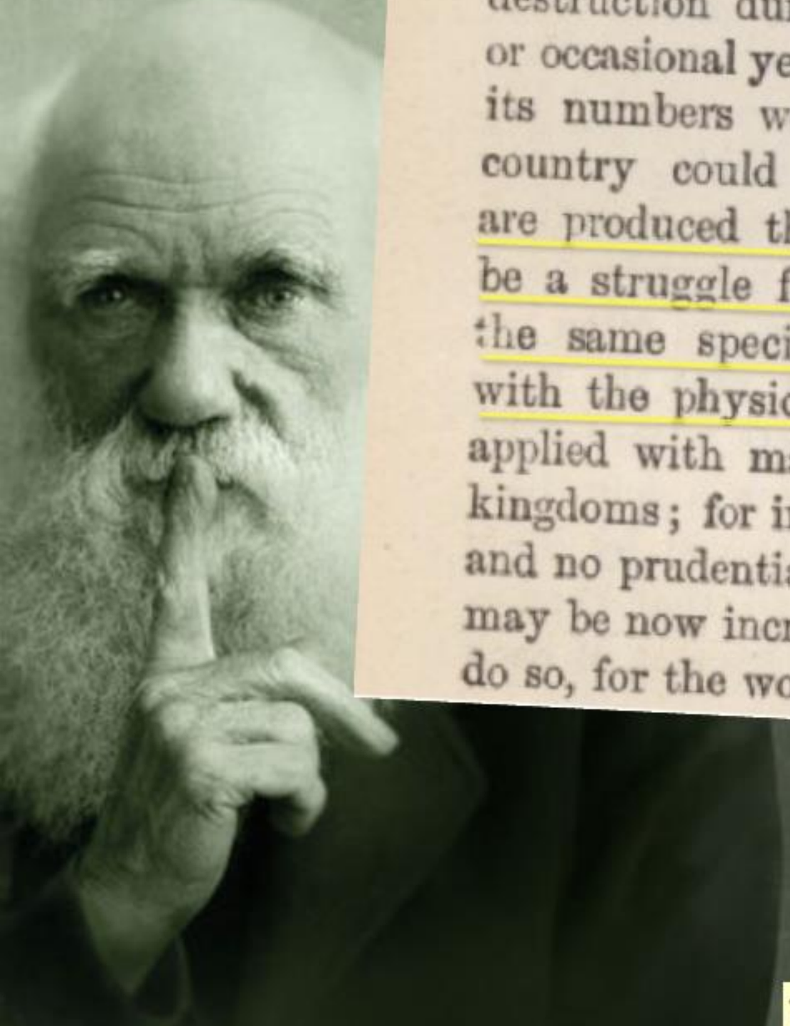
The struggle for existence

Charles Darwin
1809-1882

struggle for existence
+
heritable variation
↓
driving force of evolutionary change



Dia from David Claessen



Geometrical Ratio of Increase.

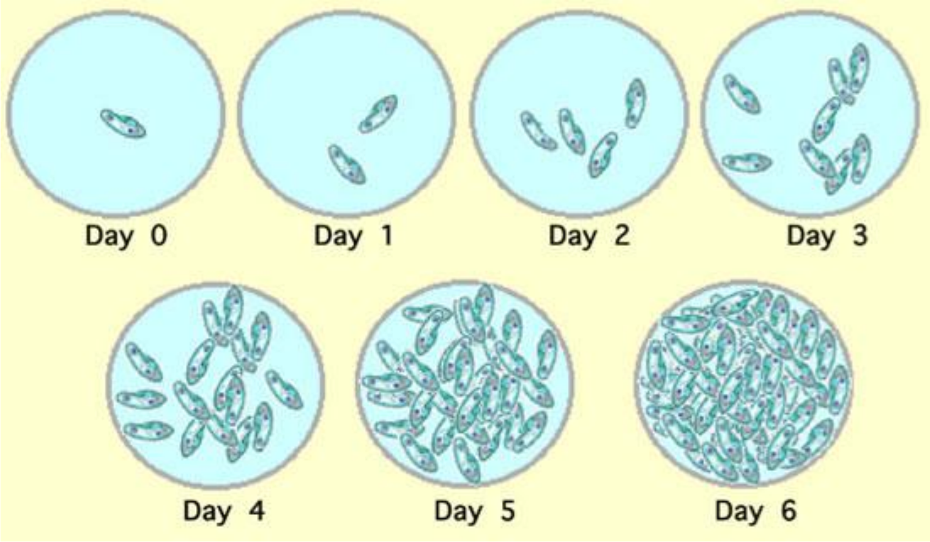
A struggle for existence inevitably follows from the high rate at which all organic beings tend to increase. Every being, which during its natural lifetime produces several eggs or seeds, must suffer destruction during some period of its life, and during some season or occasional year, otherwise, on the principle of geometrical increase, its numbers would quickly become so inordinately great that no country could support the product. Hence, as more individuals are produced than can possibly survive, there must in every case be a struggle for existence, either one individual with another of the same species, or with the individuals of distinct species, or with the physical conditions of life. It is the doctrine of Malthus applied with manifold force to the whole animal and vegetable kingdoms; for in this case there can be no artificial increase of food, and no prudential restraint from marriage. Although some species may be now increasing, more or less rapidly, in numbers, all cannot do so, for the world would not hold them.

Dia from David Claessen

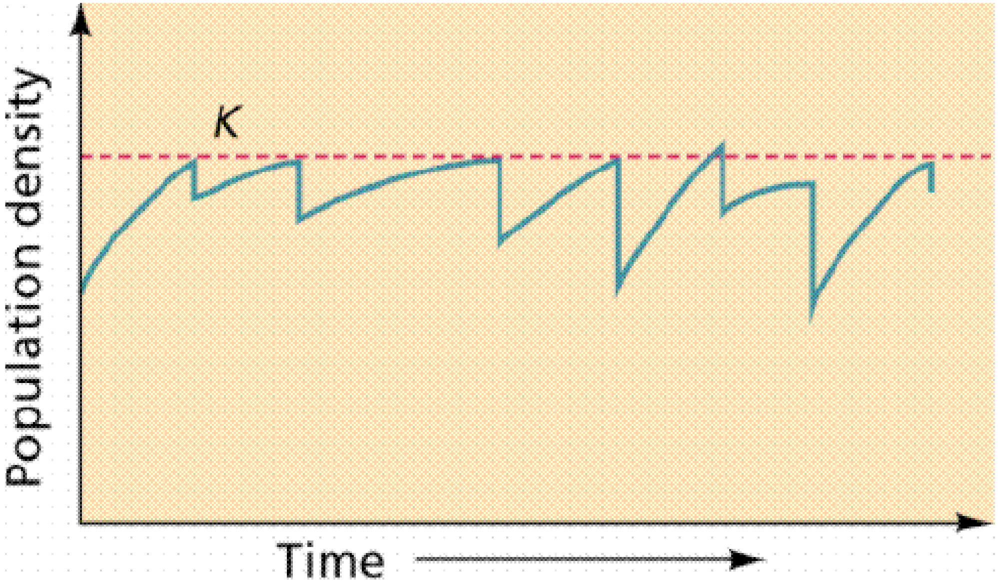
The origin of this struggle

Two basic observations

1. All populations tend to grow exponentially



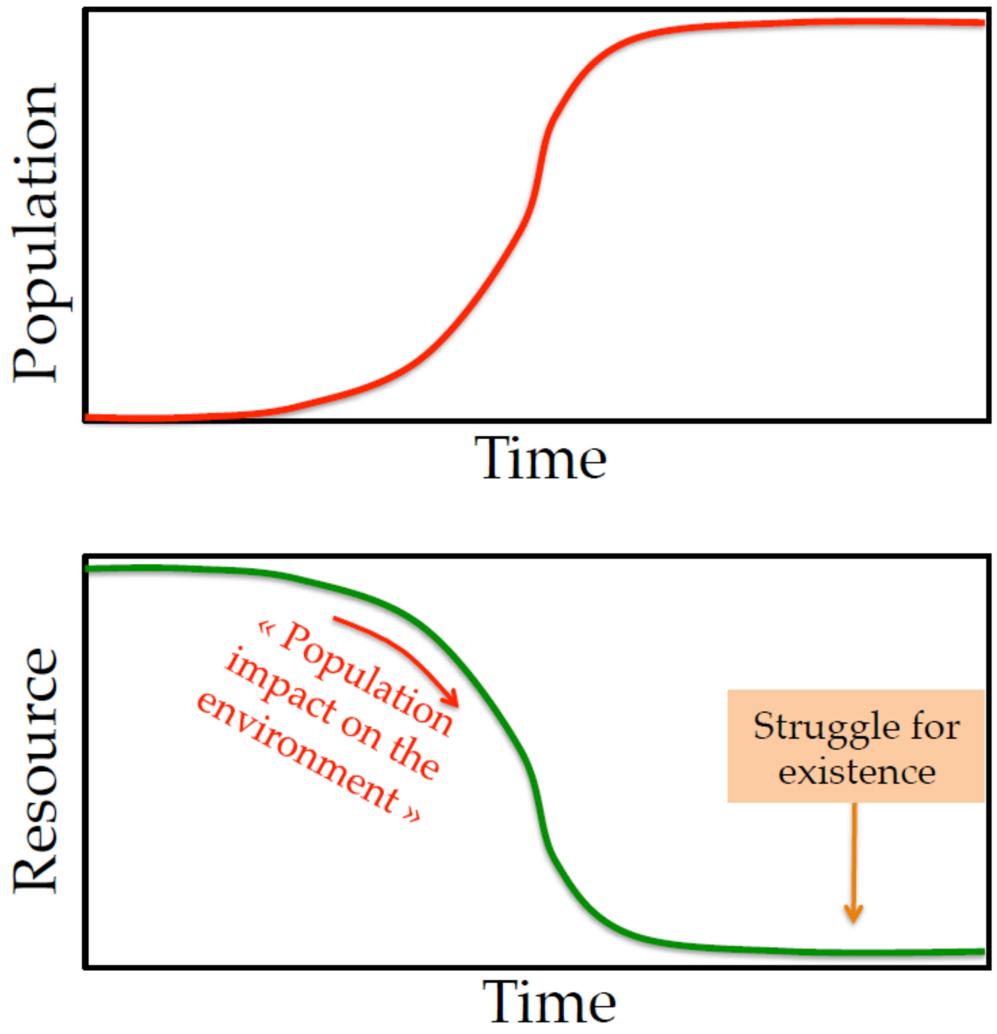
2. Exponentially growing populations are kept in check by regulatory mechanisms

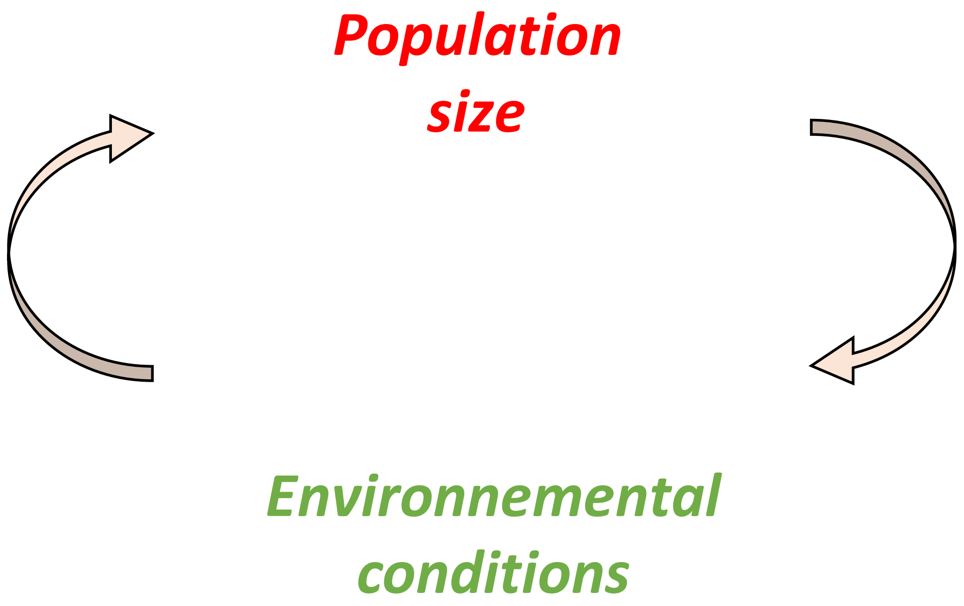


Sylvie Oddou-Muratorio, 1/10/2024

Dia from David Claessen

The origin of this struggle is a feedback loop





A very simple model example

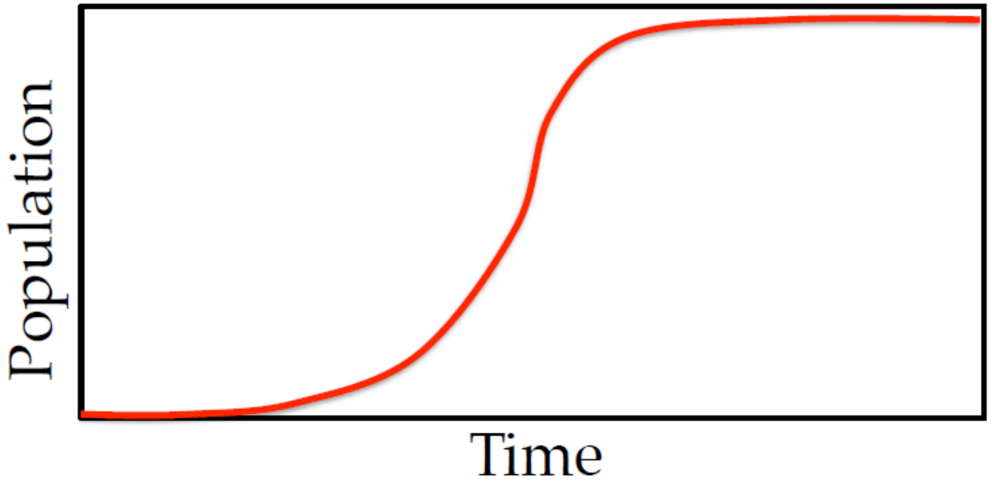
$$\frac{dN}{dt} = r(E)N$$ Exponential growth

with $r(E) = \rho(E) - \mu(E)$

$\mu(E) = \mu_0$ Constant mortality

$\rho(E) = \rho_0 E$ Food dependent reproduction

$E = 1 - \frac{N}{\kappa}$ Population impact on the environment



$$\frac{dN}{dt} = r_{max} N \left(1 - \frac{N}{K}\right)$$

with

$r_{max} = \rho_0 - \mu_0$

$K = \kappa(1 - \mu_0/\rho_0)$

Sylvie Oddou-Muratorio, 1/10/2024

A simple mathematical model….

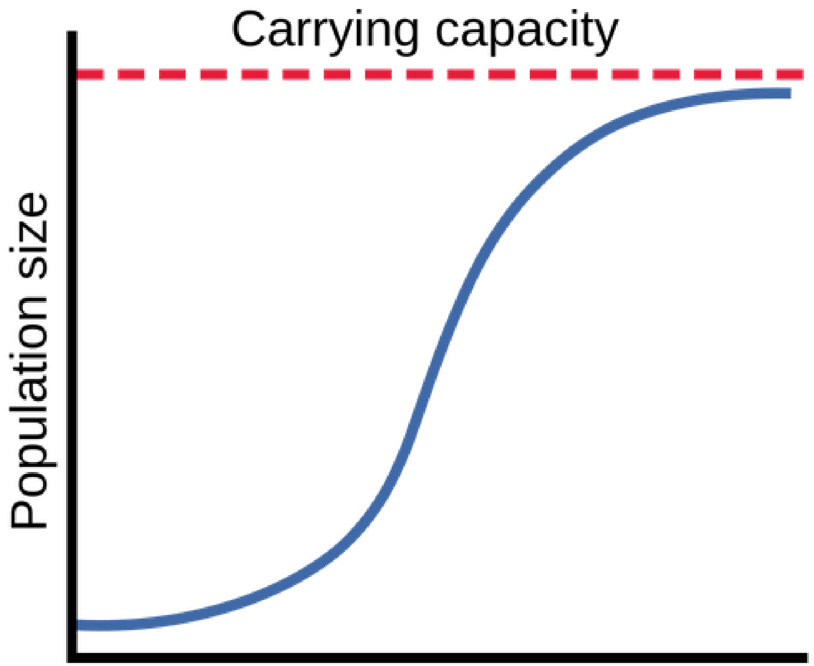
Current population size

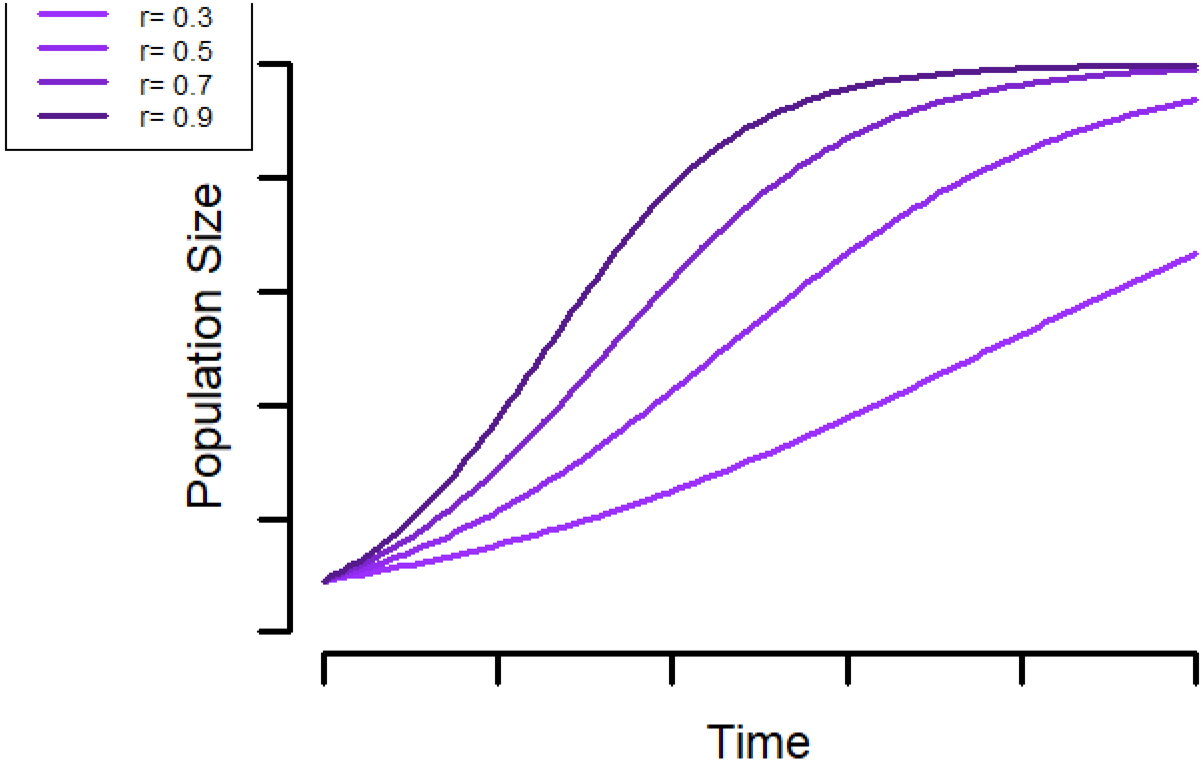
$$\frac{dN}{dt} = r_{max} N \left(1 - \frac{N}{K}\right)$$

Rate of change in population size

Maximum per capita population growth rate

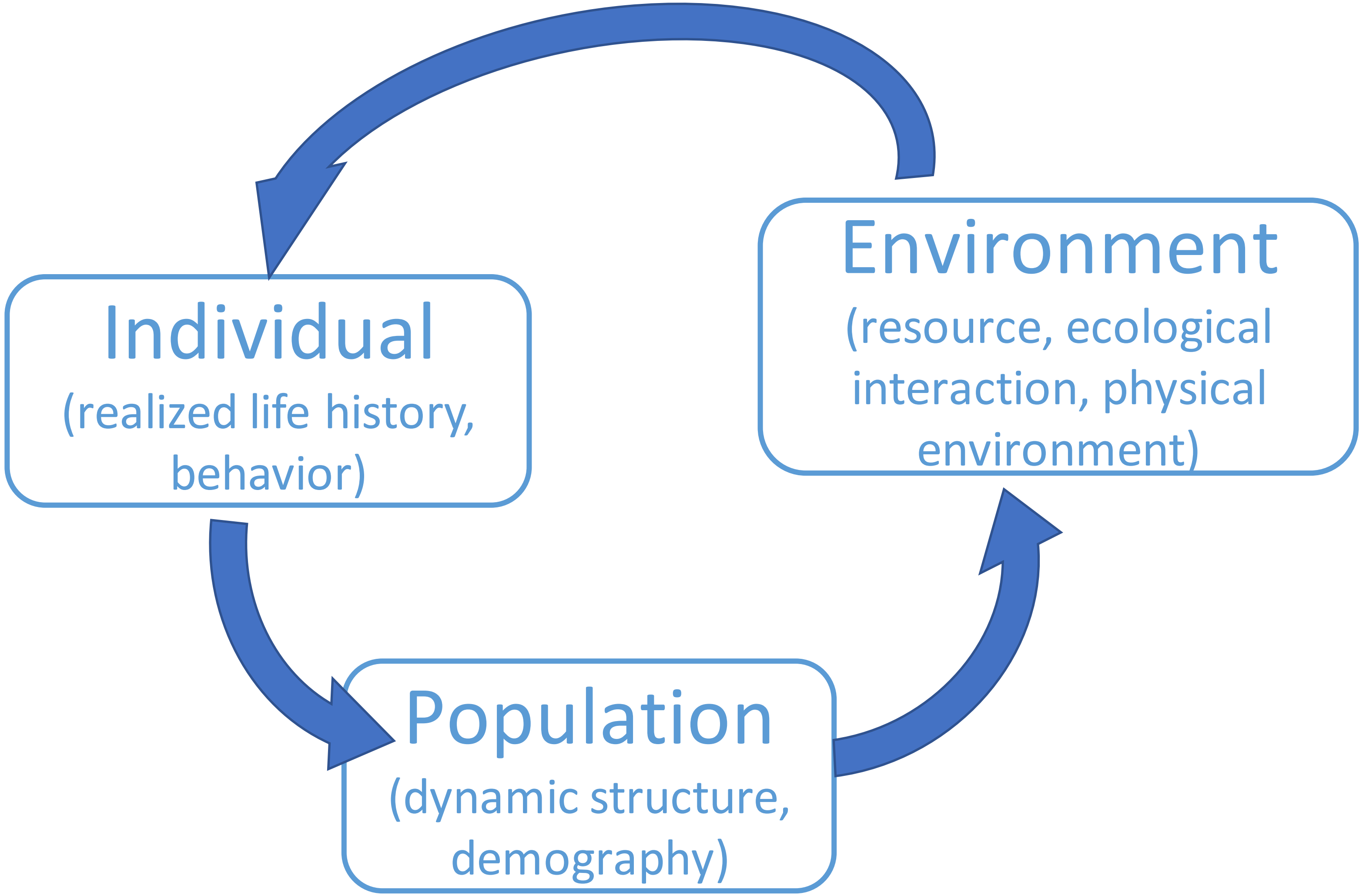
Carrying capacity





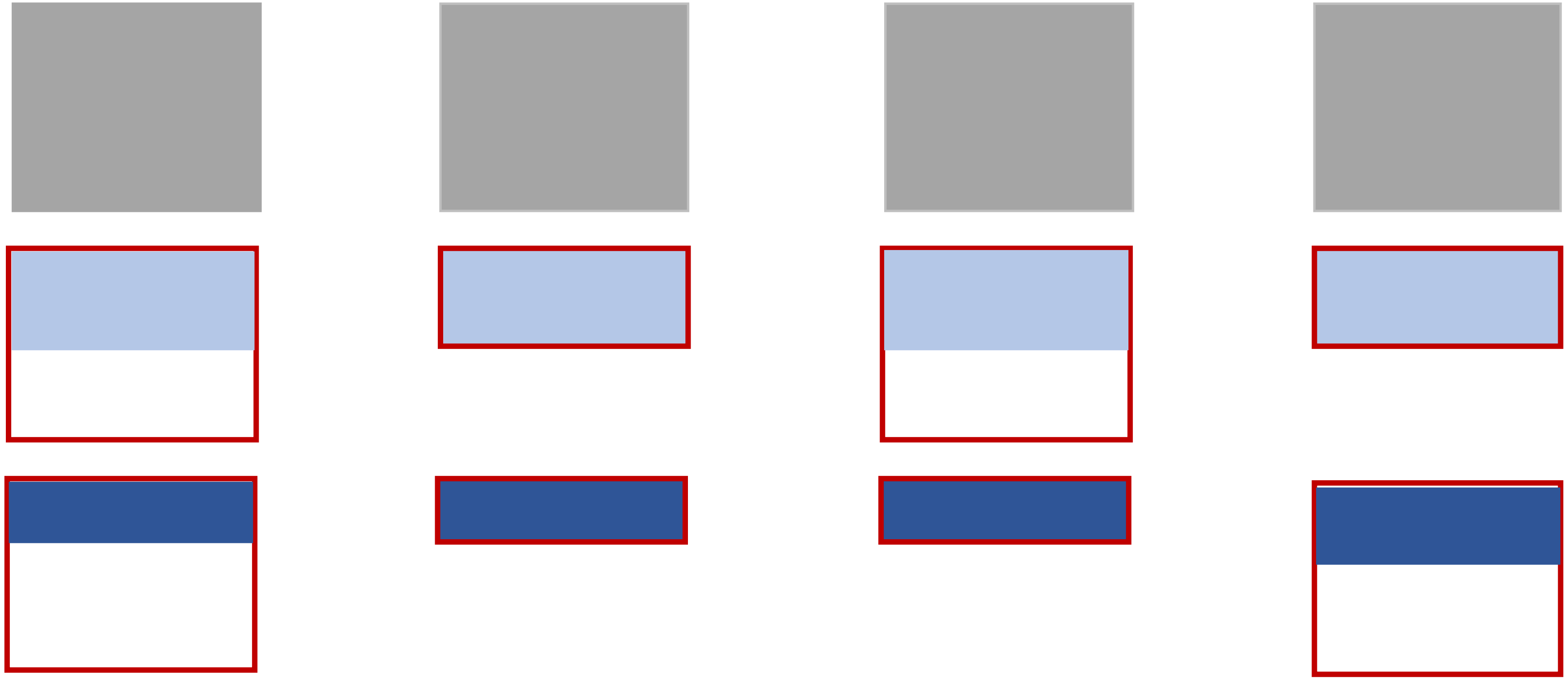
Sylvie Oddou-Muratorio, 1/10/2024

…to study when might evolution influence population dynamics



Density-dependence drives the influence of evolution on r_{max} and K

	Scenario A No density-dependence	Scenario B Full density-dependence	Scenario C J→A density-dependence	Scenario D P→J density-dependence



propagules produced by the population

juveniles / carrying capacity

adults / carrying capacity

r_{max} ↑

K_1 ↑

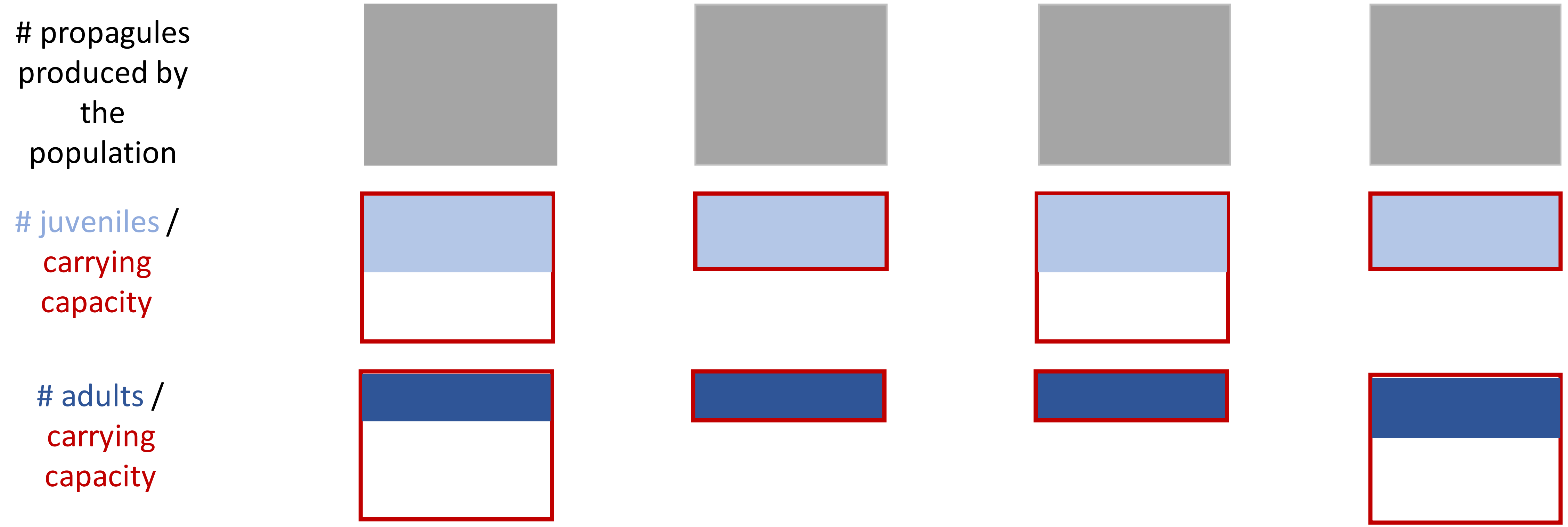
K_2 ↑

Impacts on :

N1 = the number of propagules

N2= the number of adults

Density-dependence drives the influence of evolution on r_{max} and K



	Scenario A No density-dependence	Scenario B Full density-dependence	Scenario C J→A density-dependence	Scenario D P→J density-dependence
r_{max} ↑	N_1 ↑, N_2 ↑	N_1 ↔, N_2 ↔	N_1 ↑, N_2 ↔	N_1 ↔, N_2 ↔
K_1 ↑	N_1 ↔, N_2 ↔	N_1 ↑, N_2 ↔	N_1 ↔, N_2 ↔	N_1 ↑, N_2 ↑
K_2 ↑	N_1 ↔, N_2 ↔	N_1 ↔, N_2 ↑	N_1 ↑, N_2 ↑	N_1 ↔, N_2 ↔

The relationships between individual traits and population growth

Traits that influence r_{max}

Reproduction : fecundity, reproductive rate

Survival : Juvenile survival rate, early life development (maturation)

Resource acquisition, e.g., physiological efficiency (metabolic rate), resource acquisition efficiency

Traits that influence **K**

Resource use efficiency: Foraging efficiency, energy efficiency

Competition and territoriality: Aggressive behaviors, social structure vs cooperative behaviors.

Tolerance to environmental variation: Adaptation to stress: Generalist vs. specialist:

Metabolic theories in ecology :

Metabolism = process by which individuals acquire energy/materials from their environment, and use them for maintenance, growth, reproduction

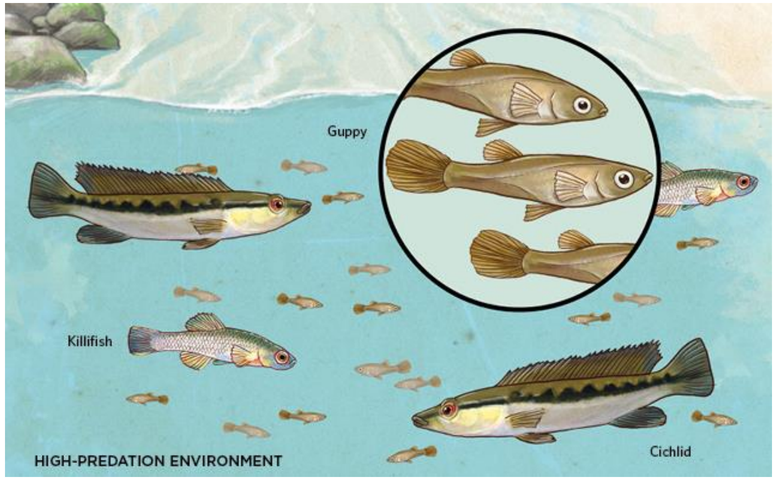
Two main theories:

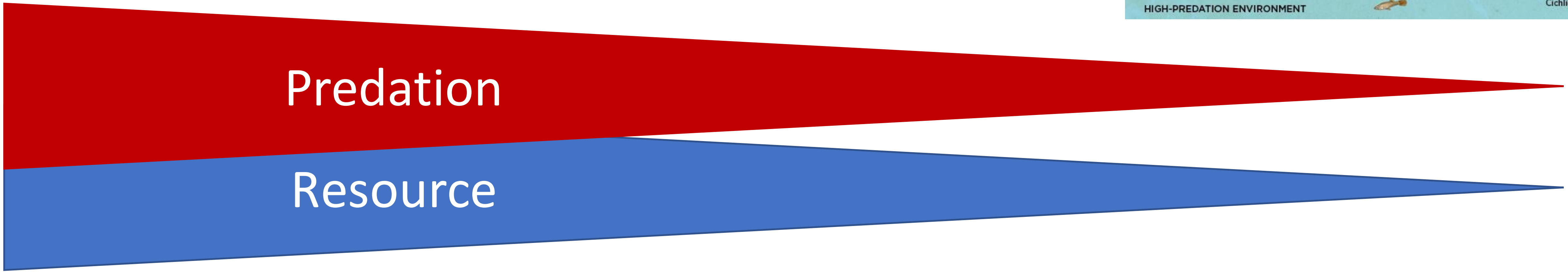
- Kooijman's dynamic energy budget (DEB) theory
- West, Brown, and Enquist (WBE) theory

Van der Meer, 2006; Kearney & White 2012

Complexity: (1) traits influencing rmax and K have generally themselves evolved under density-dependent/independent conditions

- Populations facing high density-independent mortality often evolve traits that increase rmax,
- Populations facing density-dependent mortality often evolve traits that increase competitive ability,





r-type life histories

- Early reproduction
- High reproductive effort
- Many small offspring

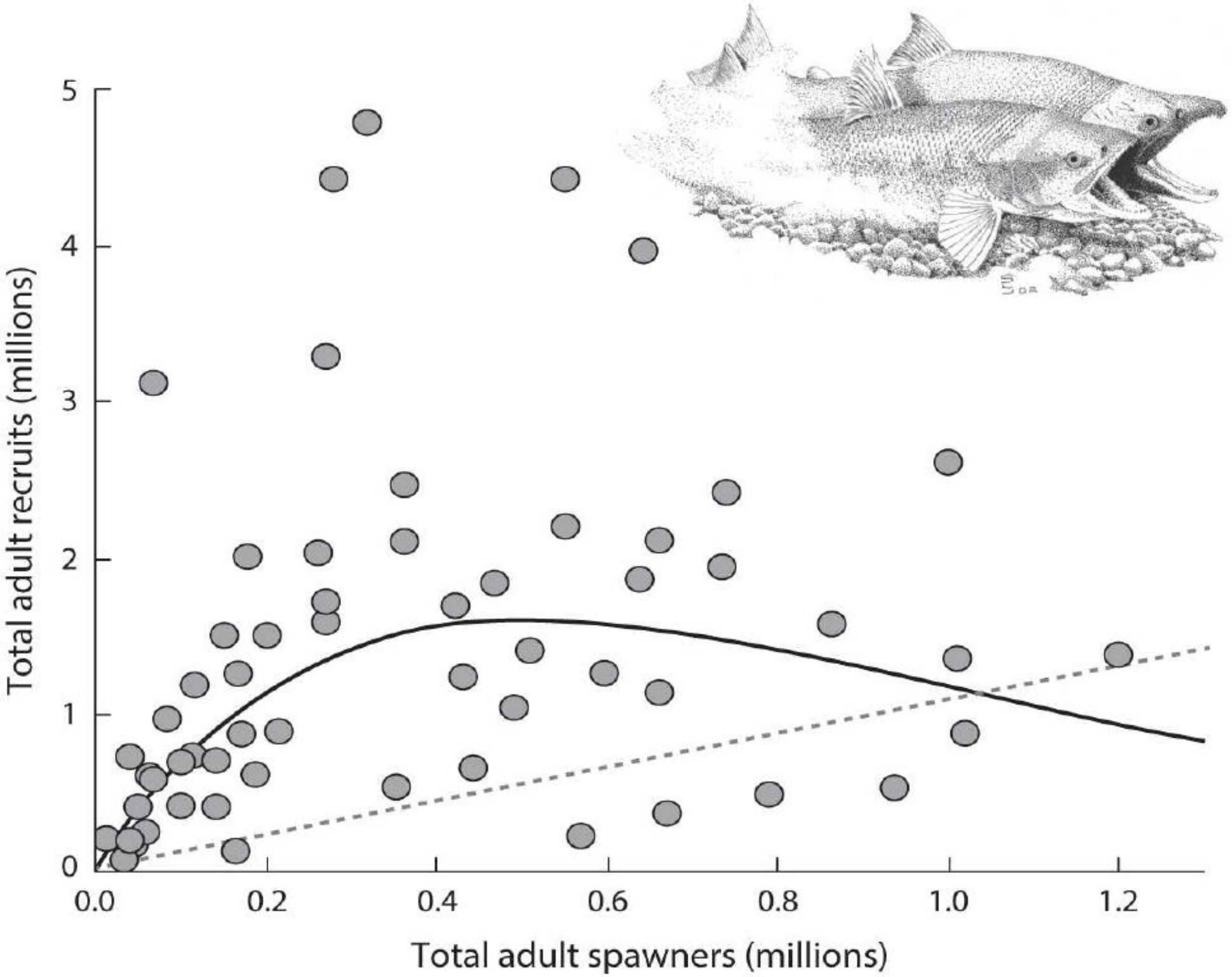
K-type life histories

- Late reproduction
- Small reproductive effort
- Few large offspring

Reznick, Bryant, & Bashey, 2002

Complexity (2) Evolution in r_{max} can affect population size under density-dependence

- high rmax can cause an **overshoot** of K, which can then lead to a sharp decrease in per capita reproductive success and, hence, a decrease in population size at subsequent stages.



the "Ricker Curve" of stock recruitment

In Hendry 2017

Complexity (3) Feedback in life-histories evolutions

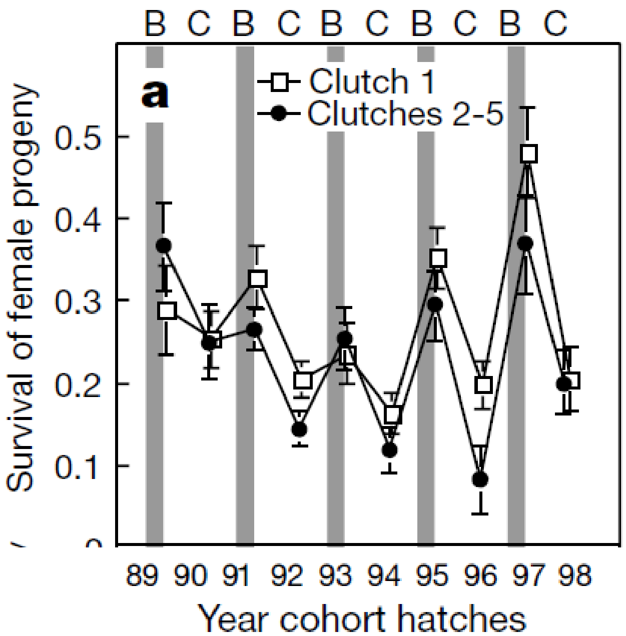
- Population density and life history evolution can influence each other, a situation that can lead to eco-evolutionary feedbacks

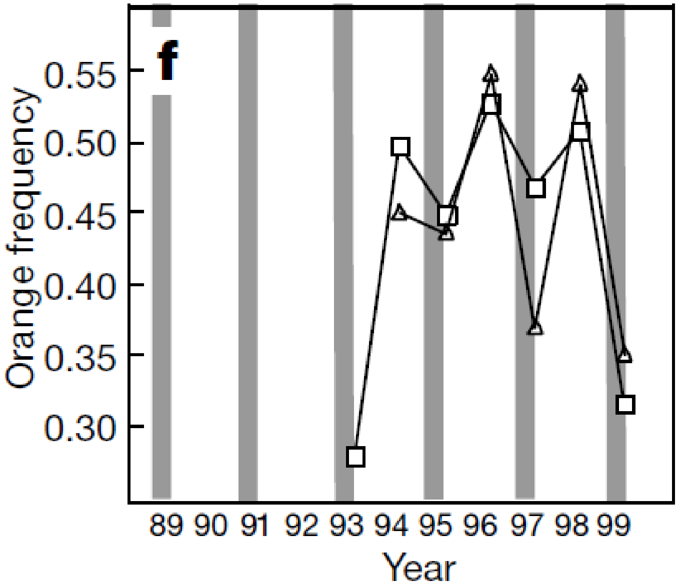
Side-blotched lizards

Orange-throated females have few large offspring (K-type life histories)

Yellow-throated females have many small offspring (r-type life histories)

Favored in years of high-density →decrease population growth





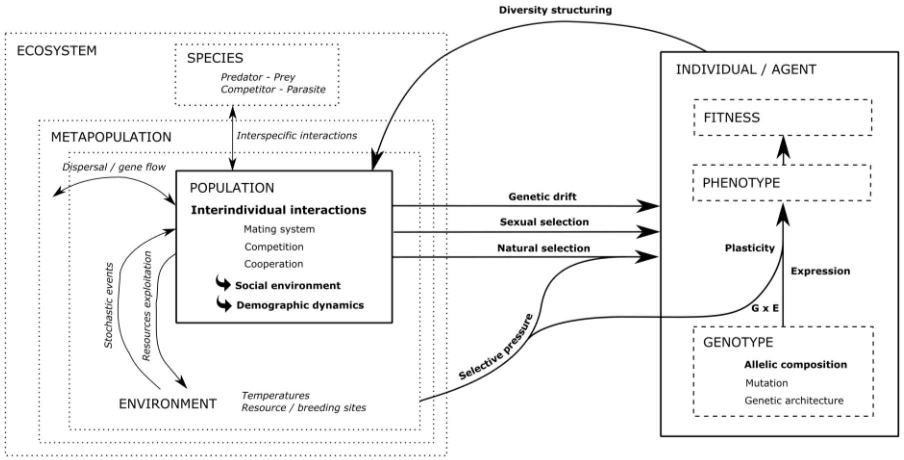
Favored in years of low-density →increase population growth

Sinervo, Svensson, & Comendant, 2000

How to detect evolutionary effects on population dynamics ?

- **Experimental manipulations**: manipulate phenotypic/genotypic distributions and monitor the resulting population dynamics: in controlled conditions (mesocosm) or in situ (reciprocal transplant experiments) (Farkas et al. 2013; Zamorano et al. 2023)
- **“Empirical” modeling**: mechanistic simulation model integrating empirical knowledge on eco-evolutionary dynamics → detailed after
- **Observational studies** : monitors the dynamics of natural populations and statistically relates year-to-year (“real time”) changes in population dynamic parameters to year-specific phenotypic trait values or allele frequencies (Hanski and Saccheri 2006)

Timema cristinae

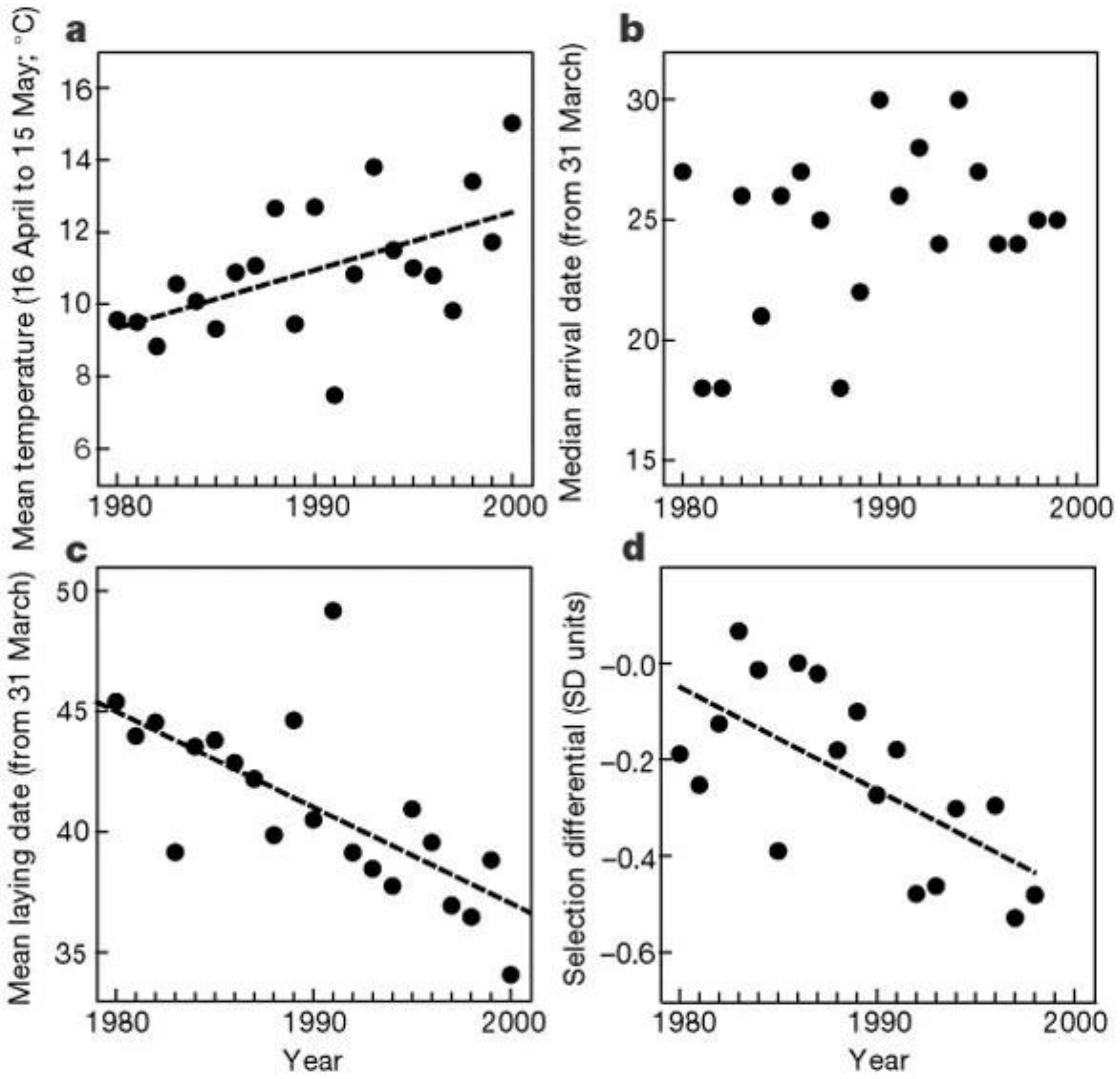


Melitaea cinxia

“Eco-evolutionary population dynamics in nature”

- Q1. To what extent does maladaptation cause population declines?
- Q2. To what extent, and how rapidly, does adaptation increase individual fitness?
- Q3. To what extent does adaptation influence population growth ?
- Q4. Does adaptation allow evolutionary rescue?
- Q5. Does adaptation aid range expansion ?
- Q6. Does intraspecific diversity influence population dynamics ?

Q1. To what extent does maladaptation cause population declines?

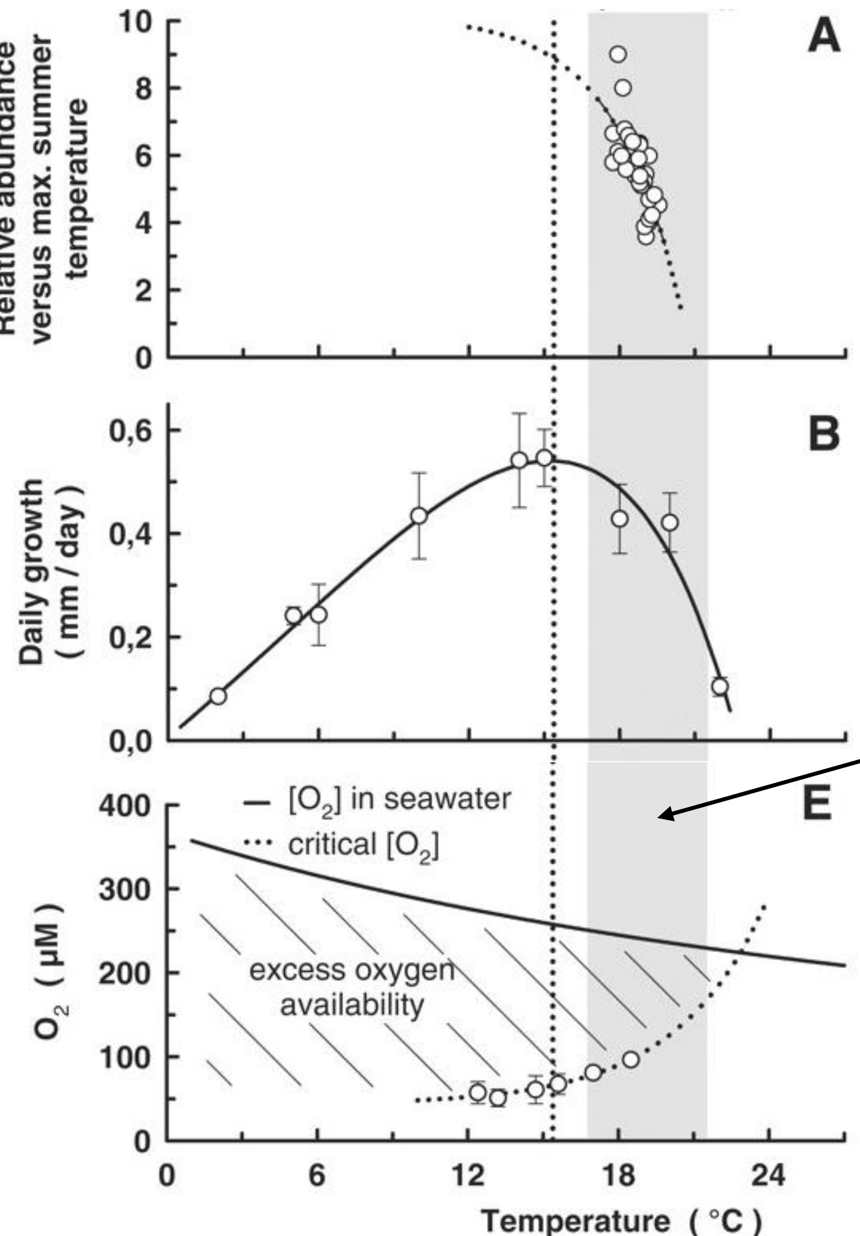


Spring temperature, breeding and spring arrival date of a pied flycatcher population in the Netherlands from 1980 to 2000

Pied Flycatcher - Ficedula hypoleuca

Both & Visser, 2001

Q1. To what extent does maladaptation cause population declines?



Thermal limitation in Eelpout, illustrated by

- The negative correlation between summer water temperatures and relative abundance
- An overshoot of daily growth for high summer temperature
- The underlying mechanism= mismatch between the demand for oxygen and the capacity of oxygen supply to tissues

Critical temperature range where an organism's ability to perform aerobically begins to decline

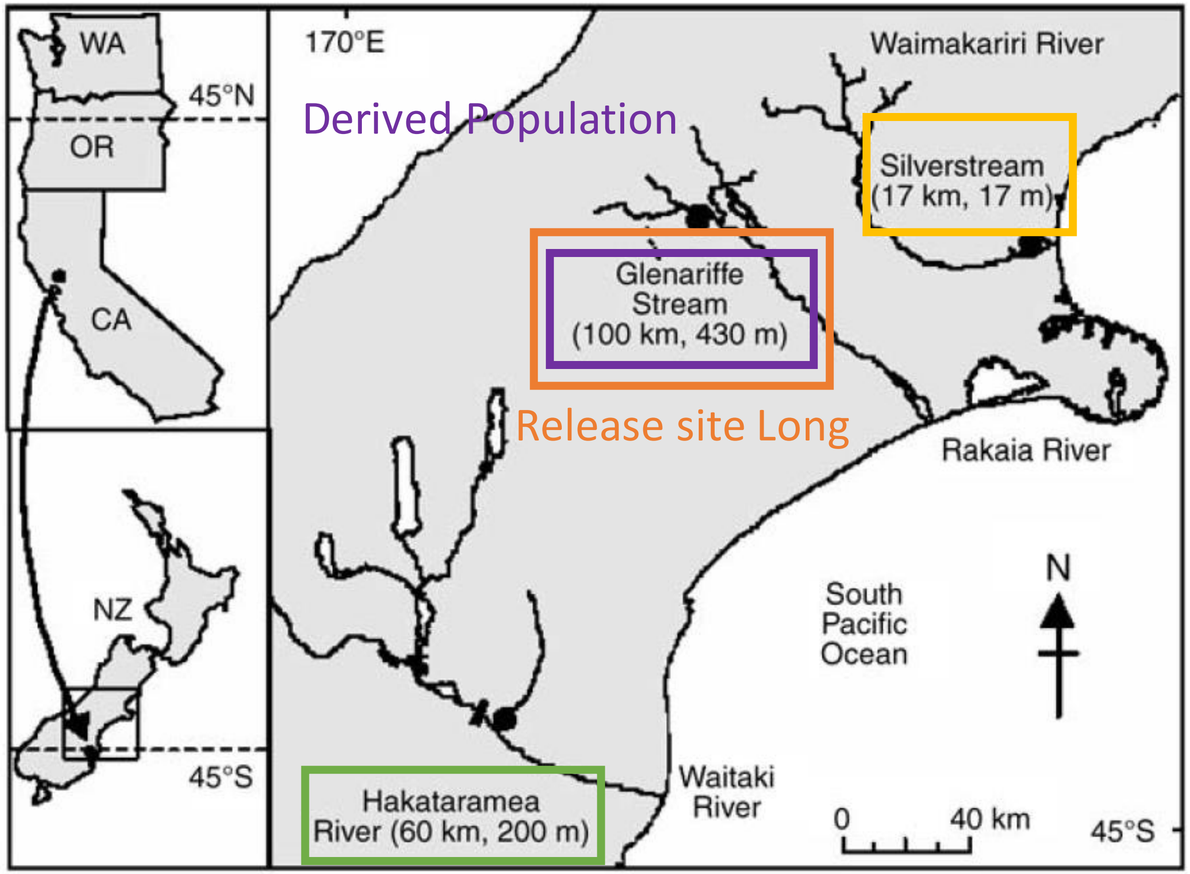
Pörtner & Knust, 2007

Eelpout, Zoarces viviparus

Q2. To what extent/ how rapidly, does adaptation increase individual fitness?

The contribution of adaptive trait changes to improvements in fitness is not well understood

Release site Short

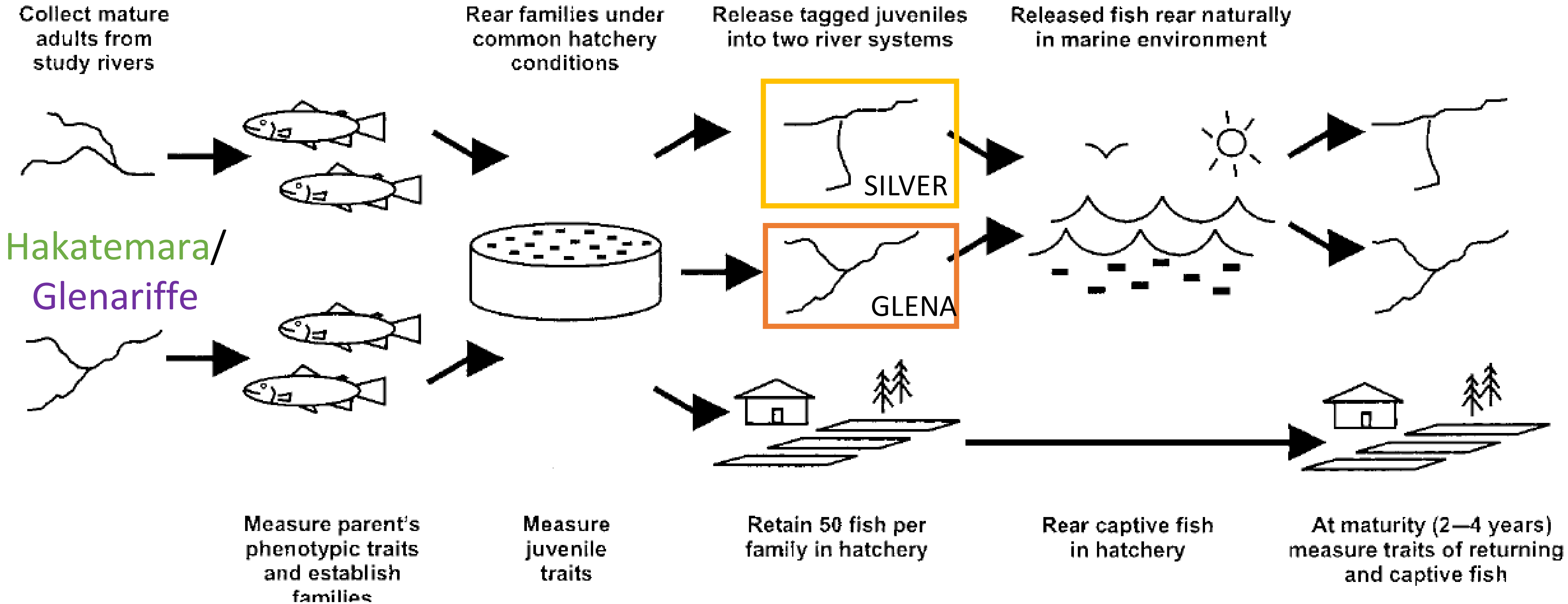


Ancestral Population

- 1901 and 1907: introduction of chinook salmon from California to New Zealand
- Common-garden studies revealed adaptive trait divergence between two populations (Hakatemara/Glenariffe) with different migration distances

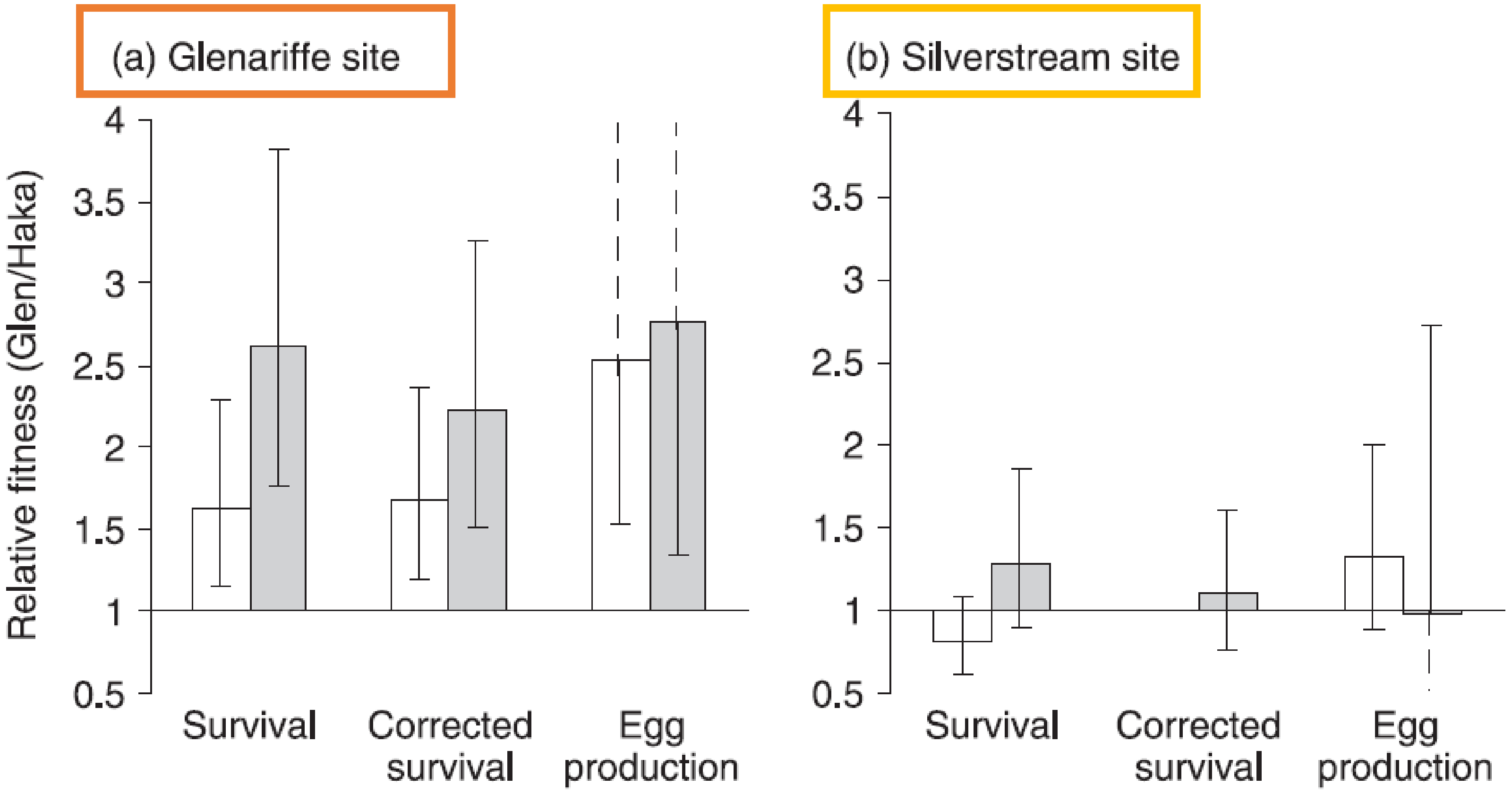
Quinn *et al.* 2001 Kinnison *et al.* 2001, 2003

Q2. To what extent/ how rapidly, does adaptation increase individual fitness?



Quinn *et al.* 2001 Kinnison *et al.* 2001, 2003

Q2. To what extent/how rapidly, does adaptation increase individual fitness?



Relative fitness of Glenariffe to Hakataramea genotypes released at two experimental sites (Glenariffe and Silverstream)

- "Reciprocal" transplant:

(a) Glenariffe genotypes outperform Hakataremea genotypes at GLENA site
(b) Glenariffe and Hakataramea genotypes perform similarly at SILVER site where neither has had the opportunity to adapt and where relative migratory (habitat) effects are minimized

Kinnison *et al.* 2008

Q3. To what extent does adaptation influence population growth ?

A partitioning approach for the rate of change in population growth

$$r(t) = r(z(t) + n(t))$$

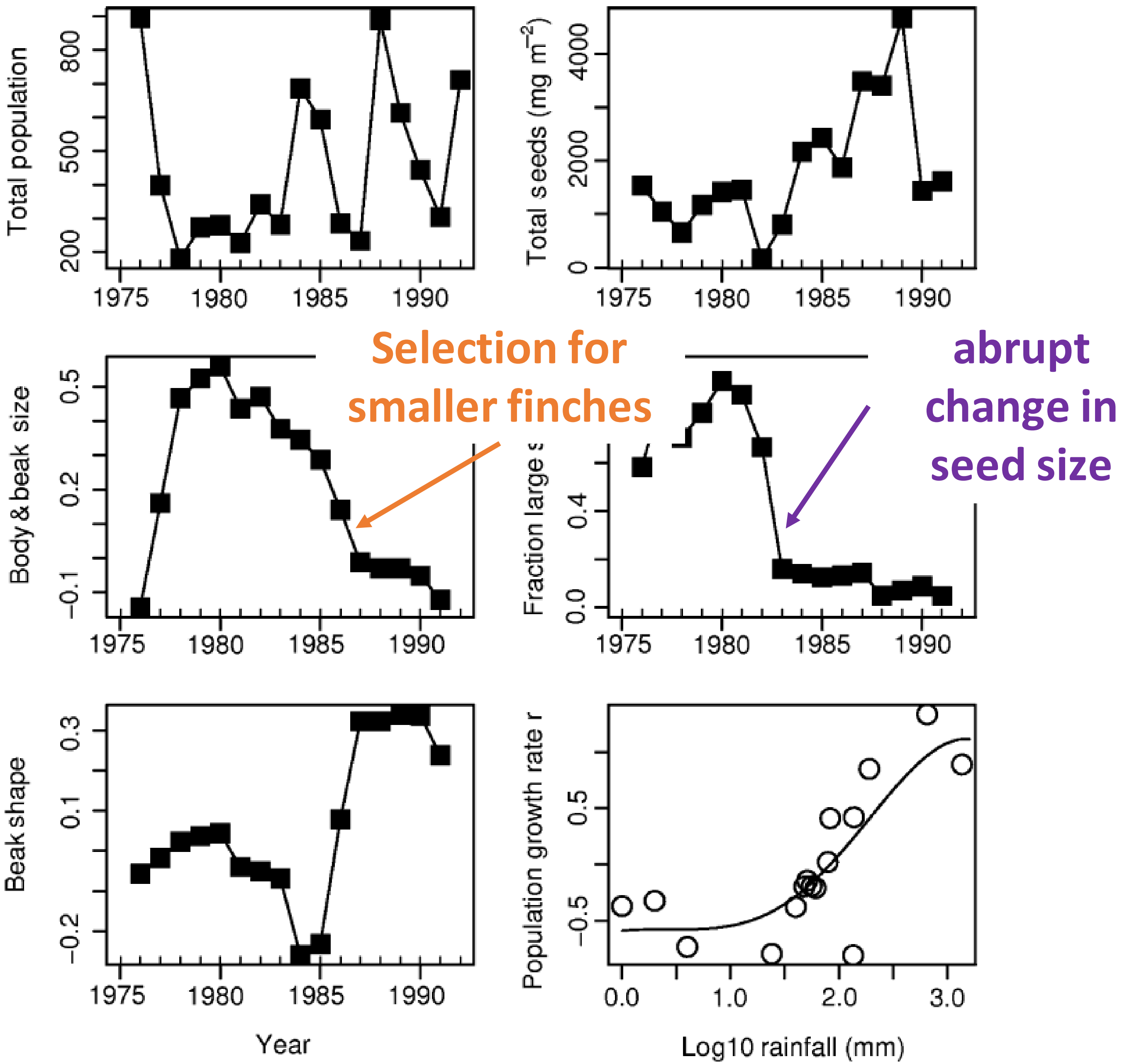
$$\frac{dr}{dt} = \frac{\partial r}{\partial z}\frac{dz}{dt} + \frac{\partial r}{\partial n}\frac{dn}{dt}$$

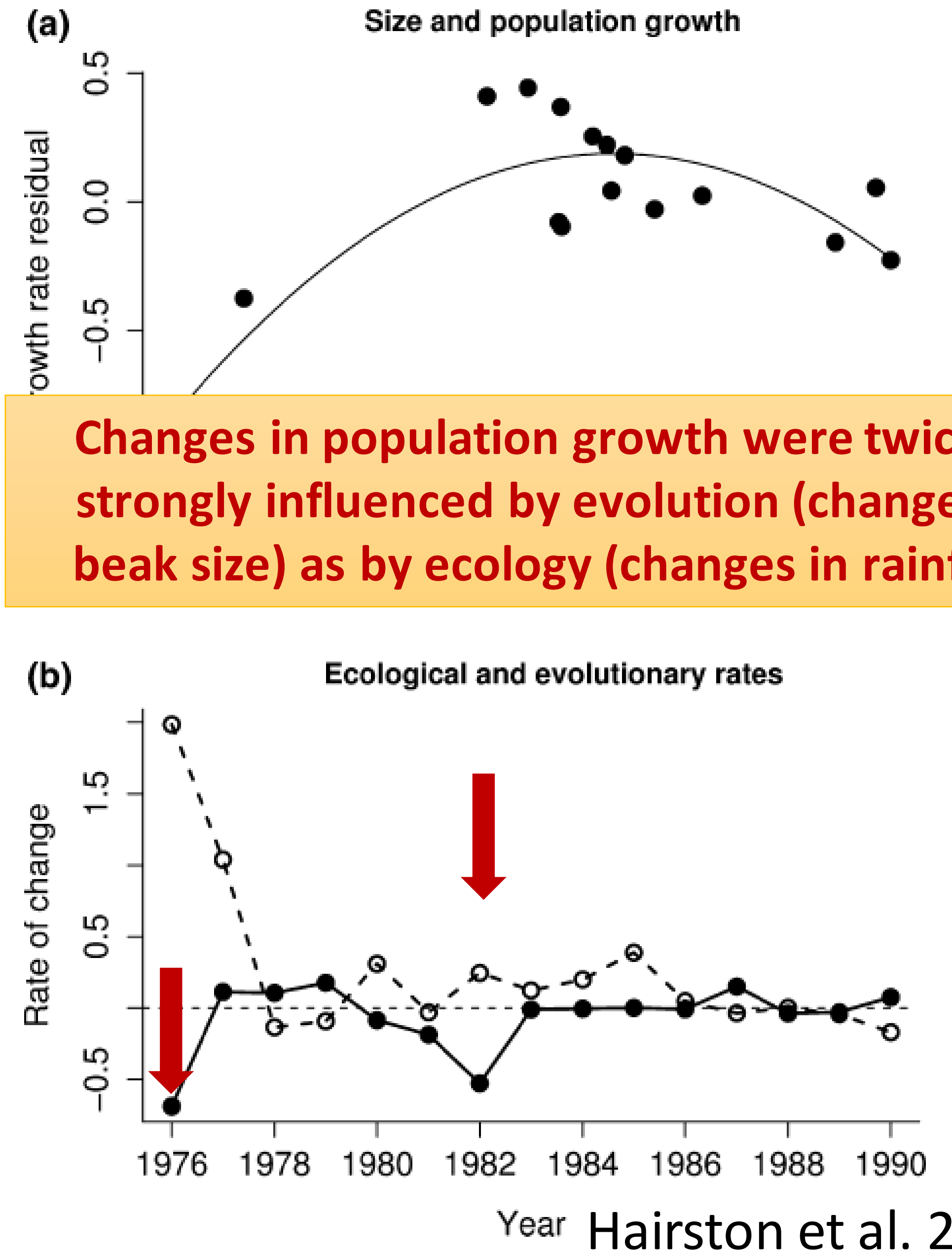
Actual rate of change in r resulting from the changes in z

Actual rate of change in r resulting from the changes in n

Hairston et al. 2005

Q3. To what extent does adaptation influence population growth ?





Changes in population growth were twice as strongly influenced by evolution (changes in beak size) as by ecology (changes in rainfall).

Hairston et al. 2005

Q3. To what extent does adaptation influence population growth ?

Limitations of the partitioning approach

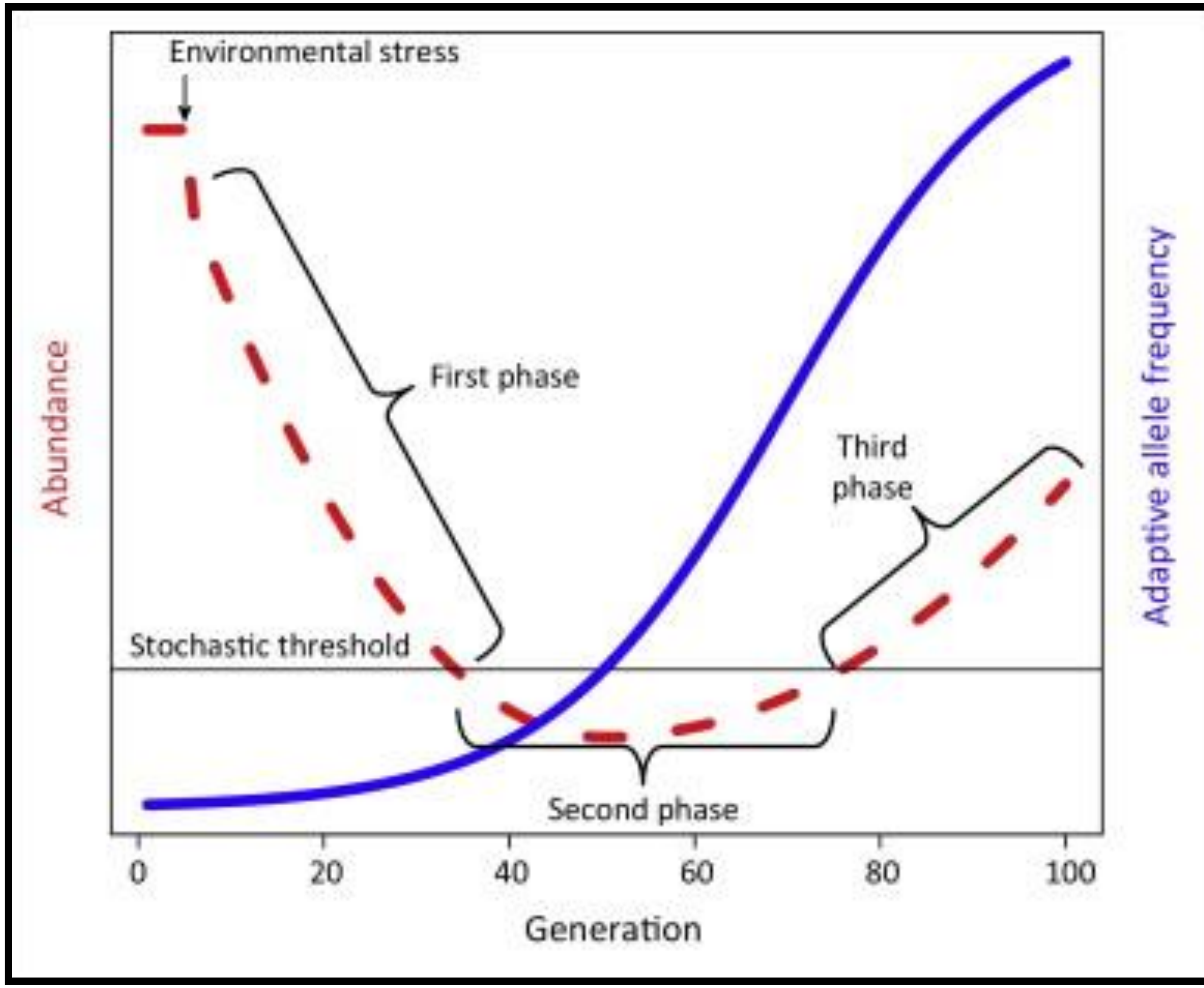
- ✓ Many phenotypic traits and ecological variables need to be considered
- ✓ The equation can incorporate an interaction term between ecology and evolution, but what about feedback ?
- ✓ Most applications consider that phenotypic change is entirely genetically based, whereas it can be influenced by plasticity
- ✓ Need for long-term data on population size, traits/genotypes and ecological variables

Q4. Does adaptation allow evolutionary rescue?

1. Rapid environmental change can cause maladaptation that reduces population size
2. This maladaptation should impose selection on phenotypes and thus promote adaptive evolution that improves individual fitness
3. Such adaptive evolution may increases population size

To what extent can adaptive evolution arrest population declines that would lead to extinction and instead stabilize /recover population size ?

Evolutionary rescue



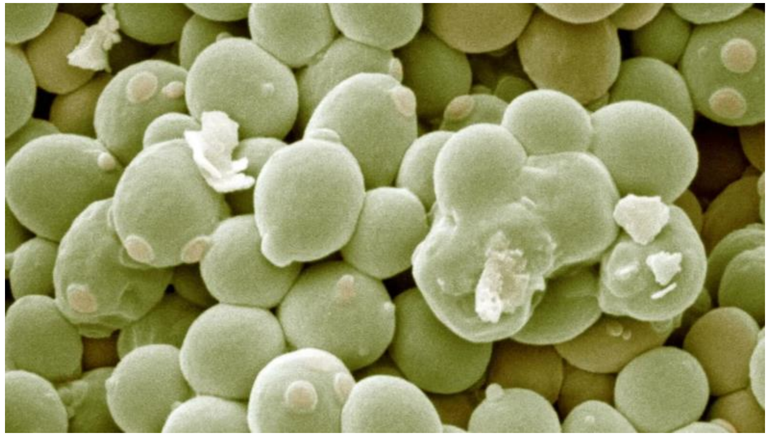
Carlson *et al.* 2014

Q4. Does adaptation allow evolutionary rescue?

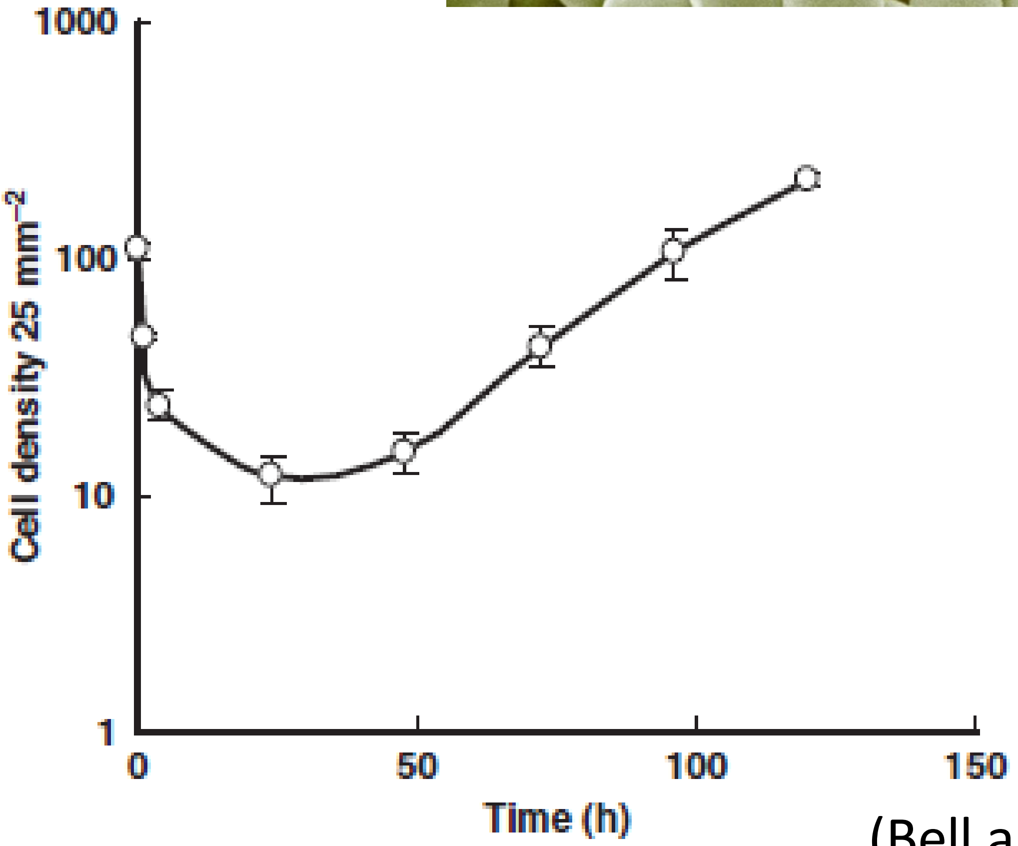
Conditions for evolutionary rescue

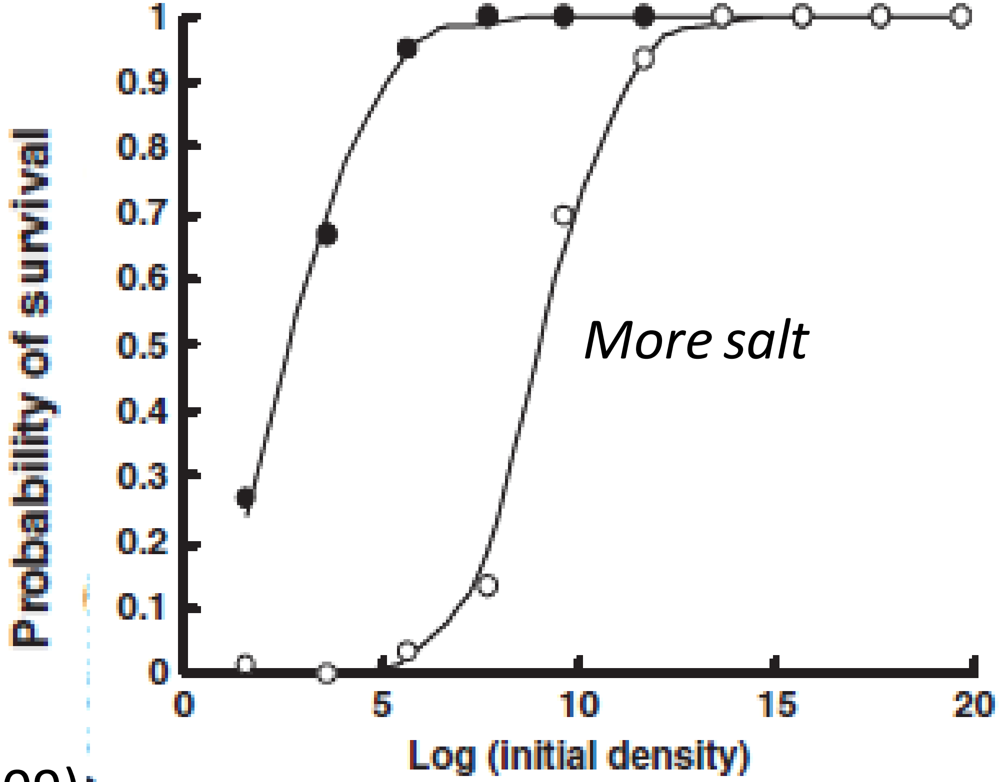
1. larger initial population sizes
2. less dramatic environmental change (lower initial maladaptation),
3. weaker stabilizing selection around the "optimum" trait value,
4. higher additive genetic variance in the direction of selection
5. shorter generation times

Q4. Does adaptation allow evolutionary rescue?



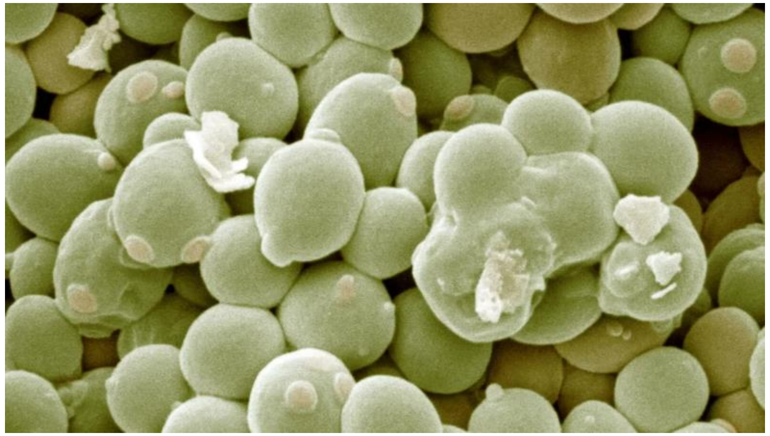
Saccharomyces cerevisiae





(Bell and Gonzalez 2009)

Q4. Does adaptation allow evolutionary rescue?

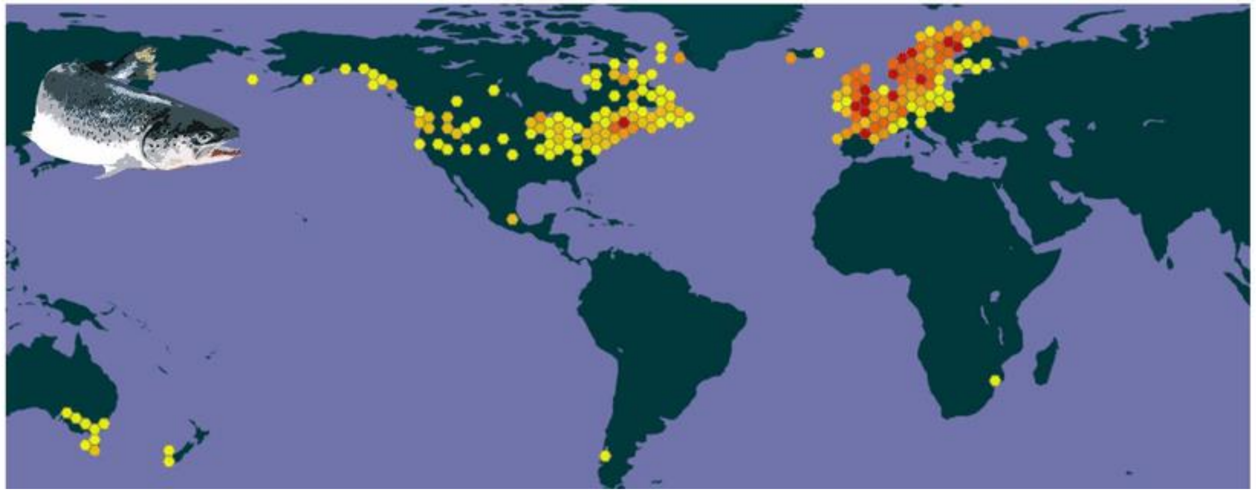


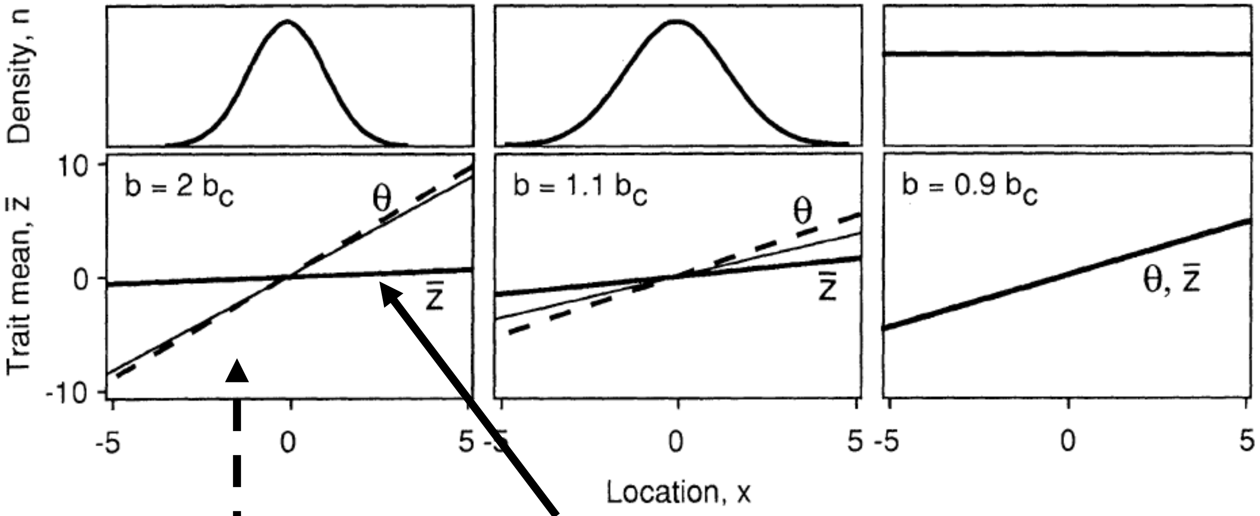
Saccharomyces cerevisiae

- **Many populations in altered environments would disappear without sufficiently rapid and effective adaptation.**
- **This evolutionary rescue is most likely when environmental change is small, initial population size is large, and appropriate genetic variation is high.**
- **These conclusions are based on theoretical models and laboratory studies, whereas we really have no idea when evolutionary rescue will or will not take place in nature.**

(Bell and Gonzalez 2009)

Q5. Does adaptation aid range expansion ?





Stable solution for trait z

Optimal value for trait z

What is a species distribution range ?
Which factors drive species distribution range ?

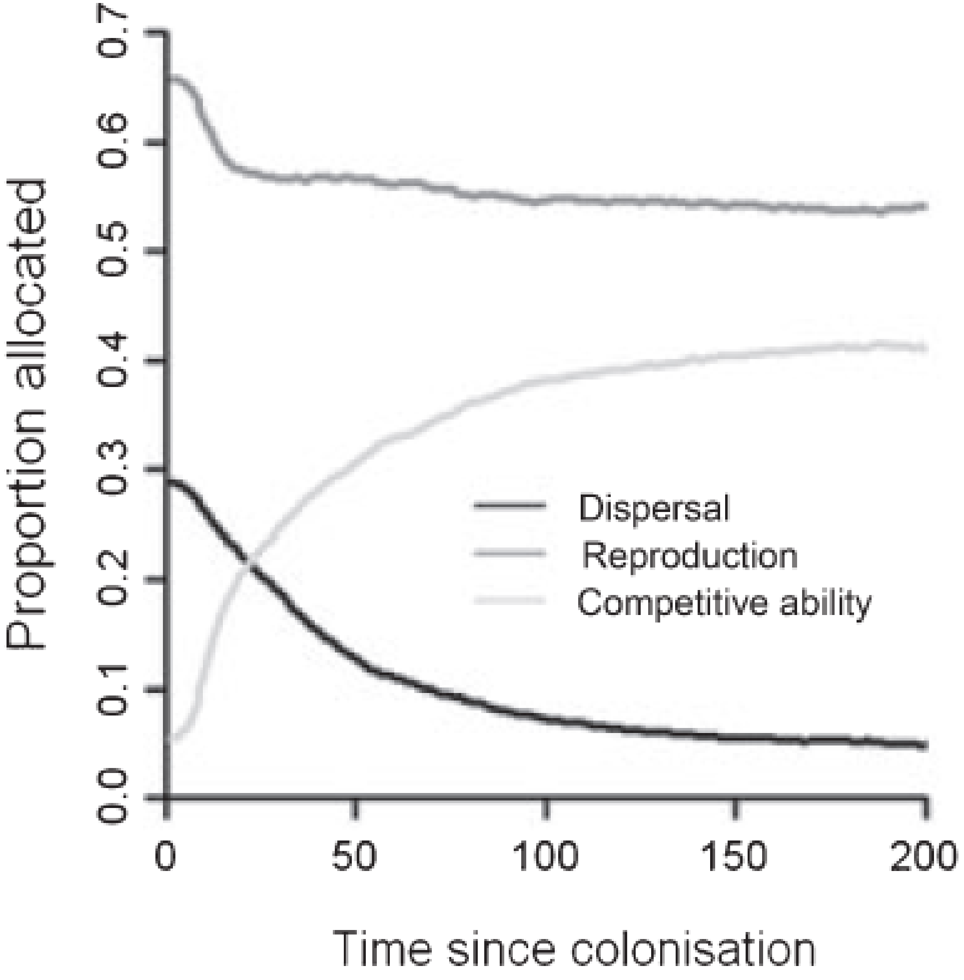
- **Environmental factors**: **climate,** habitat availability
- **Ecological interactions**: competition, predation, parasitism, mutualism
- **Anthropogenic factors**
- **Evolutionary factors**

The balance between migration, gene flow, and local adaptation determines whether a species can expand its range or remains limited to a smaller geographic area

Kirkpatrick and Barton 1997

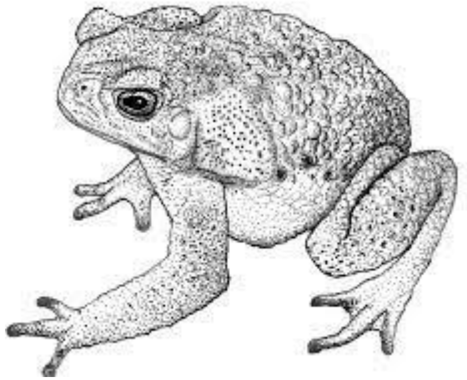
Q5. Does adaptation aid range expansion ?
What can we learn from species introduction ?

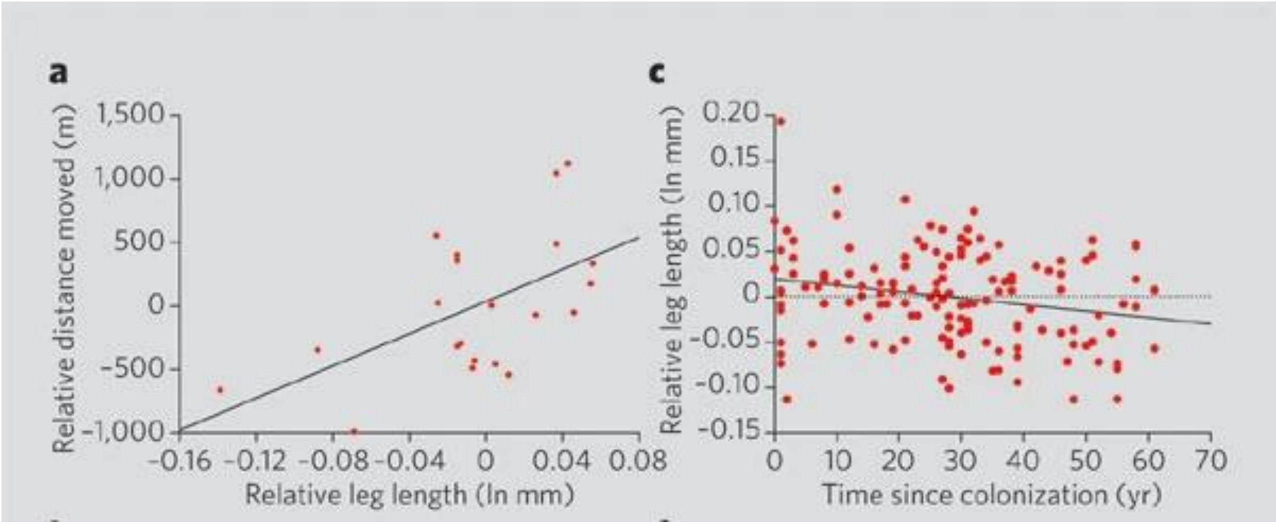
...



Burton *et al.* 2010

Cane toad, Bufo marinus



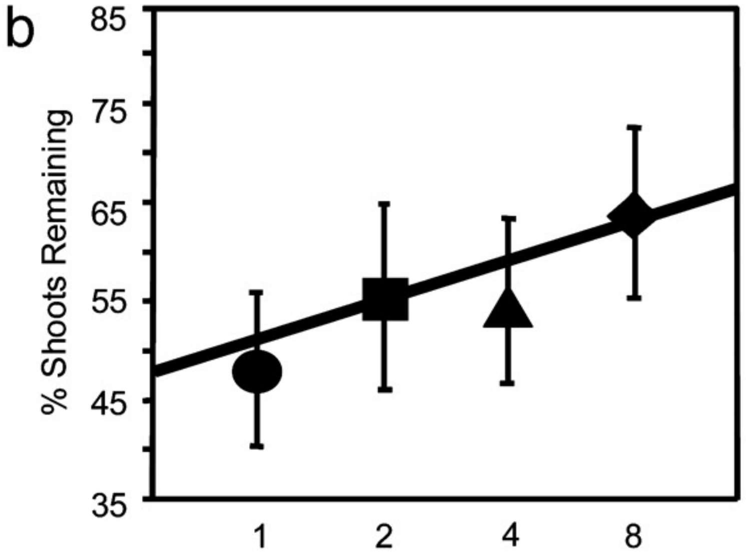


Phillips *et al.* 2006; Phillips 2009

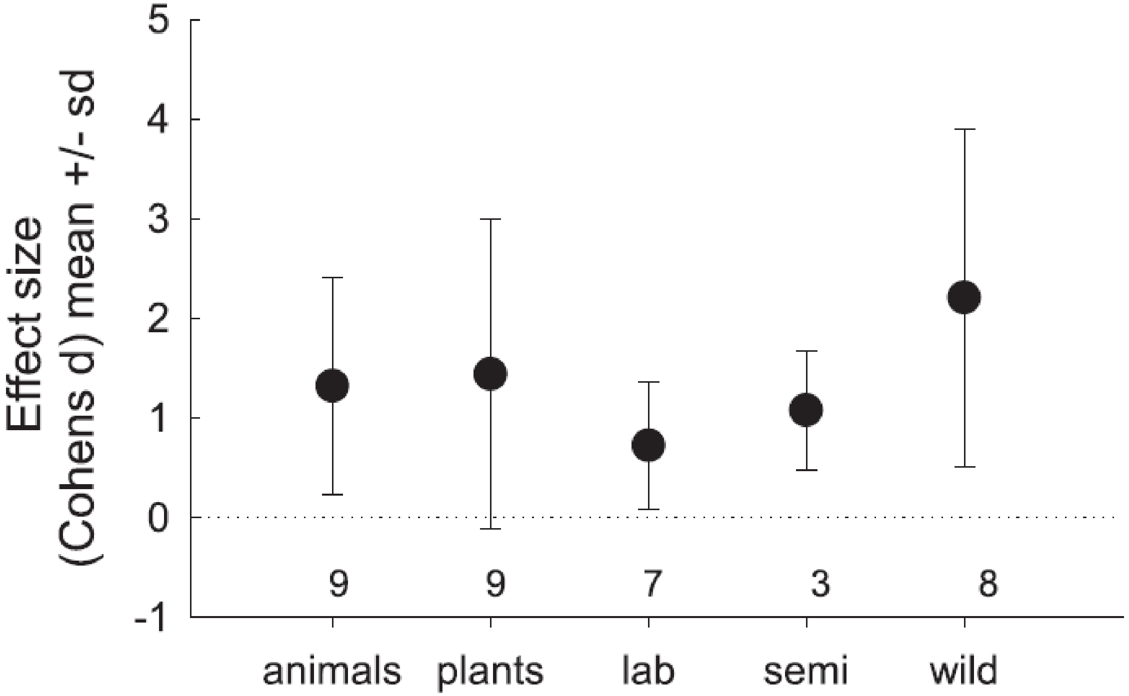
Q6. Does intraspecific diversity influence population dynamics ?

Zoostera marina

- ✓ In *zoostera marina,* more genetically diverse plots were more resistant to disturbance by geese (Hughes and Stachowicz 2004)
- ✓ Meta-analysis: a greater genotypic/phenotypic diversity of a founding population increases the probability of successful establishment (Forsman 2014)

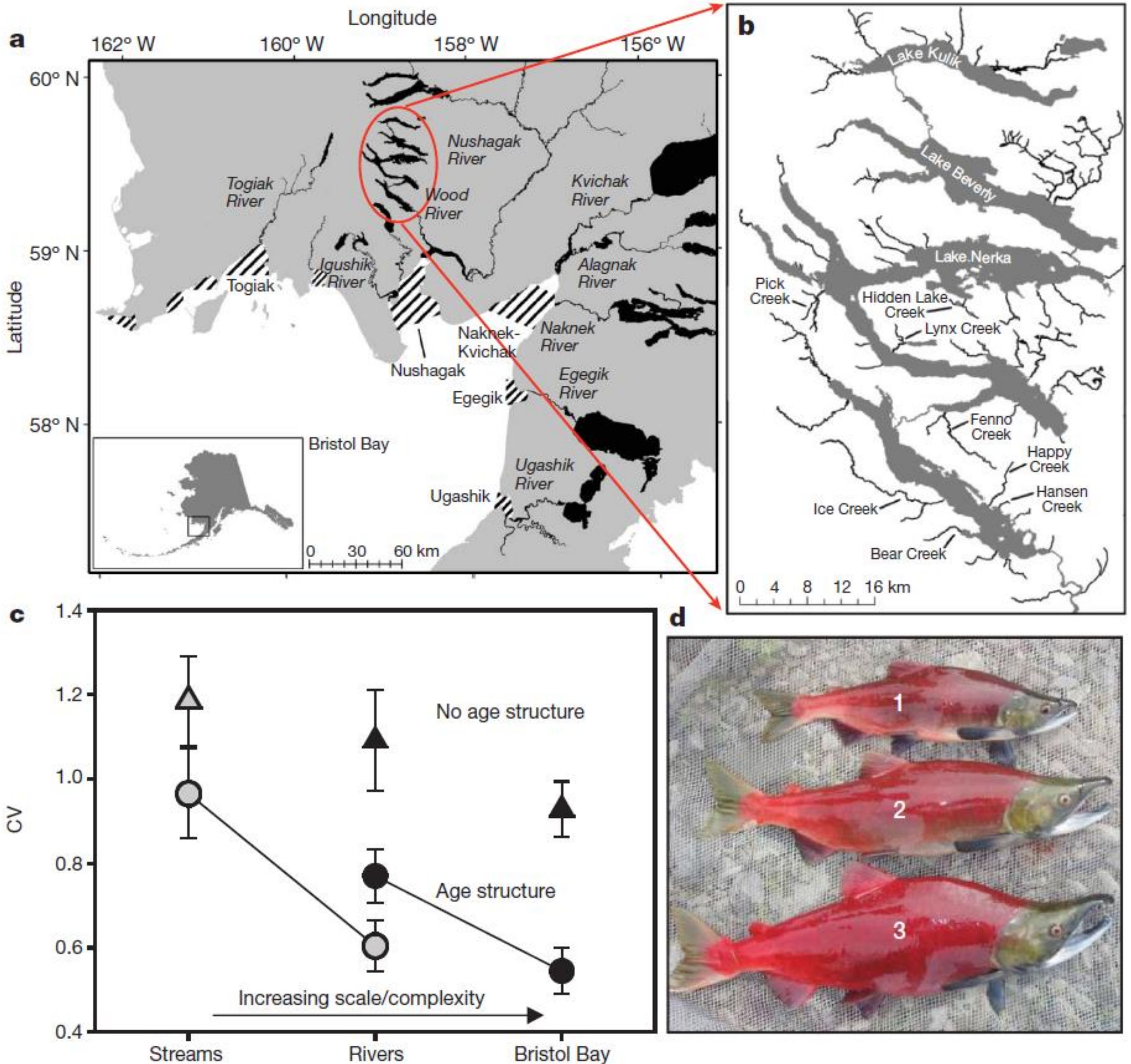


Number of genotypes



Q6. Does intraspecific diversity influence population dynamics ?

Nursery lake in black



- ✓ Each year, fishery targets adult sockeye salmon returning from the open ocean to spawn in fresh water in Bristol Bay, Alaska
- ✓ High interannual variability in total returns, but it decreases with increasing spatial/temporal scale
- ✓ The size of the overall metapopulation (all fish returning to Bristol Bay) is about half as variable as would be expected if the population-specific interannual fluctuations were instead synchronized among year

➢ **Diversity among local populations within a metapopulation thus has a dramatic positive influence on reducing variation in overall population density**

(Schindler *et al.* 2010)

Take-home message

- ✓ This chapter focuses on the evo-to-eco side of eco-evolutionary dynamics, exploring how evolutionary changes impact ecological processes such as population size, growth rate, and structure.
- ✓ The effects of evolutionary change on population dynamics vary based on factors like density dependence and eco-evolutionary feedback loops.
- ✓ While laboratory experiments have shown clear eco-evolutionary dynamics at the population level, evidence from natural populations remains more circumstantial.
- ✓ Maladaptation, often triggered by environmental change, leads to population declines, suggesting that evolution helps many populations maintain their abundance over time.
- ✓ Several studies have correlated population growth with evolutionary change, but direct evidence of evolutionary rescue in nature is scarce.
- ✓ Intraspecific diversity within populations plays a crucial role in traits like colonization, resistance to disturbance, and extinction risk.
- ✓ Evolution is also important for range expansion, but formal studies proving this process are still limited.

References

Bell, G., & Gonzalez, A. (2009). Evolutionary rescue can prevent extinction following environmental change. Ecology Letters, 12(9), 942–948. doi: 10.1111/j.1461-0248.2009.01350.x

Both Christiaan, & Visser. E, M. (2001). Adjustment to climate change isconstrained by arrival date in along-distance migrant bird. *Nature*, *411*(May), 296–298.

Burton, O. J., Phillips, B. L., & Justin M. J. Travis. (2010). Trade-offs and the evolution of life-histories during range expansion. Ecology Letters, 1210–1220. doi: 10.1111/j.1461-0248.2010.01505.x

Carlson, S. M., Cunningham, C. J., & Westley, P. A. H. (2014). Evolutionary rescue in a changing world. Trends in Ecology & Evolution, 29(9), 521–530. doi: 10.1016/j.tree.2014.06.005

Farkas, T. E., Mononen, T., Comeault, A. A., Hanski, I., & Nosil, P. (2013). Evolution of camouflage drives rapid ecological change in an insect community. Current Biology, 23(19), 1835–1843. doi: 10.1016/j.cub.2013.07.067

Forsman, A. (2014). Effects of genotypic and phenotypic variation on establishment are important for conservation, invasion, and infection biology. Proceedings of the National Academy of Sciences of the United States of America, 111(1), 302–307. doi: 10.1073/pnas.1317745111

Grant, P. R., & Grant, B. R. (2002). Unpredictable evolution in a 30-year study of Darwin’s finches. Science, 296(5568), 707–711. doi: 10.1126/science.1070315

Hairston, N. G., Ellner, S. P., Geber, M. A., Yoshida, T., & Fox, J. A. (2005). Rapid evolution and the convergence of ecological and evolutionary time. Ecology Letters, 8(10), 1114–1127. doi: 10.1111/j.1461-0248.2005.00812.x

Hanski, I., & Saccheri, I. (2006). Molecular-level variation affects population growth in a butterfly metapopulation. PLoS Biology, 4(5), 719–726. doi: 10.1371/journal.pbio.0040129

Hughes, A. R., & Stachowicz, J. J. (2004). Genetic diversity enhances the resistance of a seagrass ecosystem to disturbance. *Proceedings of the National Academy of Sciences of the United States of America*, *101*(24), 8998–9002. doi: 10.1073/pnas.0402642101

Kearney, M. R., & White, C. R. (2012). Testing metabolic theories. *American Naturalist*, *180*(5), 546–565. doi: 10.1086/667860

Kinnison, M. T., Unwin, M. J., & Quinn, T. P. (2003). Migratory costs and contemporary evolution of reproductive allocation in male chinook salmon. *Journal of Evolutionary Biology*, *16*(6), 1257–1269. doi: 10.1046/j.1420-9101.2003.00631.x

Kinnison, Michael T., Unwin, M. J., Hendry, A. P., & Quinn, T. P. (2001). Migratory costs and the evolution of egg size and number in introduced and indigenous salmon populations. *Evolution*, *55*(8), 1656–1667. doi: 10.1111/j.0014-3820.2001.tb00685.x

Kinnison, Michael T., Unwin, M. J., & Quinn, T. P. (2008). Eco-evolutionary vs. habitat contributions to invasion in salmon: Experimental evaluation in the wild. *Molecular Ecology*, *17*(1), 405–414. doi: 10.1111/j.1365-294X.2007.03495.x

Kirkpatrick, M., & Barton, N. H. (1997). Evolution of a Species' Range. *The American Naturalist*, *150*(1), 1–23. doi: 10.1086/286054

Phillips, Ben L. (2009). The evolution of growth rates on an expanding range edge. *Biology Letters*, *5*(6), 802–804. doi: 10.1098/rsbl.2009.0367

Phillips, Benjamin L., Brown, G. P., Webb, J. K., & Shine, R. (2006). Invasion and the evolution of speed in toads. *Nature*, *439*(7078), 803–803. doi: 10.1038/439803a

Pörtner, H. O., & Knust, R. (2007). Climate Change Affects Marine Fishes Through the Oxygen Limitation of Thermal Tolerance. *Science*, *315*(5808), 95–97. doi: 10.1126/science.1135471 Quinn, T. P., Kinnison, M. T., & Unwin, M. J. (2001). Evolution of chinook salmon (Oncorhynchus tshawytscha) populations in New Zealand: Pattern, rate, and process. In *Entomologia Experimentalis et Applicata* (Vol. 103, pp. 493–513). doi: 10.1007/978-94-010-0585-2_30

Reznick, D., Bryant, M. J., & Bashey, F. (2002). r- and K-selection revisited: The role of population regulation in life-history evolution. *Ecology*, *83*(6), 1509–1520. doi: 10.1890/0012-9658(2002)083[1509:raksrt]2.0.co;2

Schindler, D. E., Hilborn, R., Chasco, B., Boatright, C. P., Quinn, T. P., Rogers, L. A., & Webster, M. S. (2010). Population diversity and the portfolio effect in an exploited species. *Nature*, *465*(7298), 609–612. doi: 10.1038/nature09060

Sinervo, B., Svensson, E., & Comendant, T. (2000). 35023149. *Nature*, *406*(406), 985–988.

Van Der Meer, J. (2006). Metabolic theories in ecology. *Trends in Ecology and Evolution*, *21*(3), 136–140. doi: 10.1016/j.tree.2005.11.004

Zamorano, L. S., Gompert, Z., Fronhofer, E. A., Feder, J. L., & Nosil, P. (2023). A stabilizing eco-evolutionary feedback loop in the wild. *Current Biology*, *33*(15), 3272-3278.e3. doi: 10.1016/j.cub.2023.06.056