

Fundamentals of Ecology

Week 5, Ecology Lecture 1

Cara Brook

February 2, 2023

Where are we headed?

Week	Mon/Tues Lab	Tues Lecture	Thurs Lecture
1	0: Intro to R	Jan 3: Evolution History	Jan 5: Evolution Evidence
2	1: Hardy-Weinberg	Jan 10: Microevolution 1	Jan 12: Microevolution 2
3	2: Microevolution	Jan 17: Microevolution 3	Jan 19: Phylogenetics
4	3: Phylogenetics	Jan 24: Molecular Evolution	Jan 26: Sexual Selection
5	4: Evolution paper	Jan 31: Speciation	Feb 2: Ecology & Population Growth
6	5: Population Growth	Feb 7: Midterm	Feb 9: Single Species Population Growth & Regulation
7	6: Population Regulation	Feb 14: Species Interactions 1	Feb 16: Species Interactions 2
8	7: Disease Dynamics	Feb 21: Disease Dynamics as Population Biology 1	Feb 23: Disease Dynamics as Population Biology 2
9	8: Ecology paper	Feb 28: Community Assembly & Island Biogeography	Mar 2: Critical Transitions & Conservation Interventions

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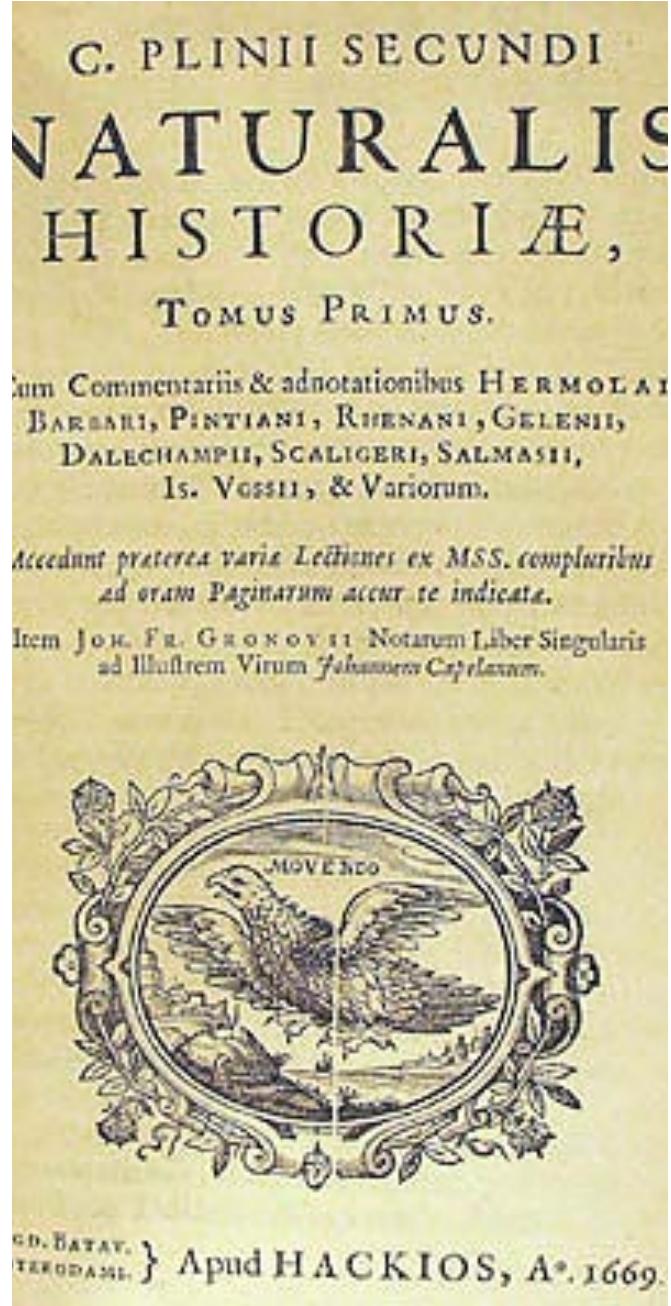
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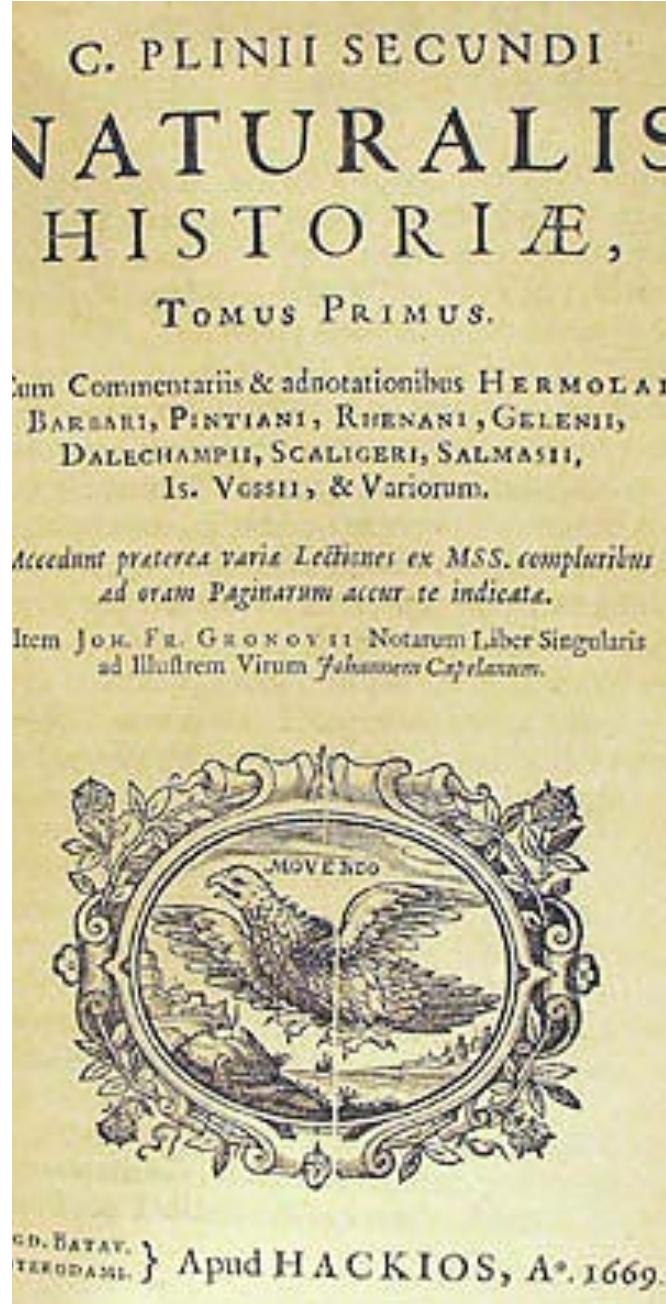
Natural history is the observational study of the living things on planet Earth.

Is natural history science?

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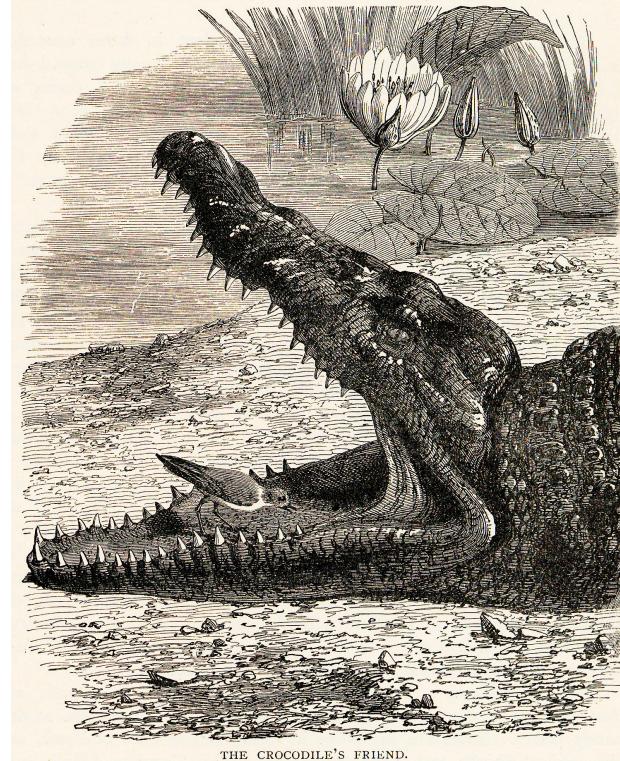
Science: the **systematic observation** of natural events and conditions in order to discover facts about them and to **formulate laws and principles** based on these facts.

– *Academic Press Dictionary of Science & Technology*

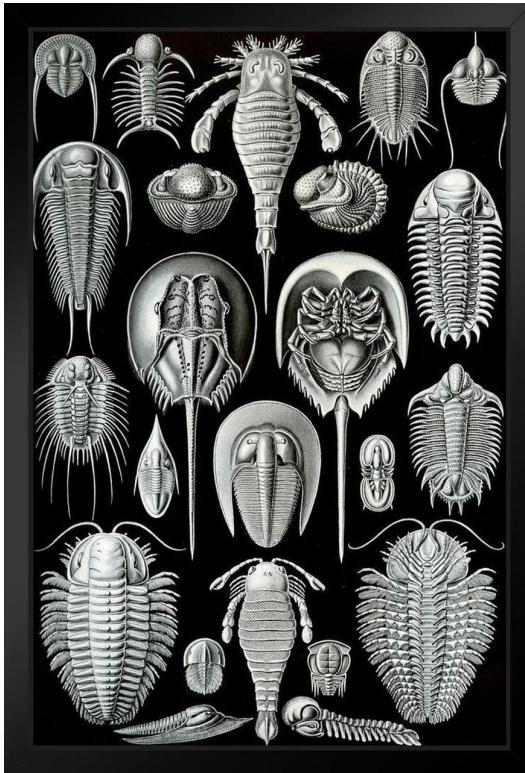


Natural history gave way to the **natural sciences** when those observations became **systematic** and were used to support **general laws and principles** describing the natural world.

Ecology is the study of the
interactions of **organisms** with
each other and their
environment.



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interactions of **organisms** with
each other and their
environment.



oikos = 'house'
+ *logia* = 'study of'

ecology

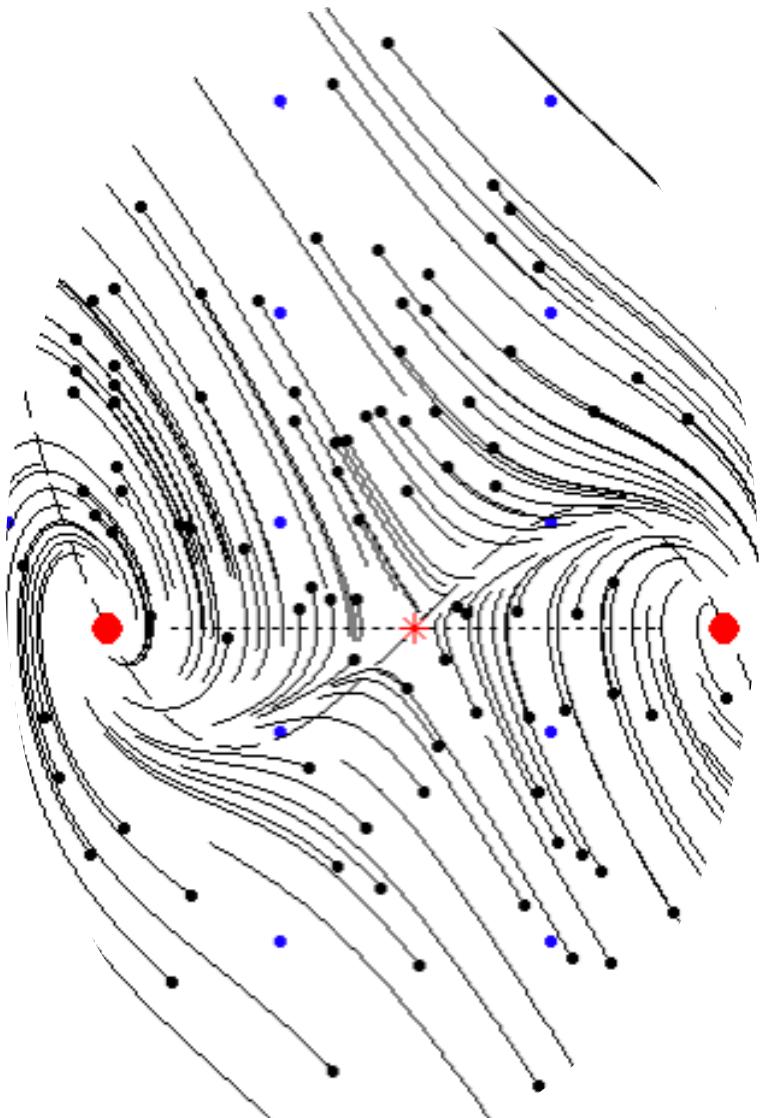
- 1866 Ernst Haeckel

“Ecology has a synonym which is **ALL.**”

-John Steinbeck

The Log from the Sea of Cortez (1941)





Ecology is the study of
the **interactions** of
organisms with each
other and their
environment.

As a science, ecology
uses **models** to formalize
general **laws and**
principles describing the
natural world.



What is a model?

What is a model? an abstract representation of a phenomenon

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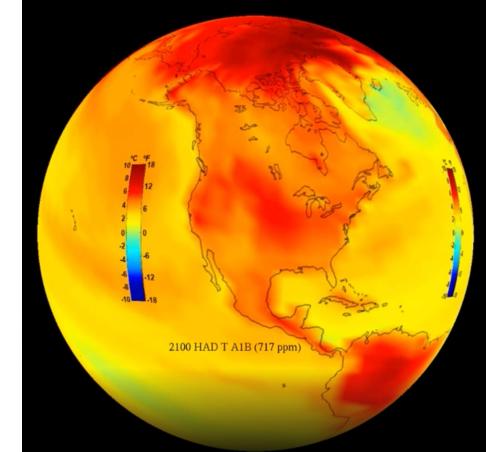
Human



Solar System



Climate



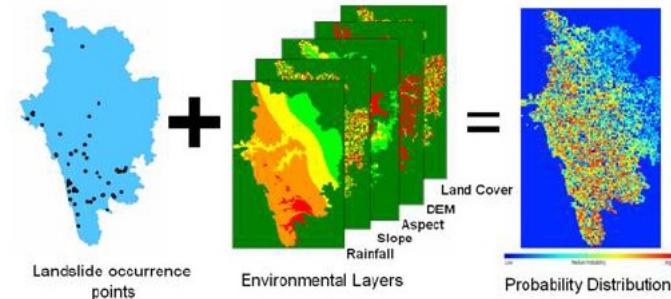
Human Genetics



Human Disease



Species Distribution

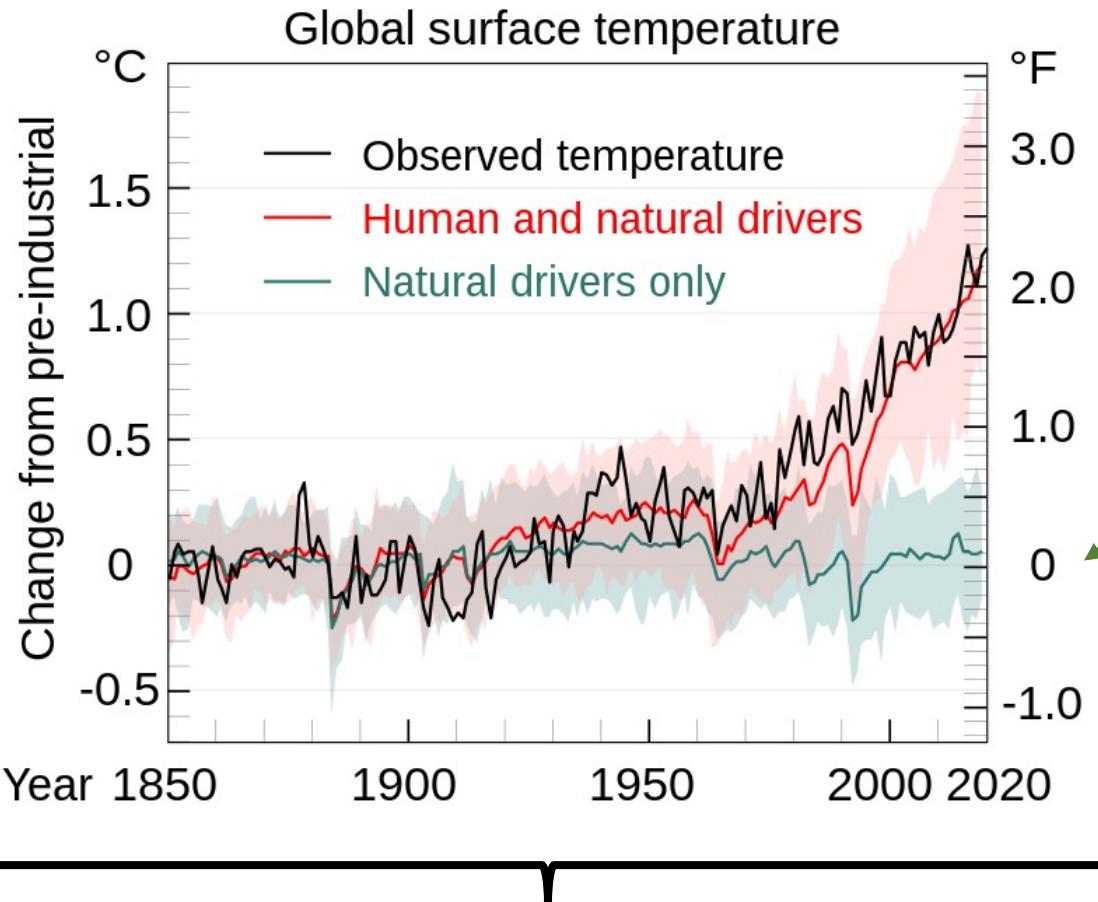


Why build models?

Why build models? to explain and predict

Why build models?

to explain and predict



Models produce 'simulated data' that is compared against the observed data.

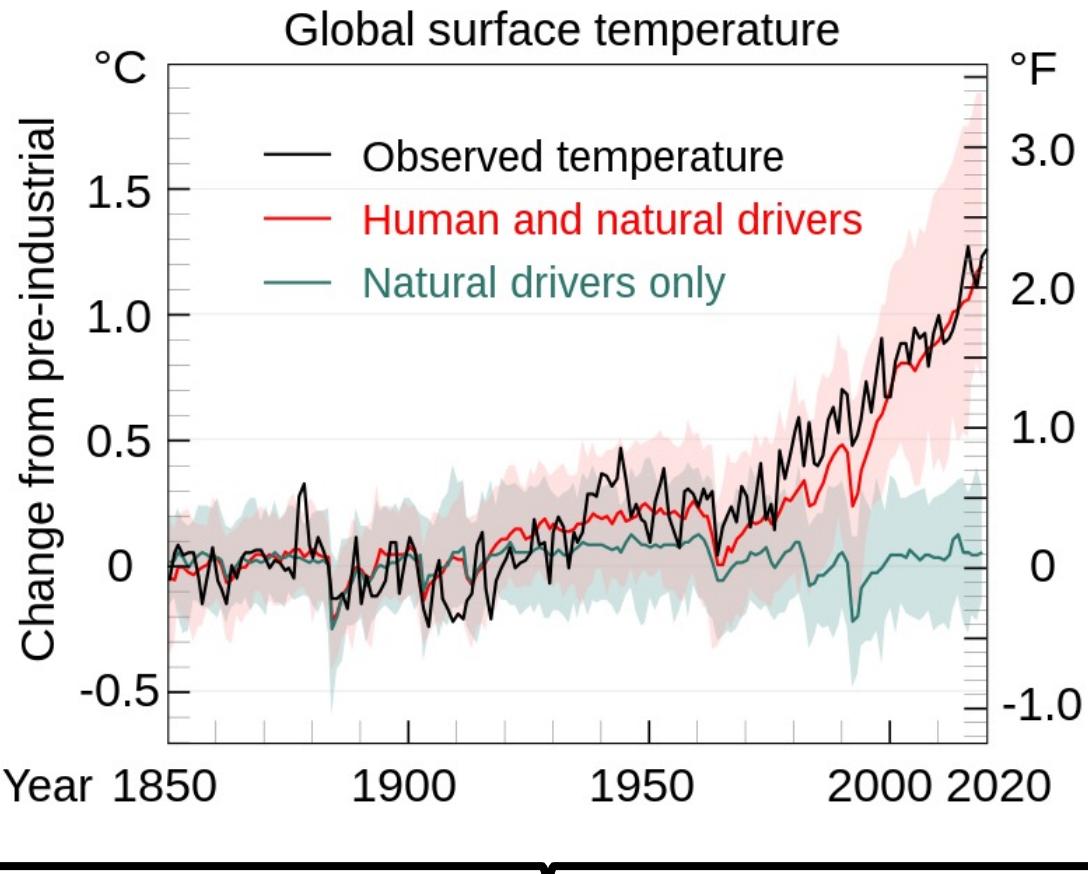
The process of adjusting the model to more closely match the data is called 'model fitting.'

explain

Why build models?

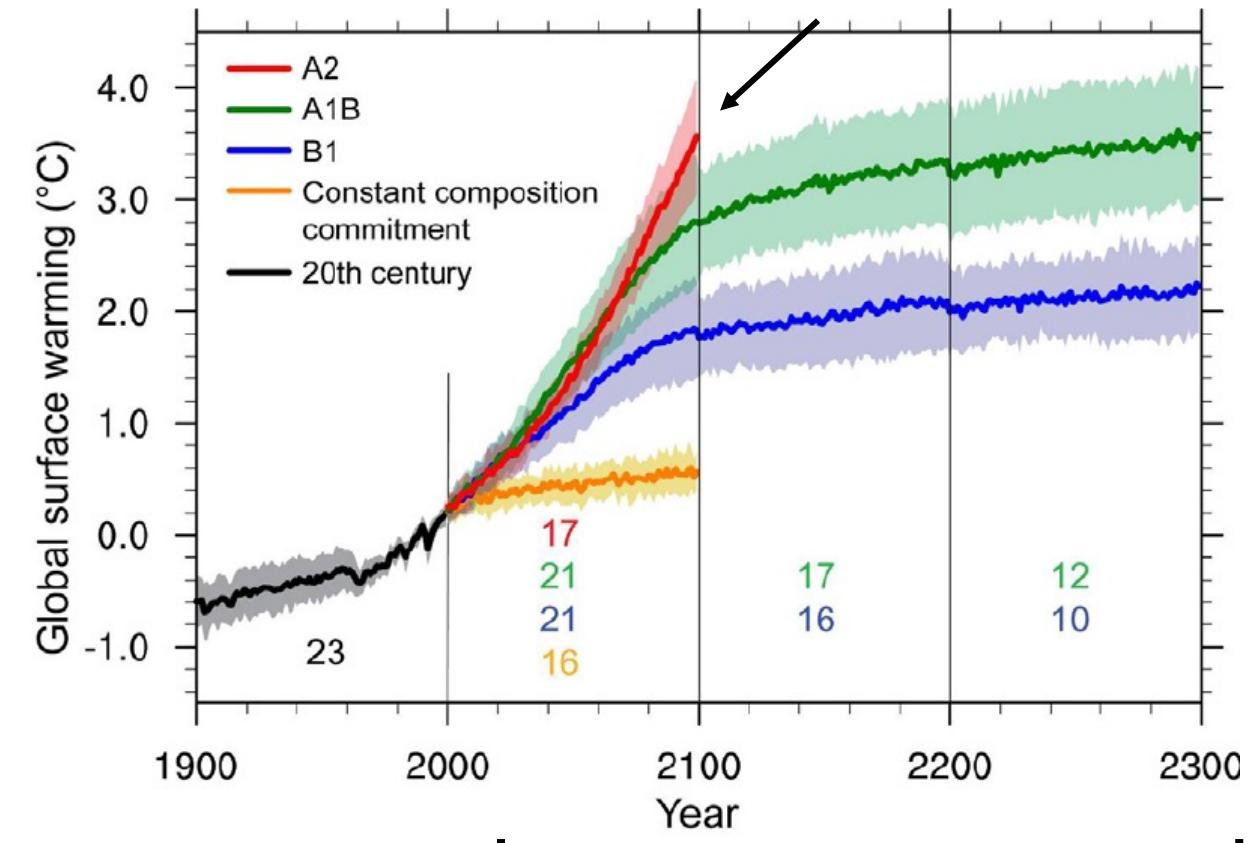
to explain and predict

Fitted models can then be used to “predict” the future, under different conditions.



(IPCC 2007)

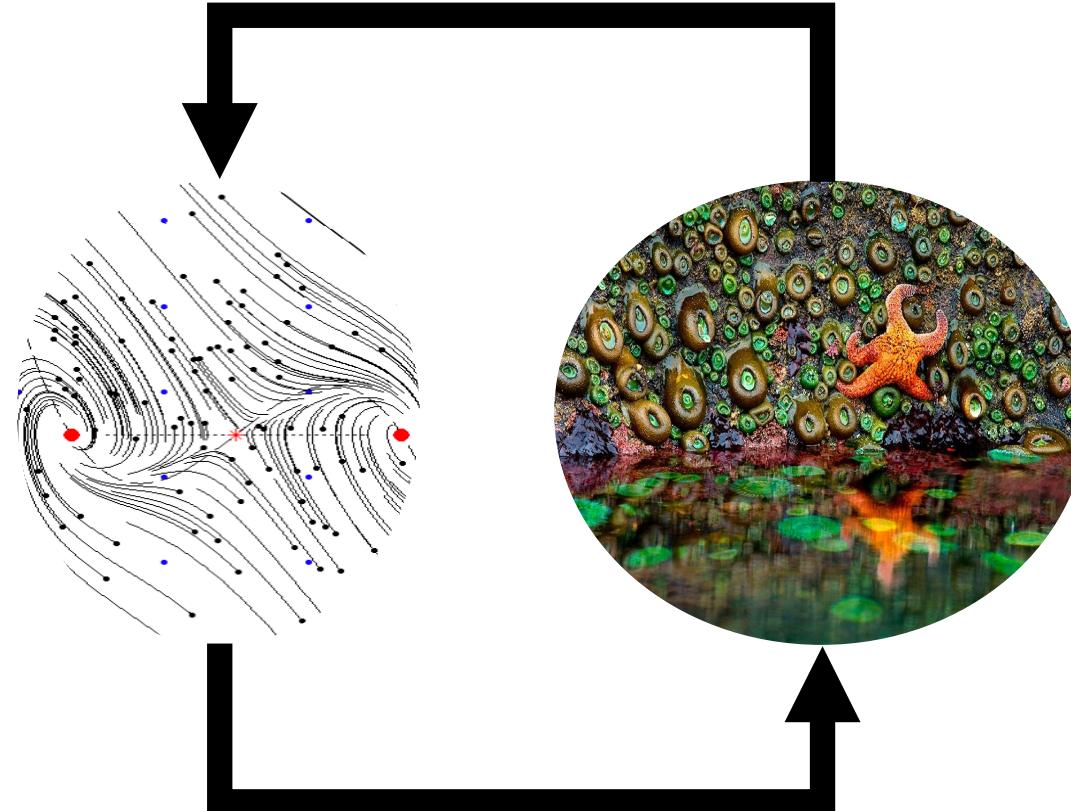
explain



predict

Two kinds of ecological models

Statistical Model
Pattern

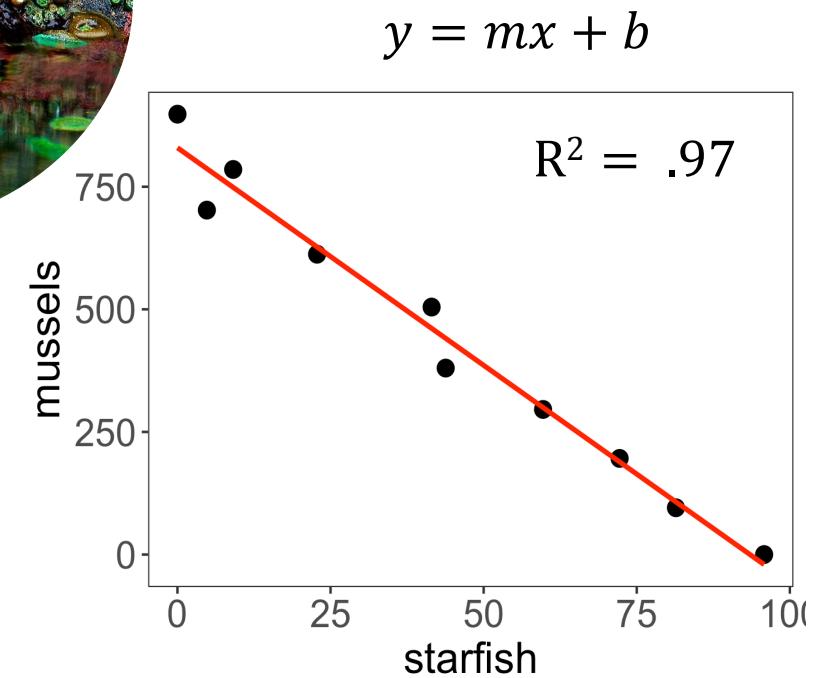
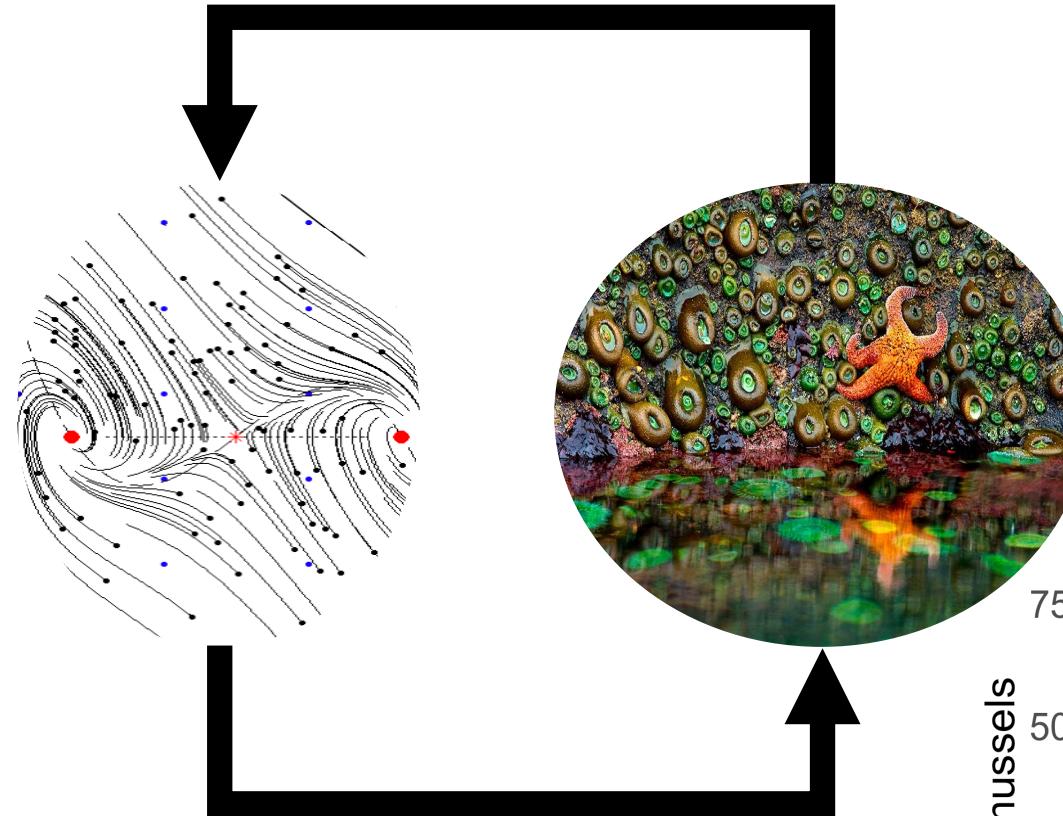


Population Model
Process

Two kinds of ecological models

Statistical Model *Pattern*

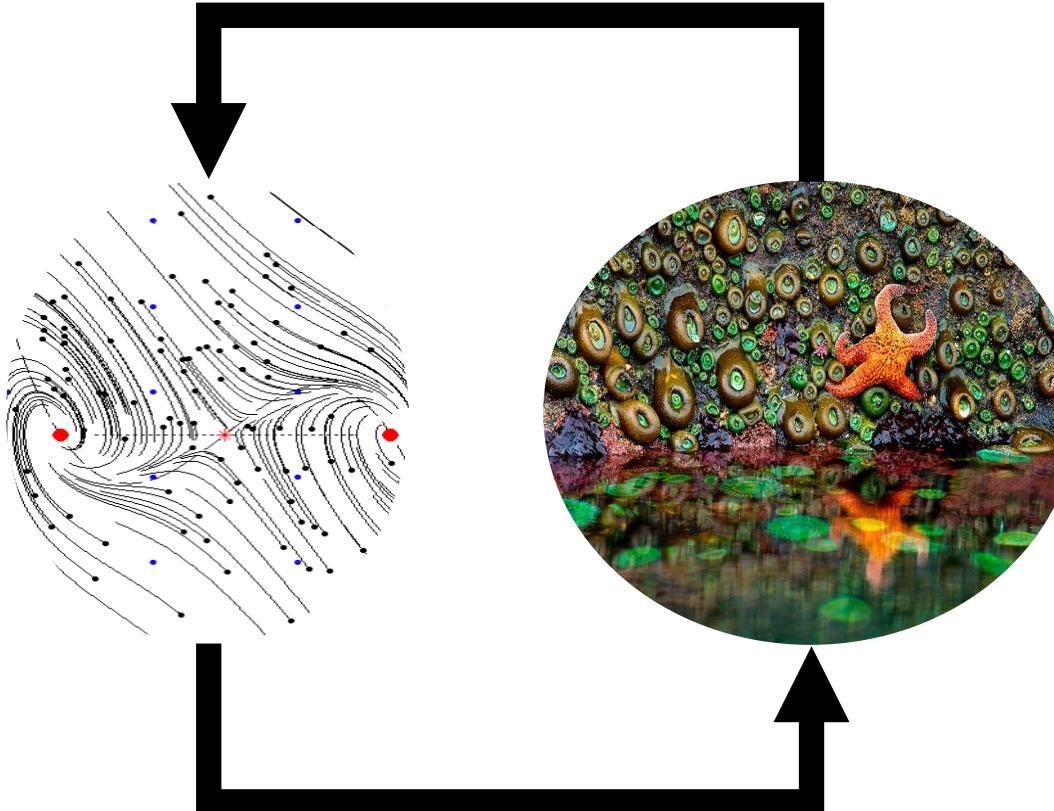
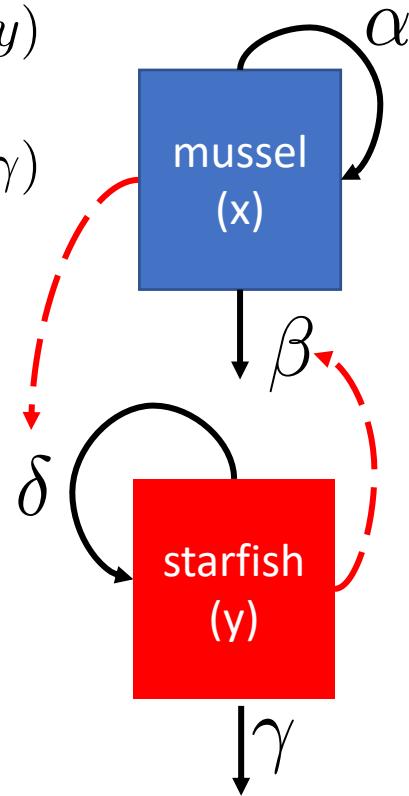
Population Model *Process*



Two kinds of ecological models

Statistical Model *Pattern*

$$\begin{aligned}\frac{dx}{dt} &= x(\alpha - \beta y) \\ \frac{dy}{dt} &= y(\delta x - \gamma)\end{aligned}$$

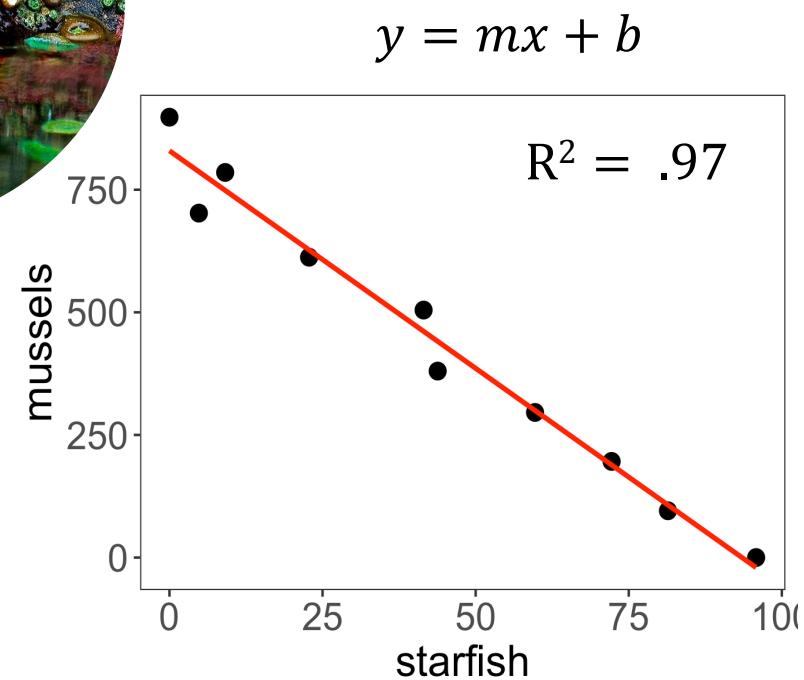
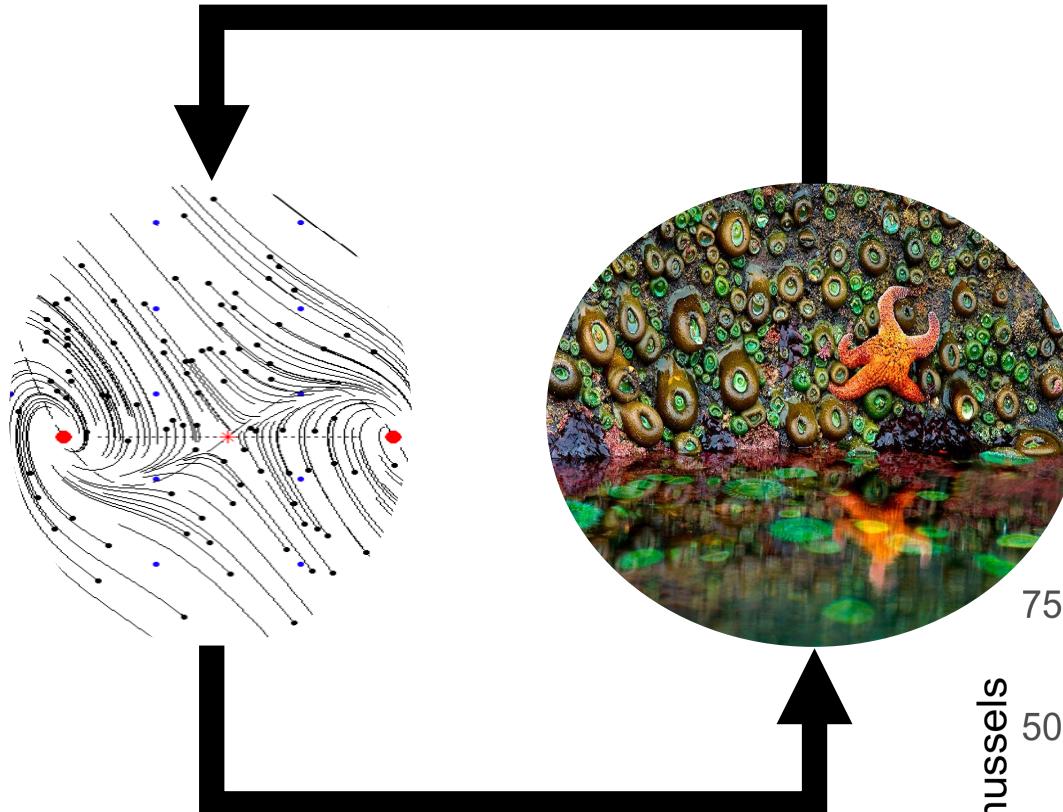
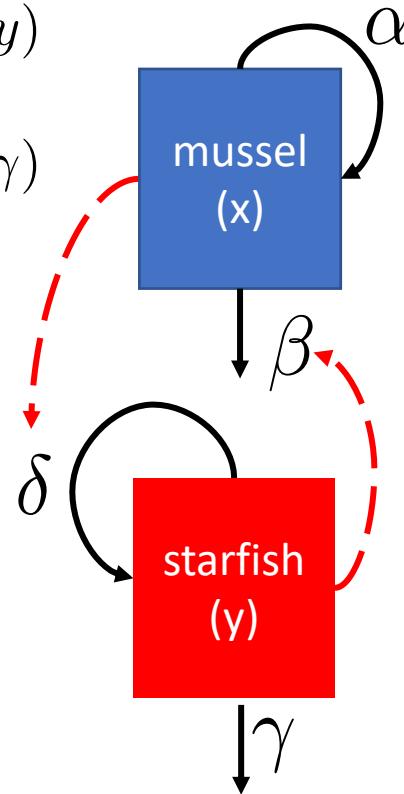


Population Model
Process

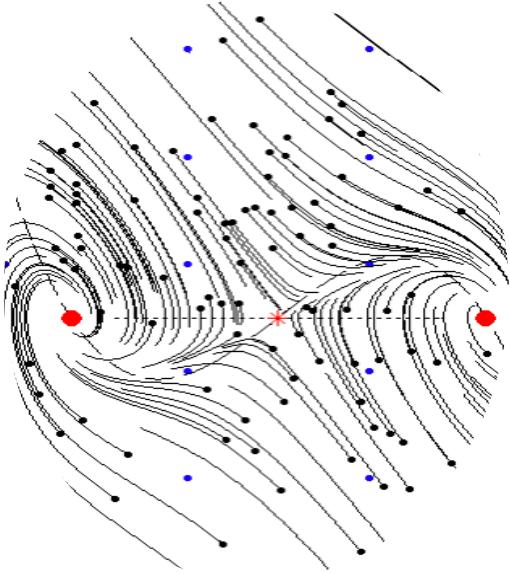
Two kinds of ecological models

Statistical Model Pattern

$$\frac{dx}{dt} = x(\alpha - \beta y)$$
$$\frac{dy}{dt} = y(\delta x - \gamma)$$



Population Model
Process



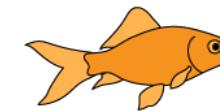
Ecology is the study of
the **interactions** of
organisms with each
other and their
environment.

dynamic
frequently changing

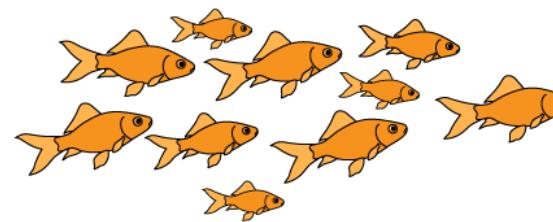
complex
many interacting parties



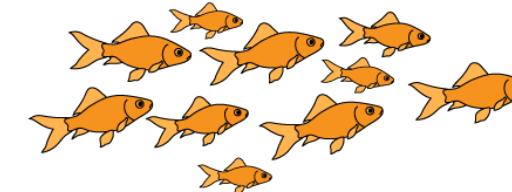
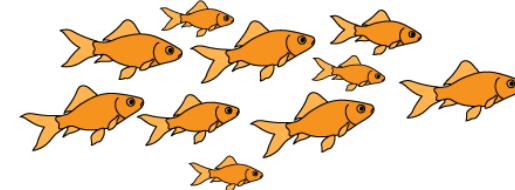
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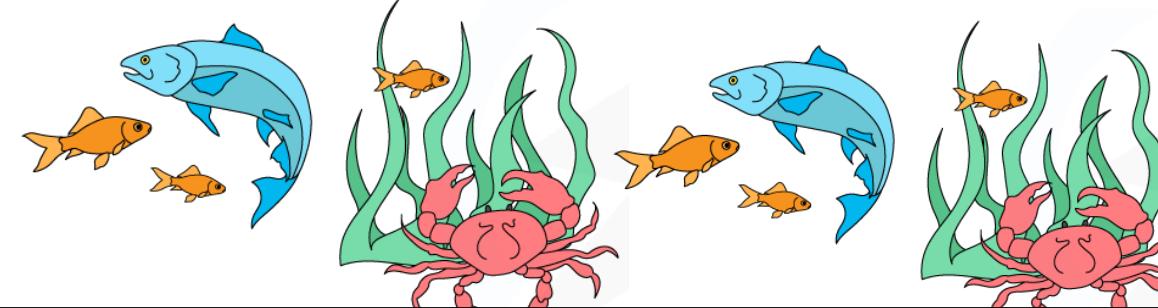
individual



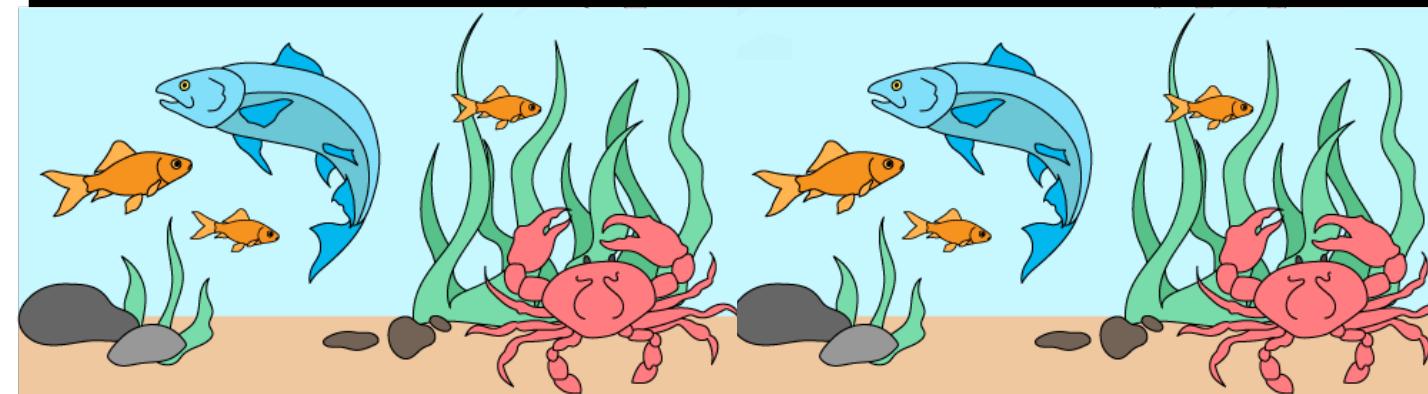
population



metapopulation

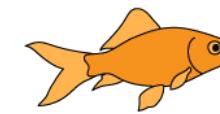


community



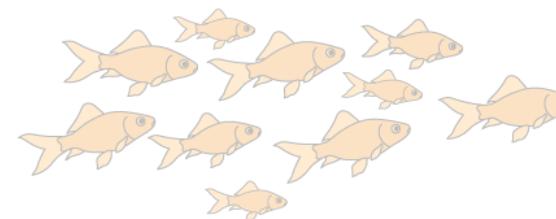
ecosystem

individual

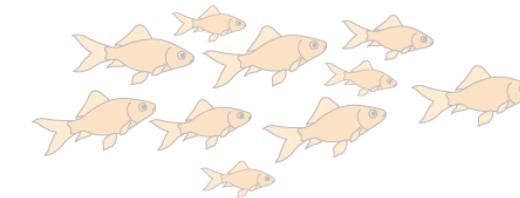
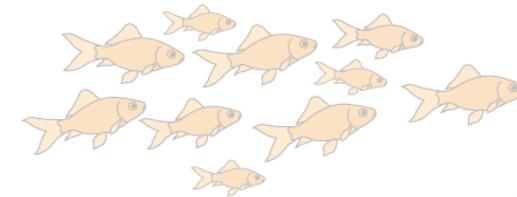


Individual:
metabolism, behavior,
life history.

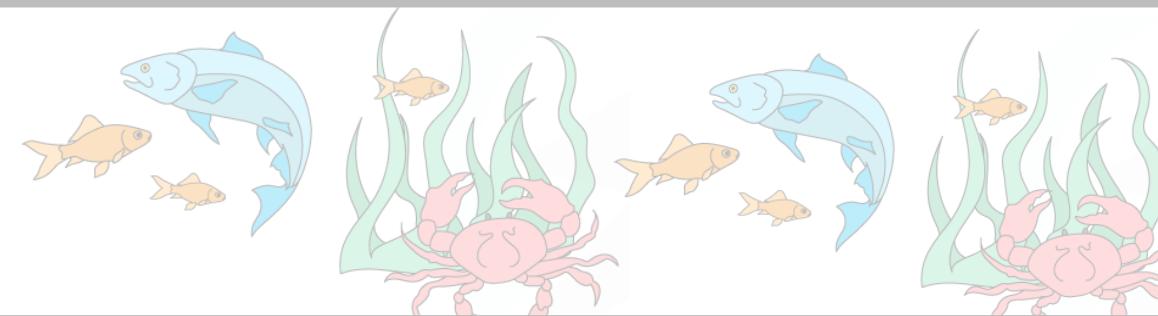
interactions of an
individual with the
environment



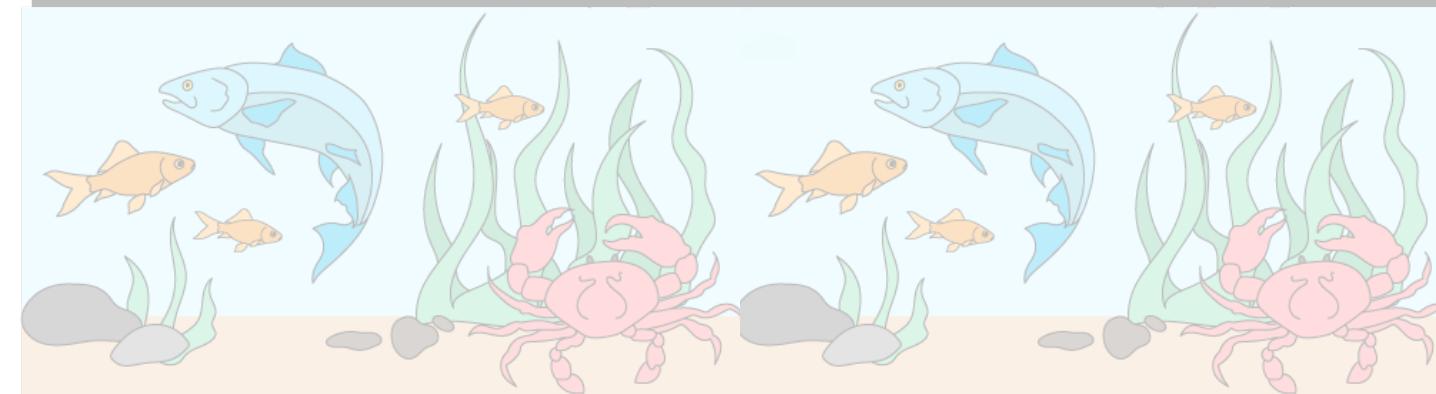
population



metapopulation

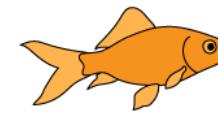


community



ecosystem

individual



Individual:
metabolism,
behavior, life history.

population

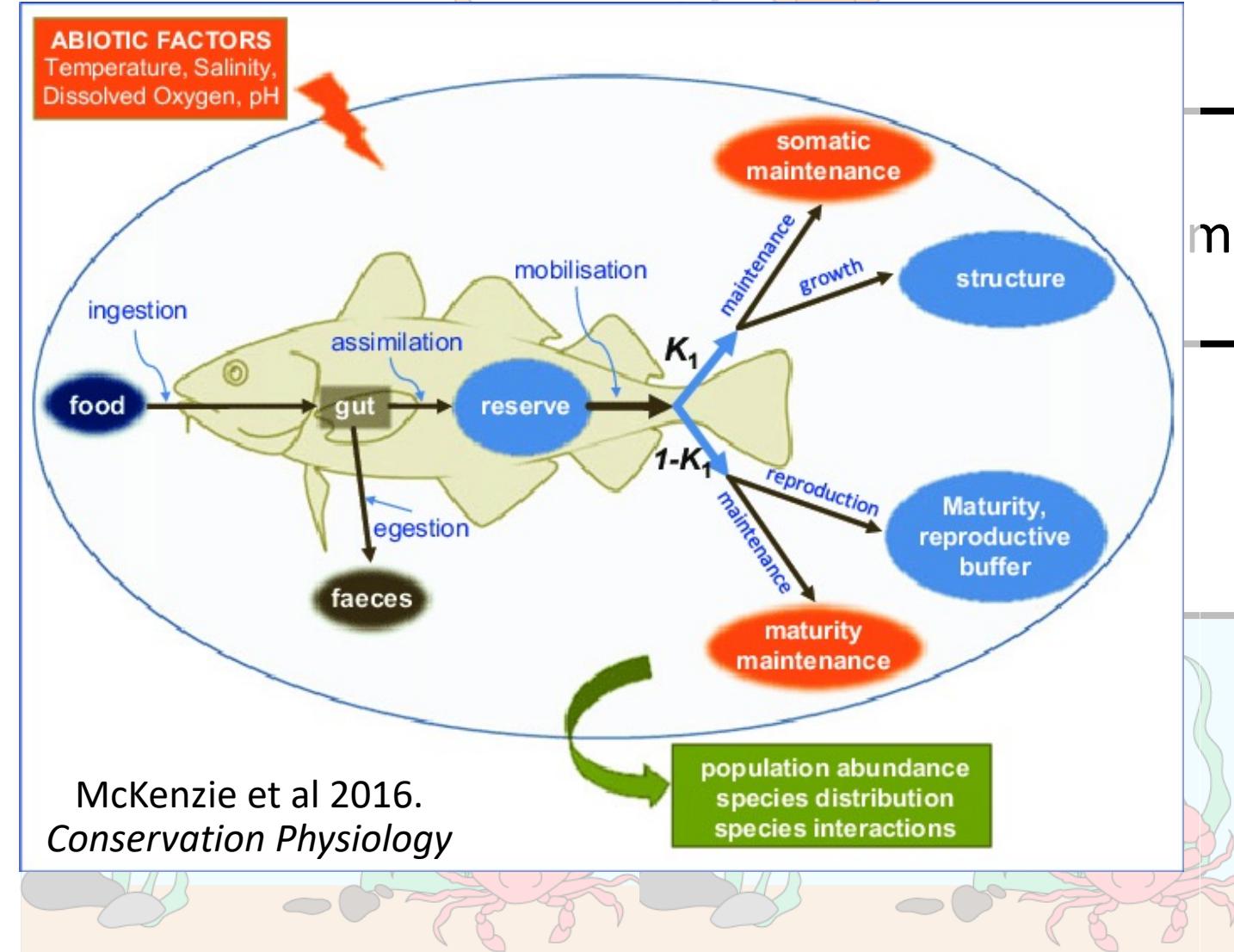
Dynamic Energy
Budget (DEB) Model

metapopulation

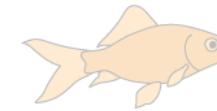
*How does a fish's
metabolism **change**
with temperature?*

community

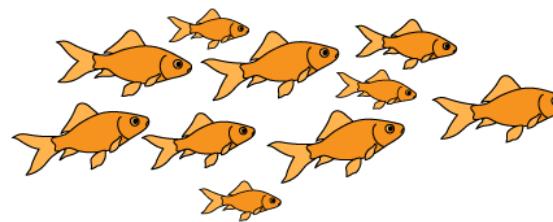
ecosystem



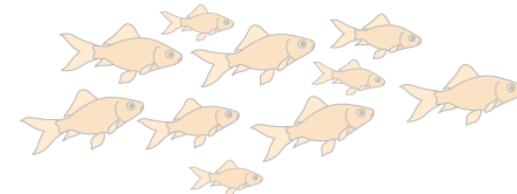
Population = multiple individuals of the same species (**conspecifics**) in the same habitat



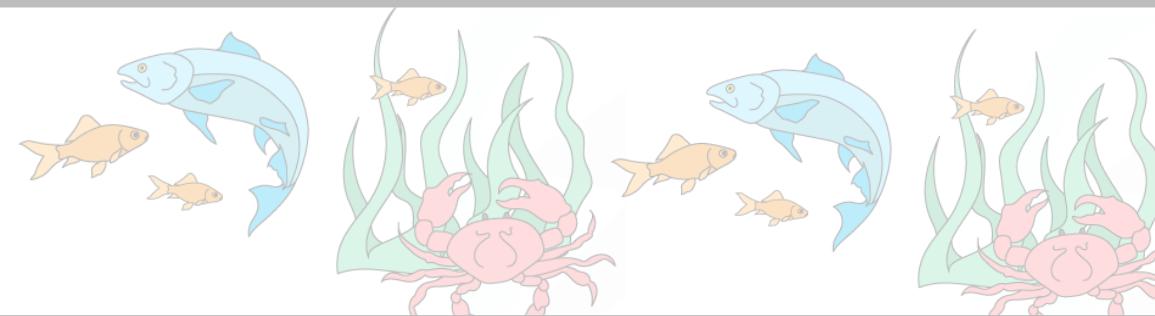
individual



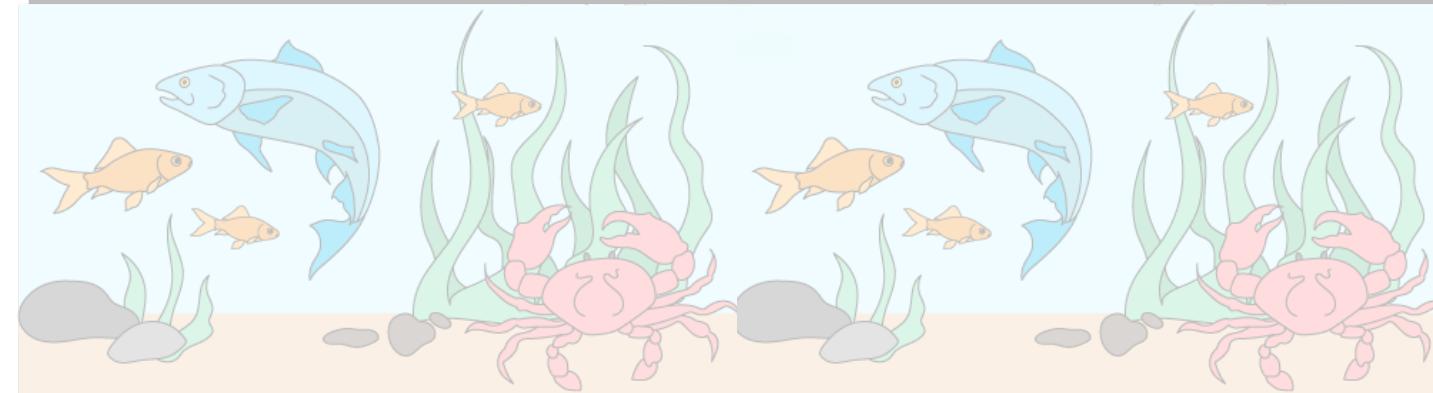
population



metapopulation

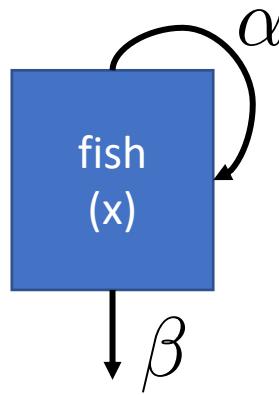


community

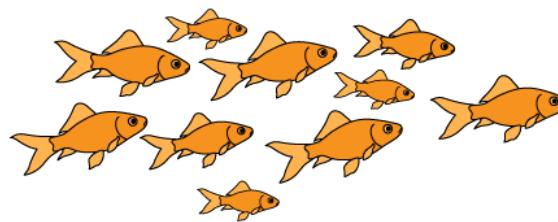


ecosystem

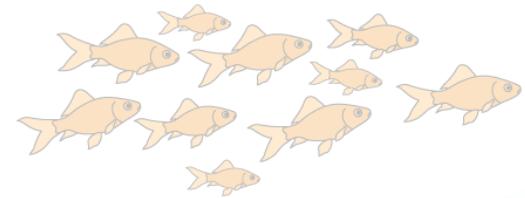
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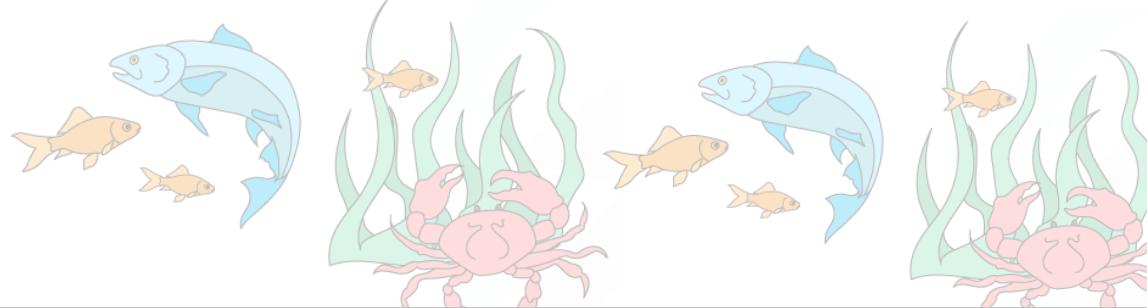
individual



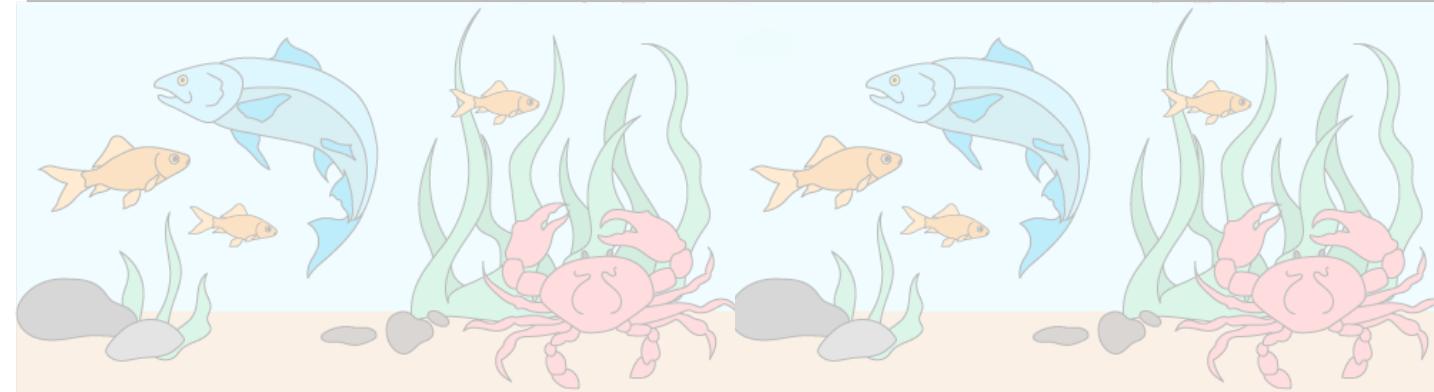
population



metapopulation



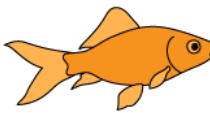
community



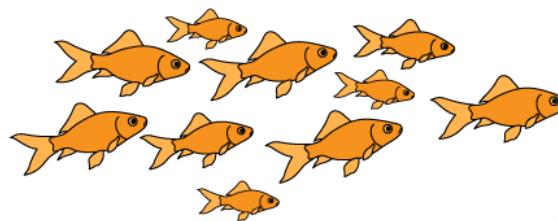
ecosystem

*How does the abundance of fish **change** through time?*

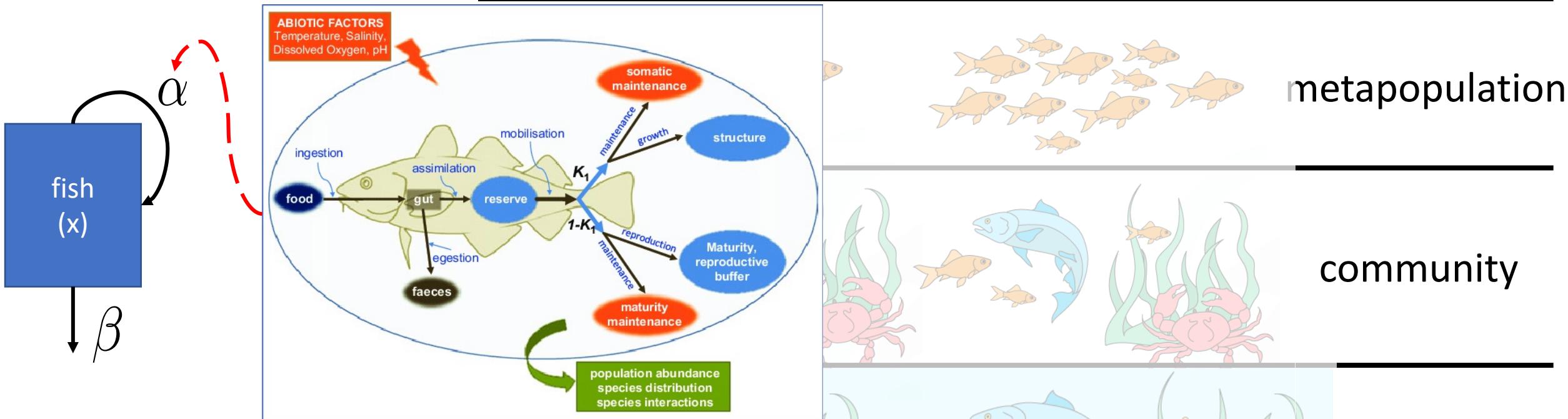
Nested Models, including a class of model known as **Integral Projection Models** (IPMs), link individual- and population-level processes



individual



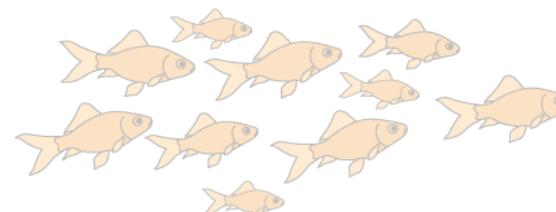
population



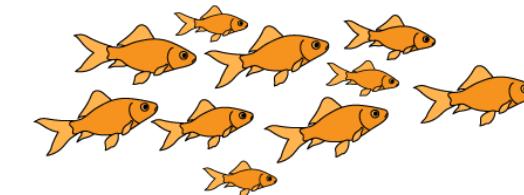
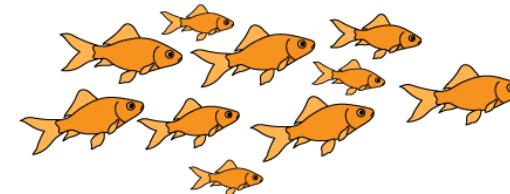
How does the abundance of fish **change** through time as temperature **changes** metabolism?

Metapopulation = sub-populations of conspecifics connected by migration or dispersal

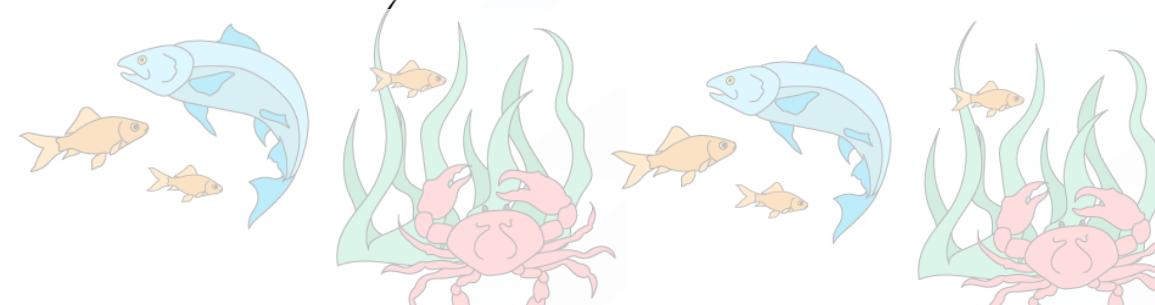
individual



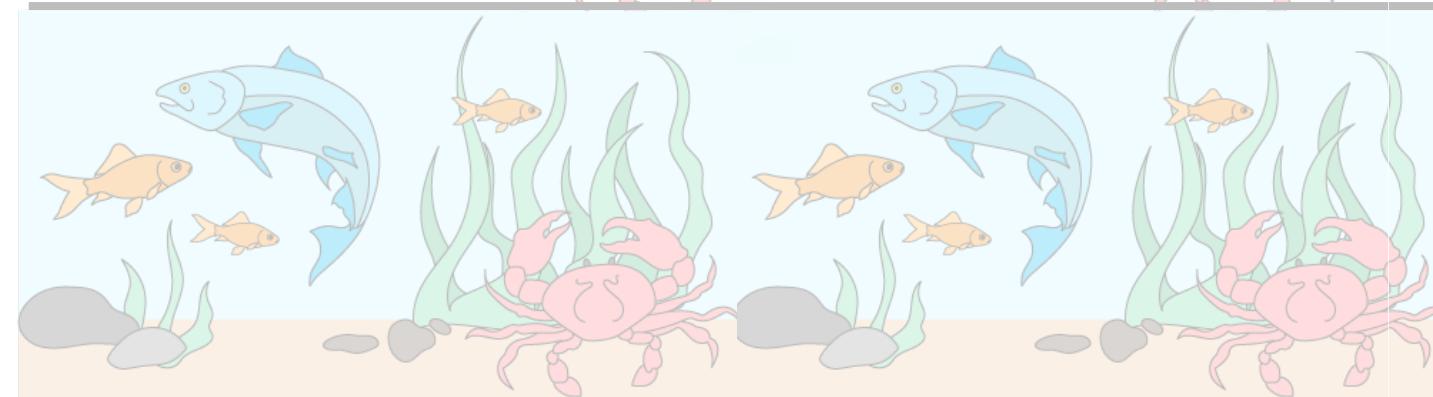
population



metapopulation



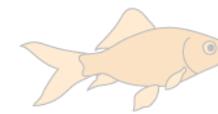
community



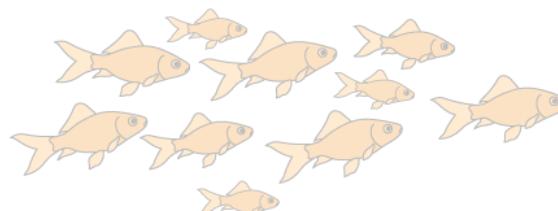
ecosystem

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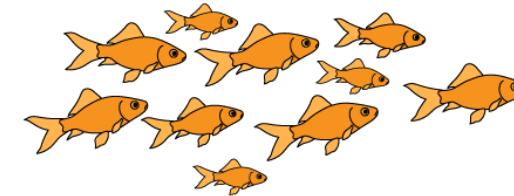
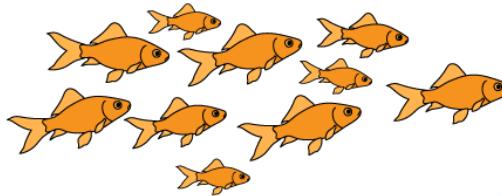
individual



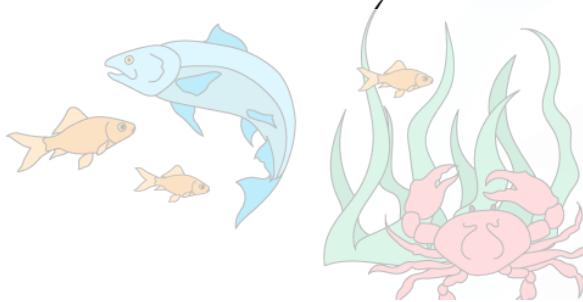
population



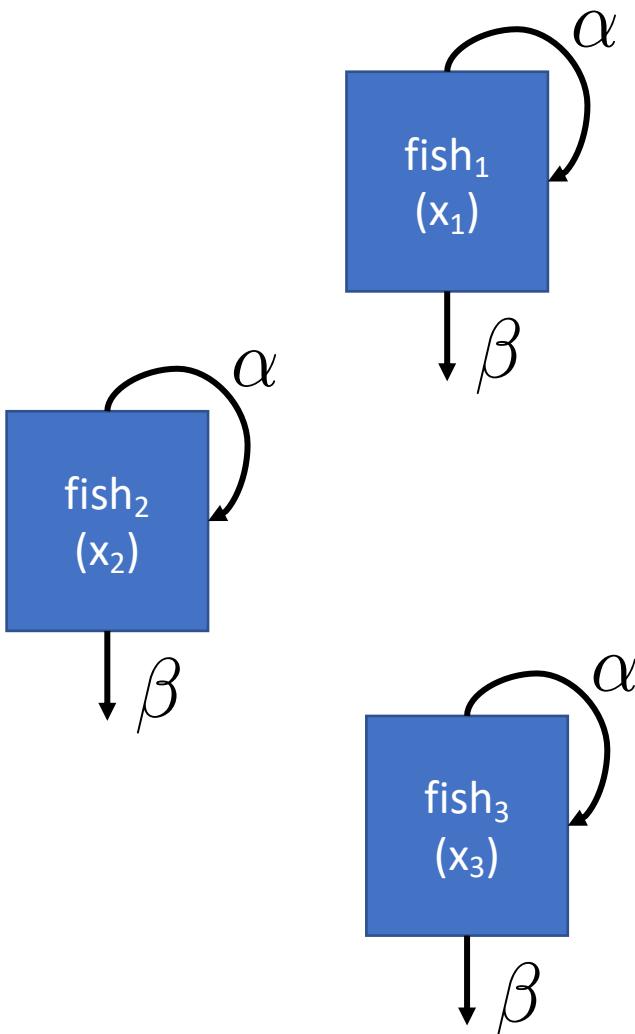
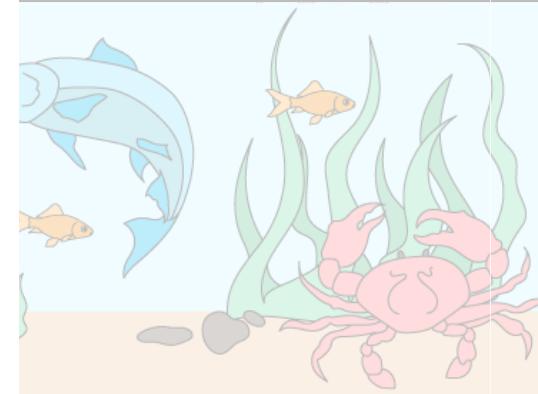
metapopulation



community



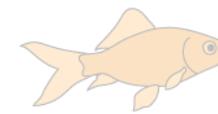
ecosystem



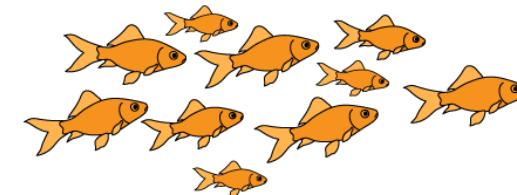
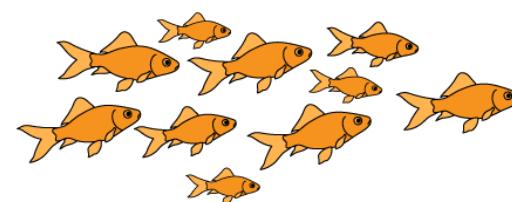
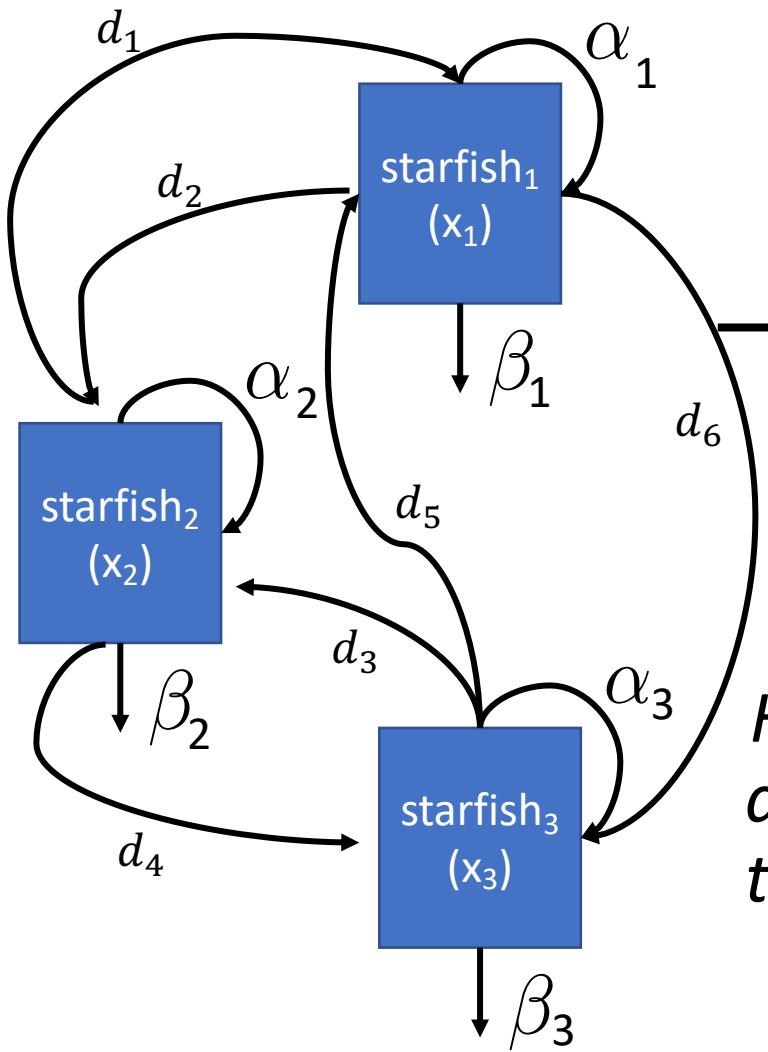
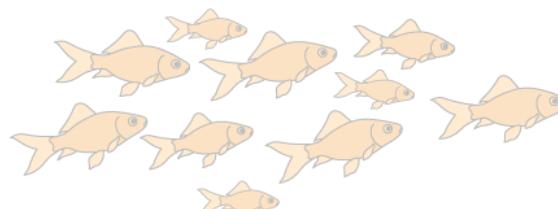
*How do the abundances of different subpopulations of the same fish **vary** in space [and time]?*

Metapopulation = sub-populations of conspecifics connected by migration or dispersal

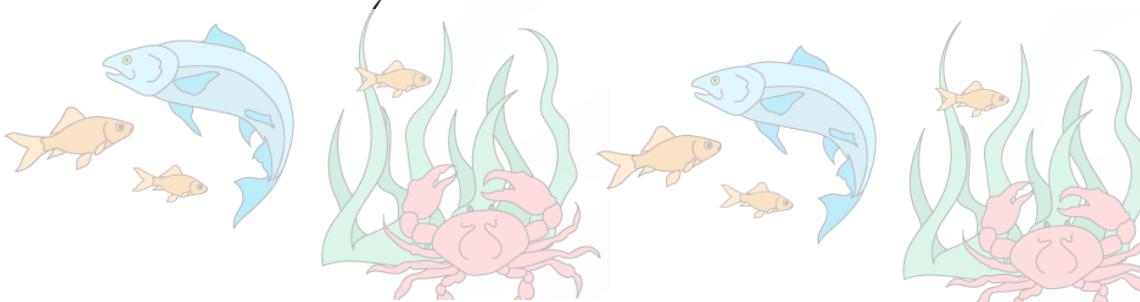
individual



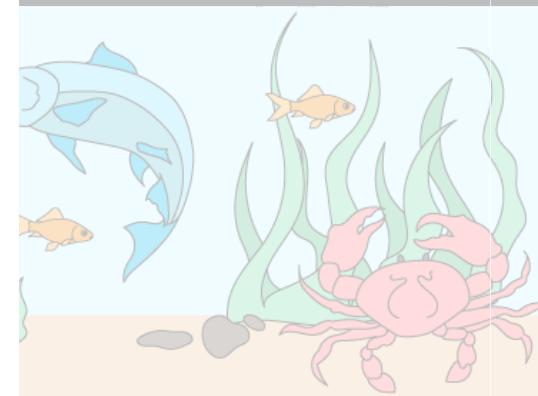
population



metapopulation



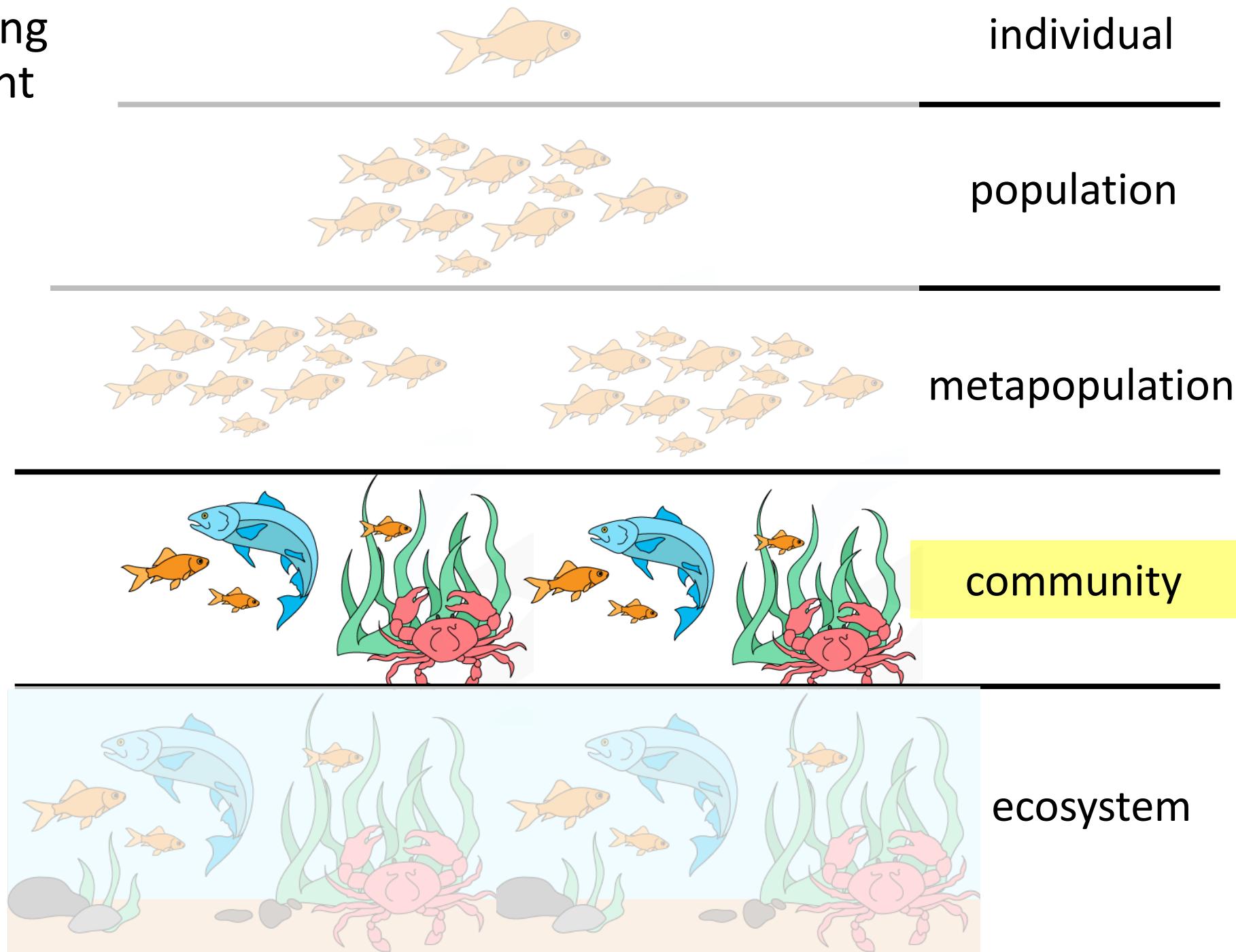
community



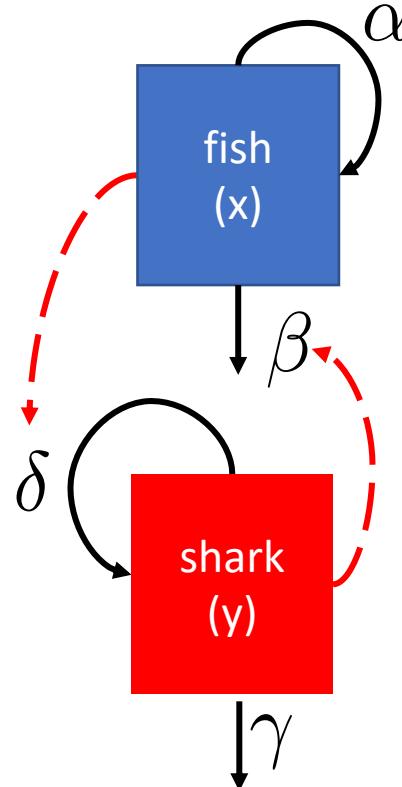
ecosystem

*How do the abundances of different subpopulations of the same fish **vary** in space [and time]?*

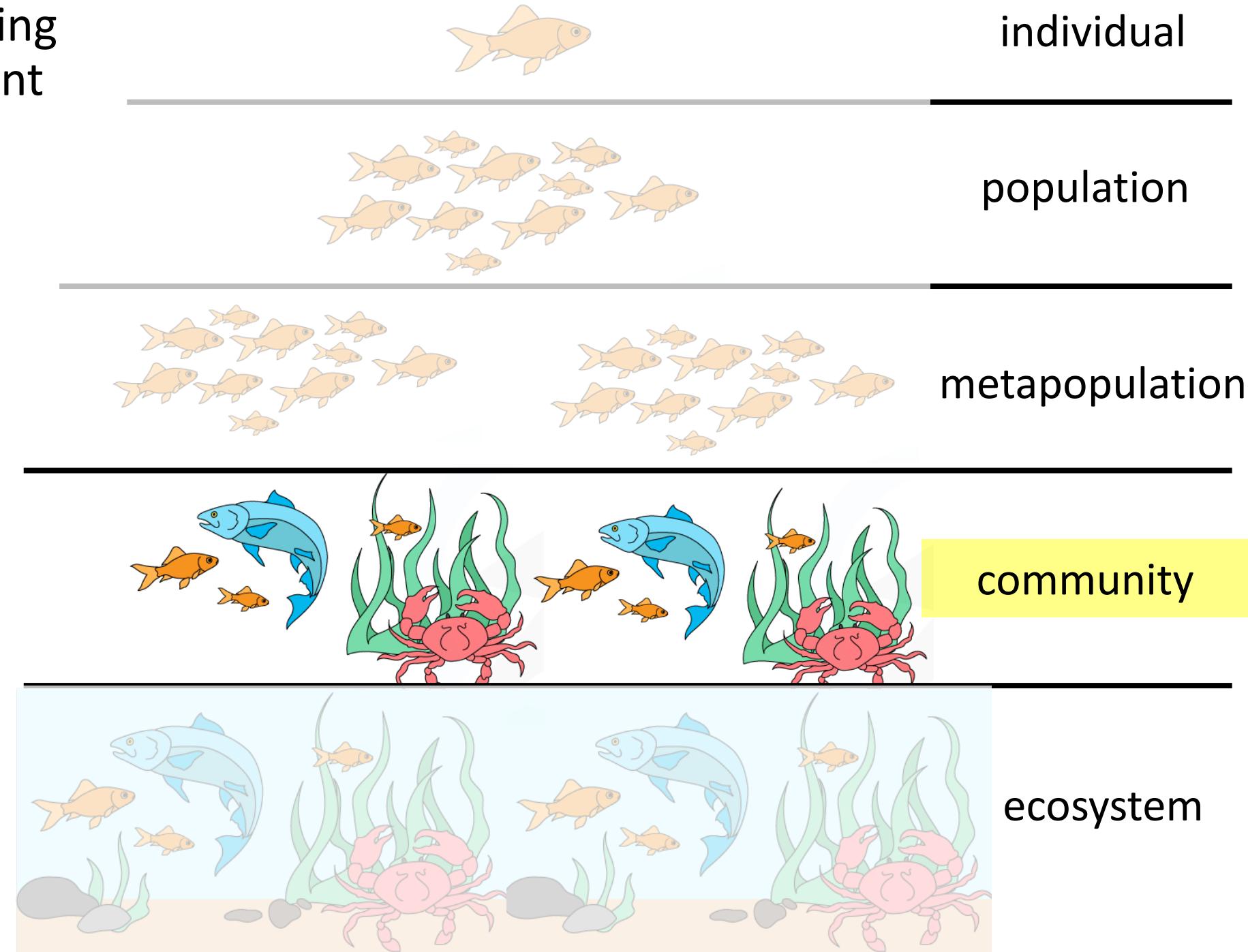
Community = interacting populations of different species



Community = interacting populations of different species

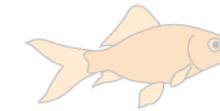


How does fish abundance **vary** with changes in shark abundance?

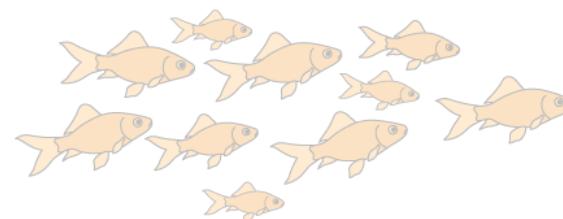


Ecosystem = communities interacting with the abiotic environment

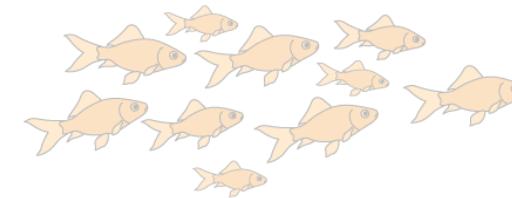
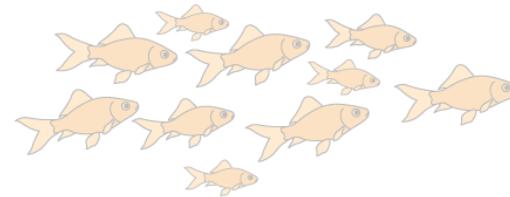
individual



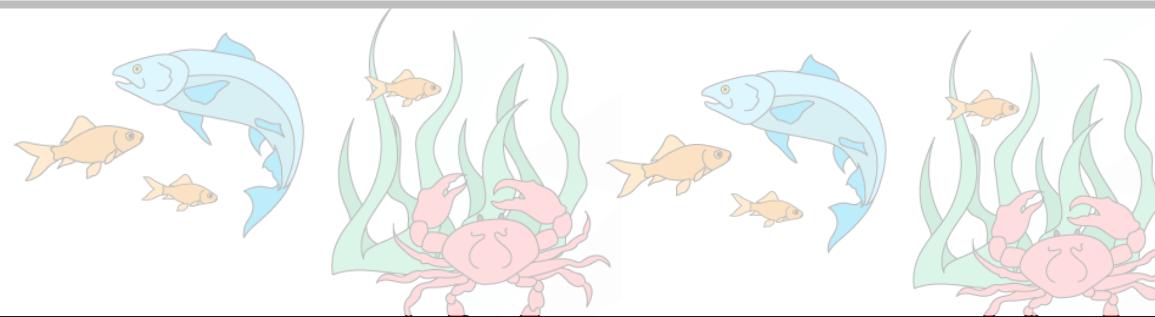
population



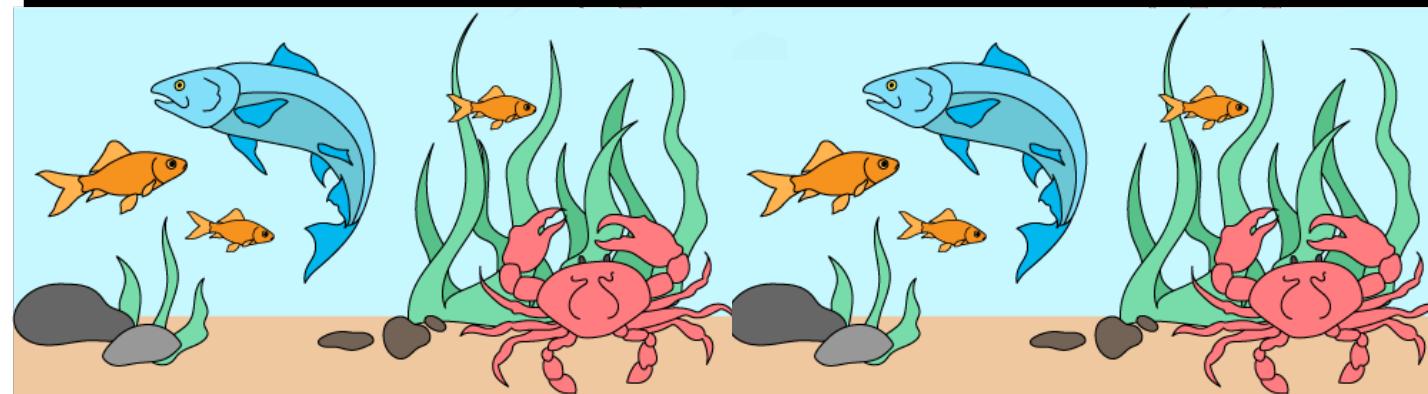
metapopulation



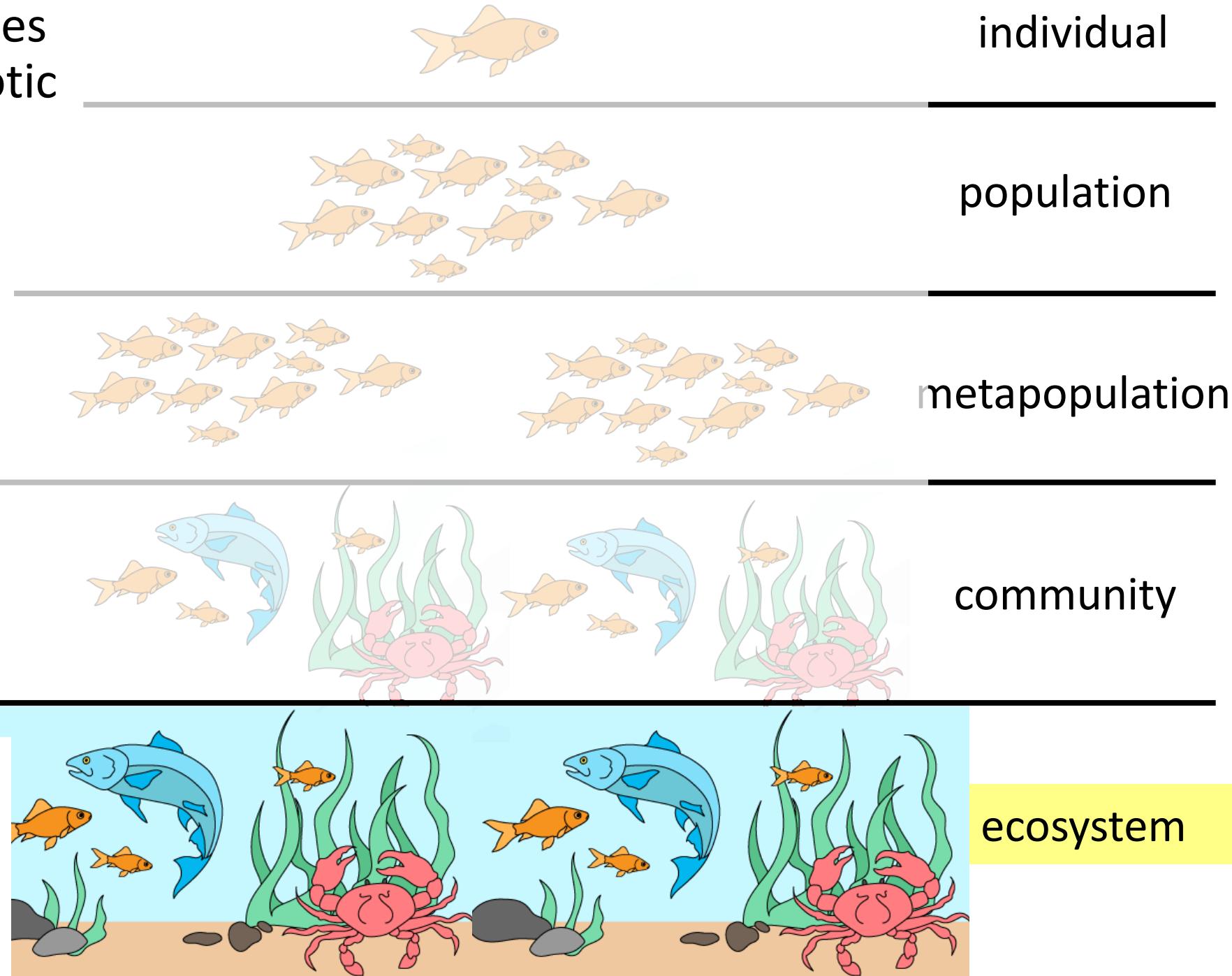
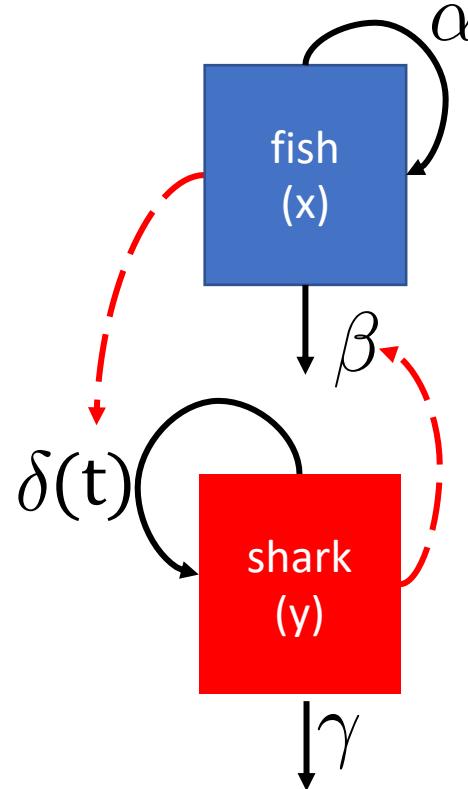
community



ecosystem



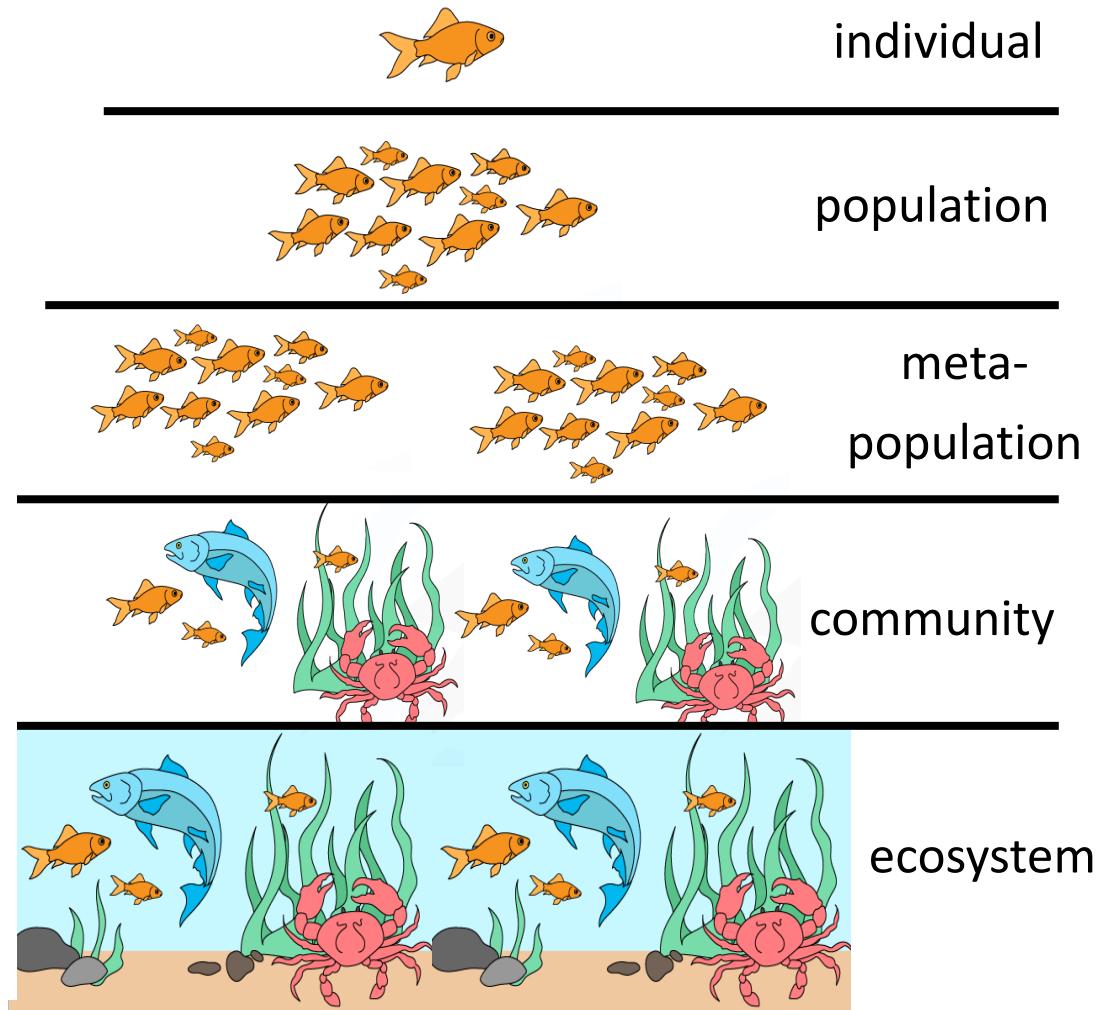
Ecosystem = communities interacting with the abiotic environment



How does fish abundance **vary** with changes in shark birth rates with **temperature**?

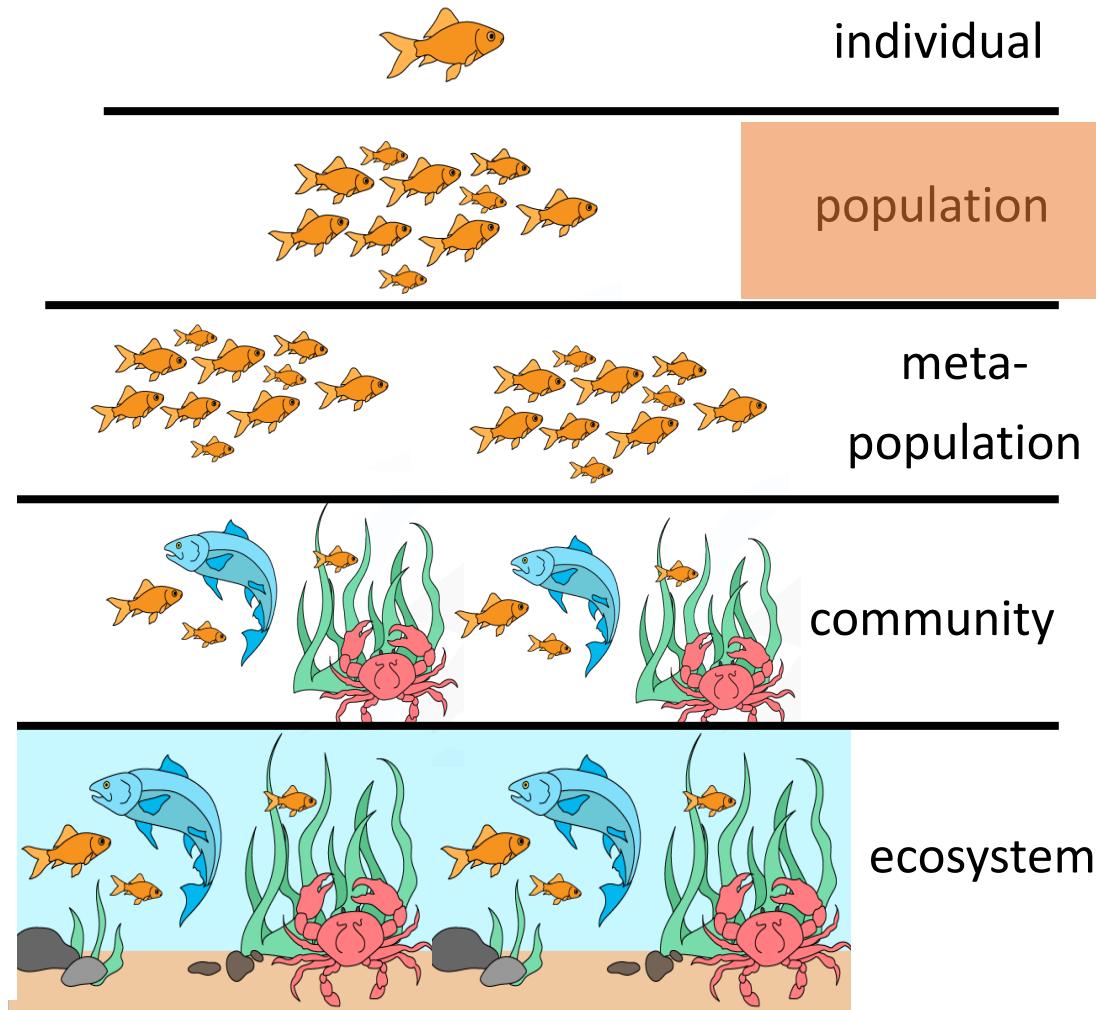
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3	2: Microevolution	Jan 17: Microevolution 3	Jan 19: Phylogenetics
4	3: Phylogenetics	Jan 24: Molecular Evolution	Jan 26: Sexual Selection
5	4: Evolution paper	Jan 31: Speciation	Feb 2: Ecology & Population Growth
6	5: Population Growth	Feb 7: Midterm	Feb 9: Single Species Population Growth & Regulation
7	6: Population Regulation	Feb 14: Species Interactions 1	Feb 16: Species Interactions 2
8	7: Disease Dynamics	Feb 21: Disease Dynamics as Population Biology 1	Feb 23: Disease Dynamics as Population Biology 2
9	8: Ecology paper	Feb 28: Community Assembly & Island Biogeography	Mar 2: Critical Transitions & Conservation Interventions



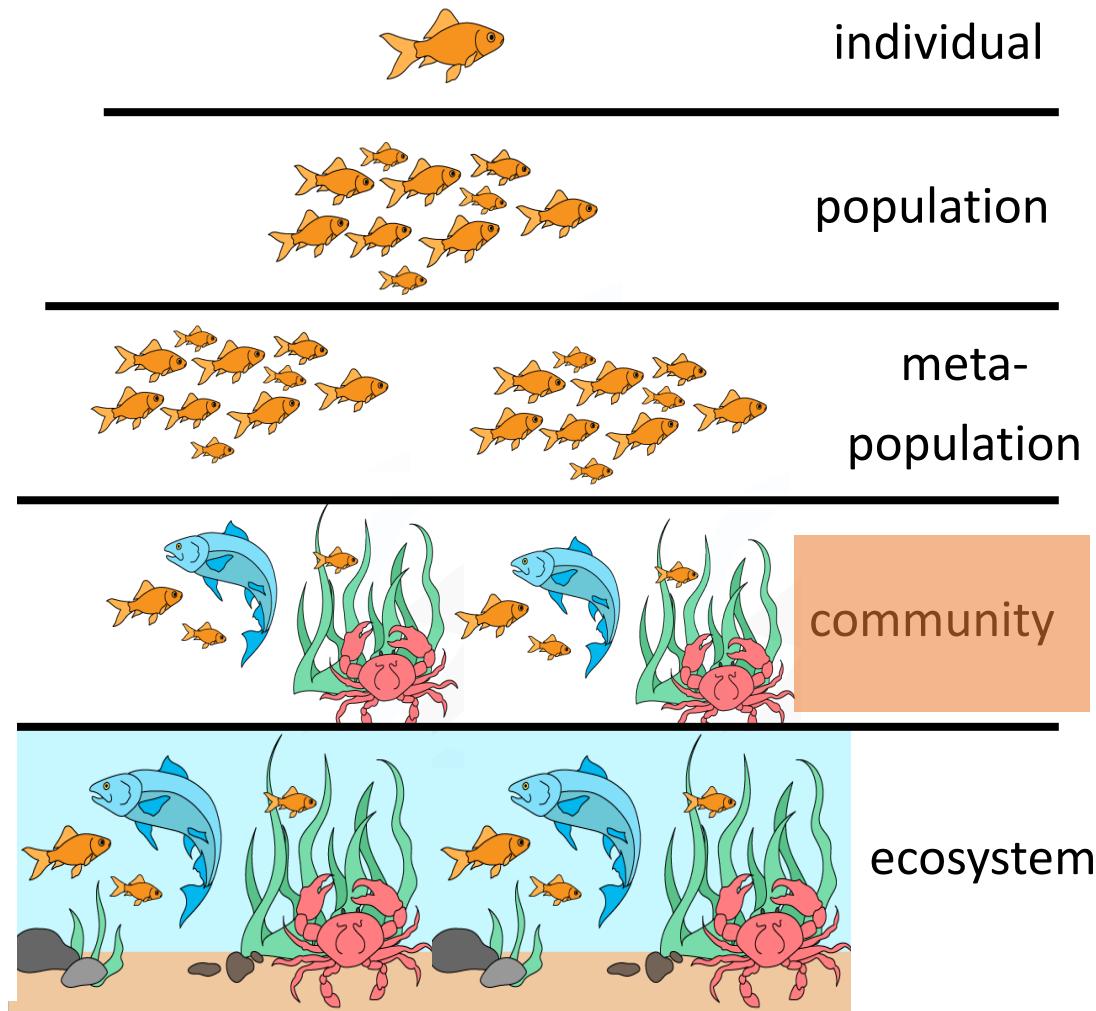
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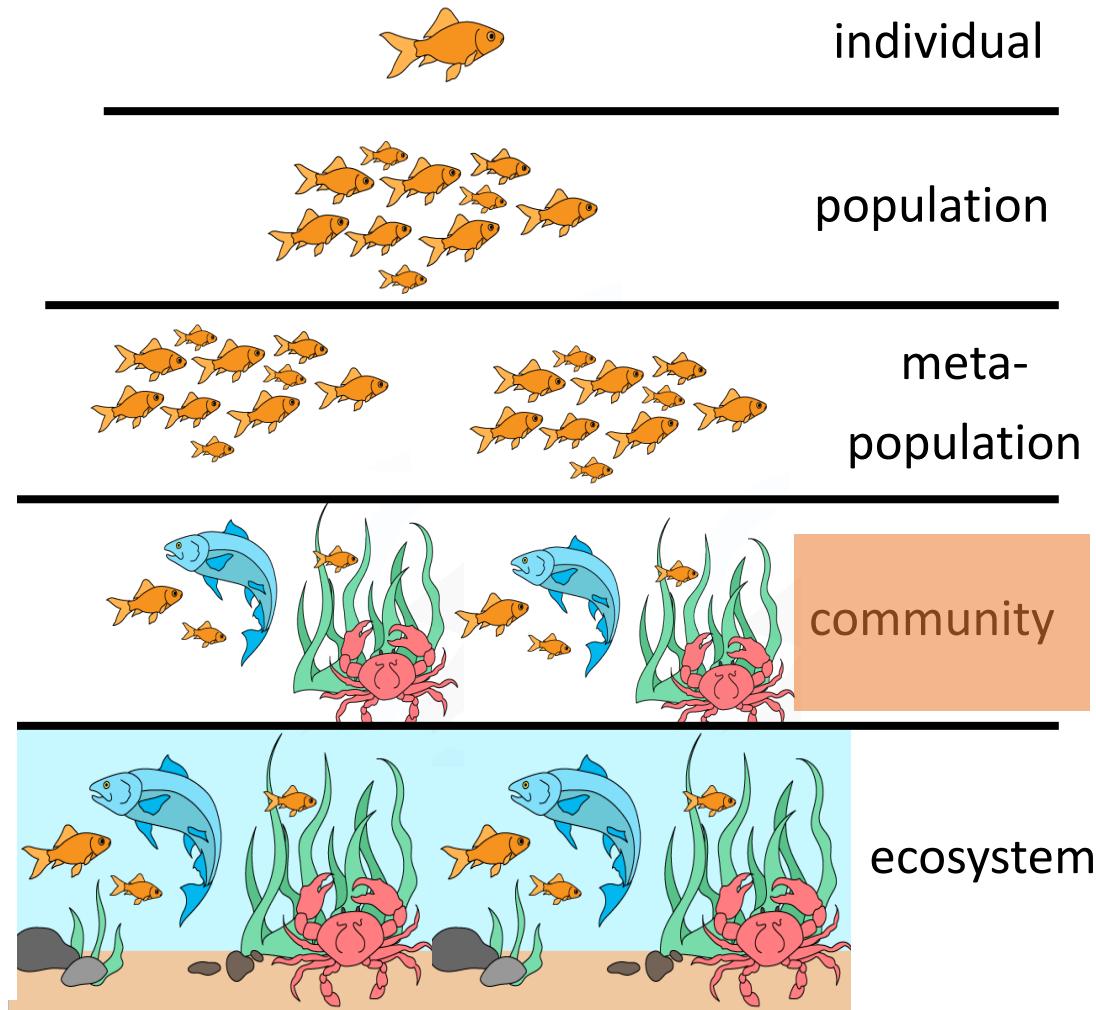
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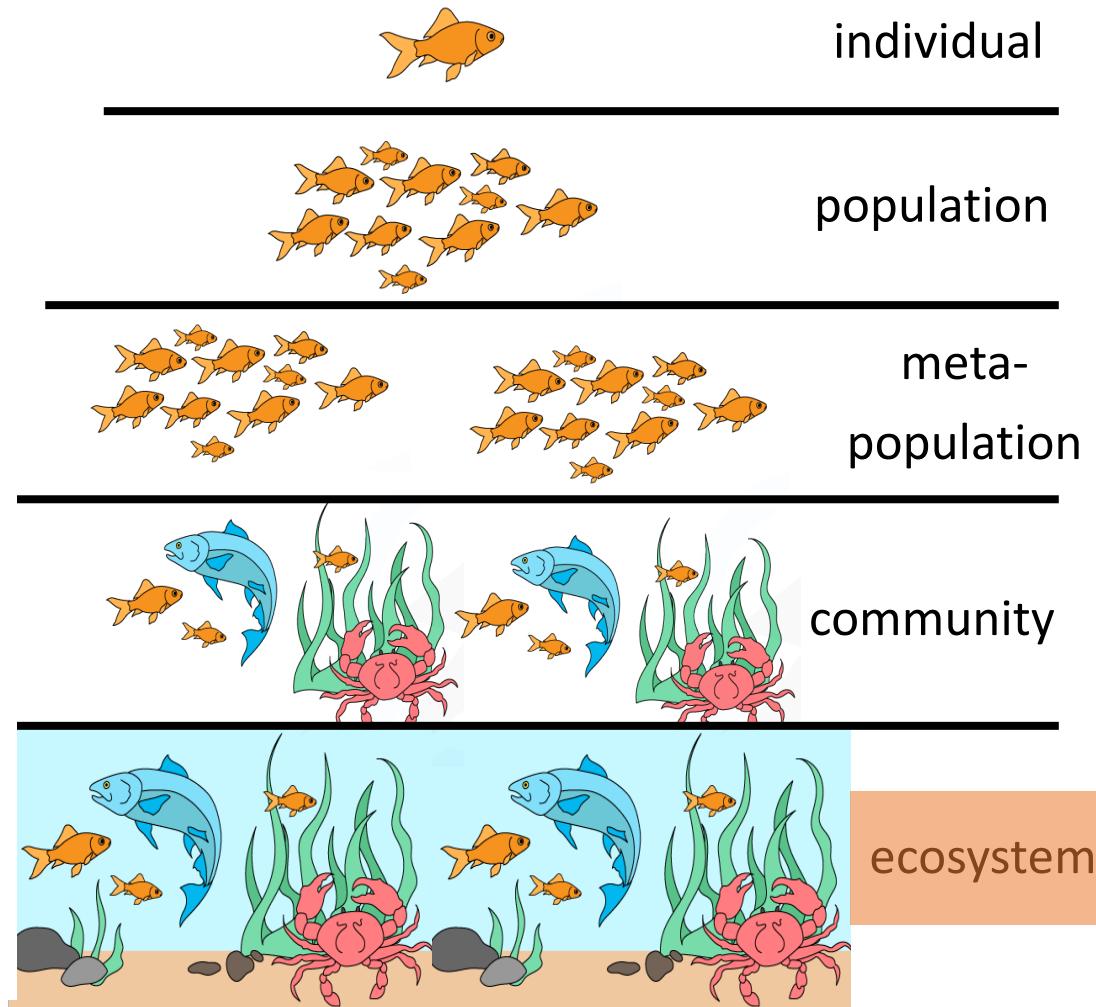
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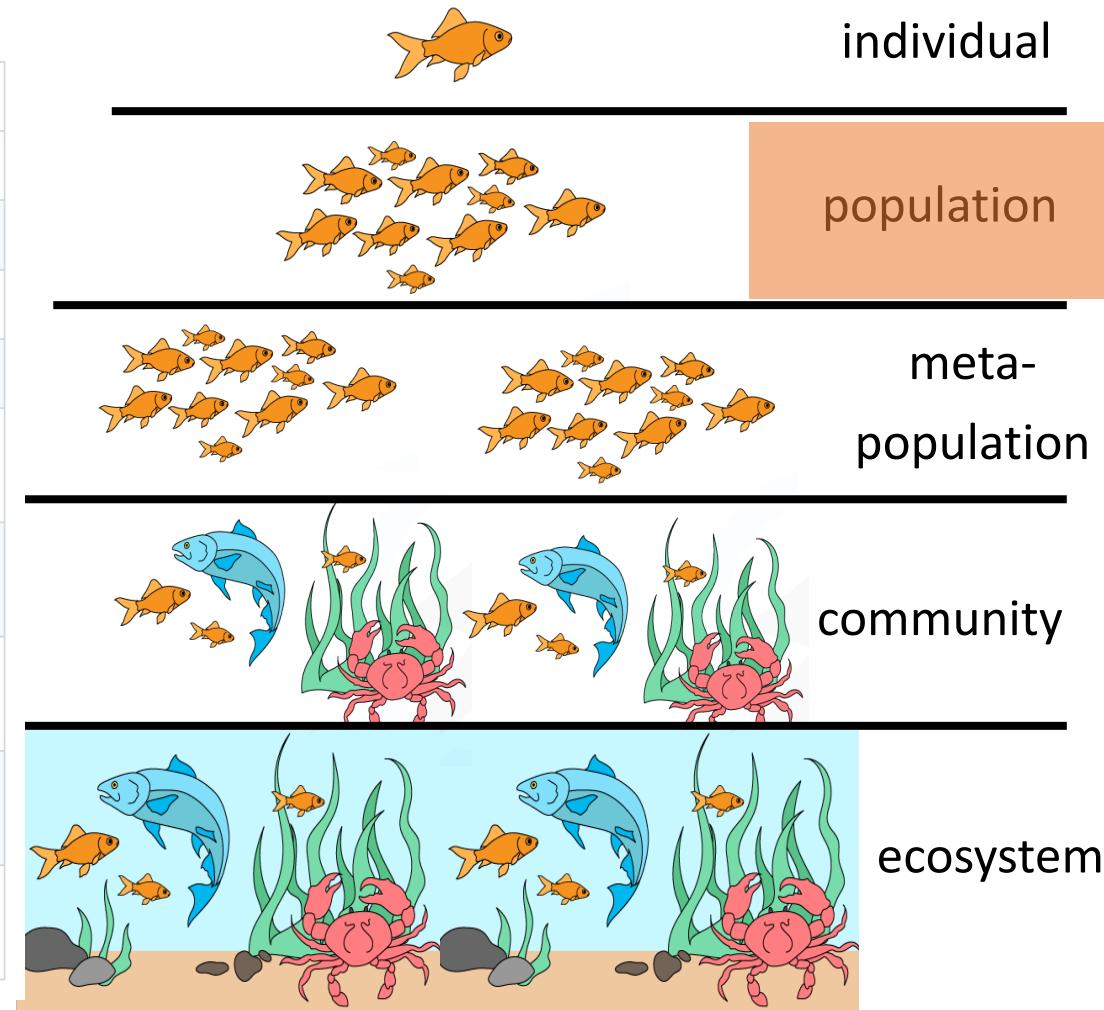
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Population Growth and Regulation

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Why do we care how populations grow?

Why do we care how populations grow?

(Shafer 1980)

DETERMINING MINIMUM VIABLE POPULATION SIZES FOR THE GRIZZLY BEAR¹

MARK L. SHAFFER,² School of Forestry and Environmental Studies, Duke University, Durham, NC 27706

Abstract: A stochastic computer simulation is presented for use in determining the relationship of population size to extinction probabilities for populations of grizzly bears (*Ursus arctos*). Published data on numbers, age, sex, reproduction, and mortality for the grizzly bear population of Yellowstone National Park were used to develop and test several simulation models. The results indicate that, for the Yellowstone grizzlies, 35 to 70 bears constitute a minimum viable population (the smallest population with a 95% probability of surviving at least 100 years). Minimum area requirements for populations of this size range from 700 to 10,000 km.²

Int. Conf. Bear Res. and Manage. 5:133–139



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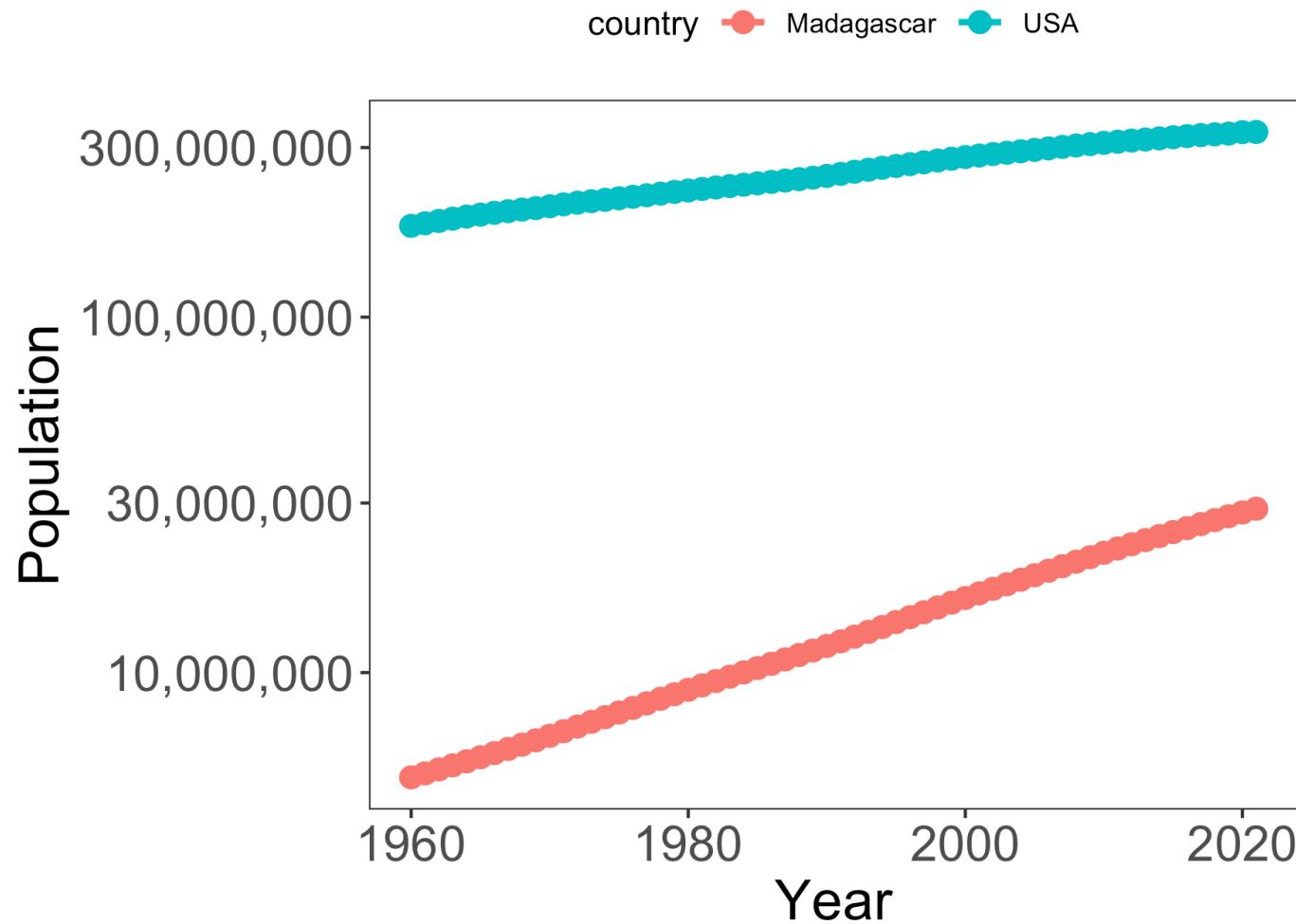
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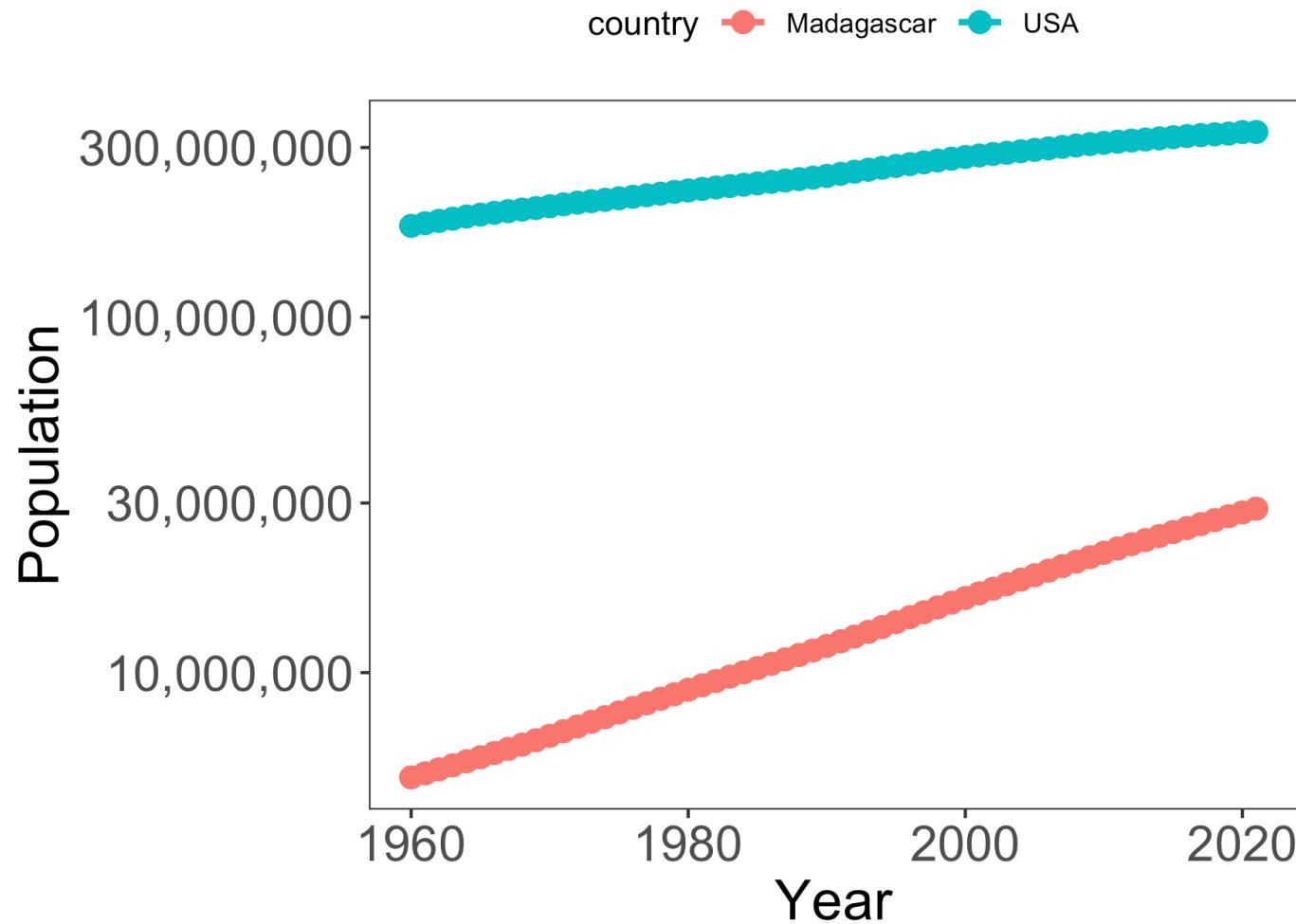


to protect populations from extinction

Why do we care how populations grow?



Why do we care how populations grow?



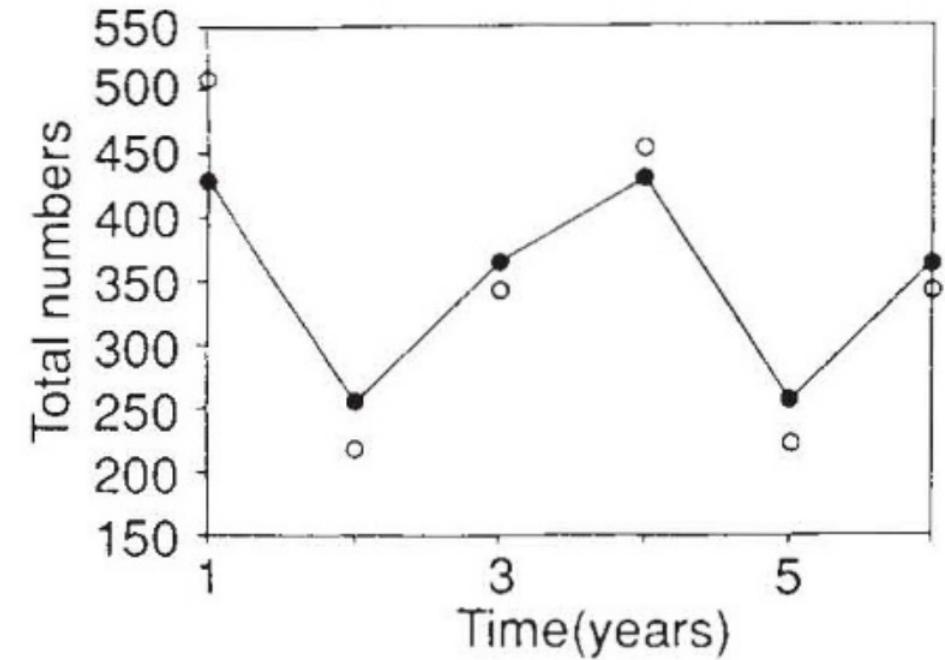
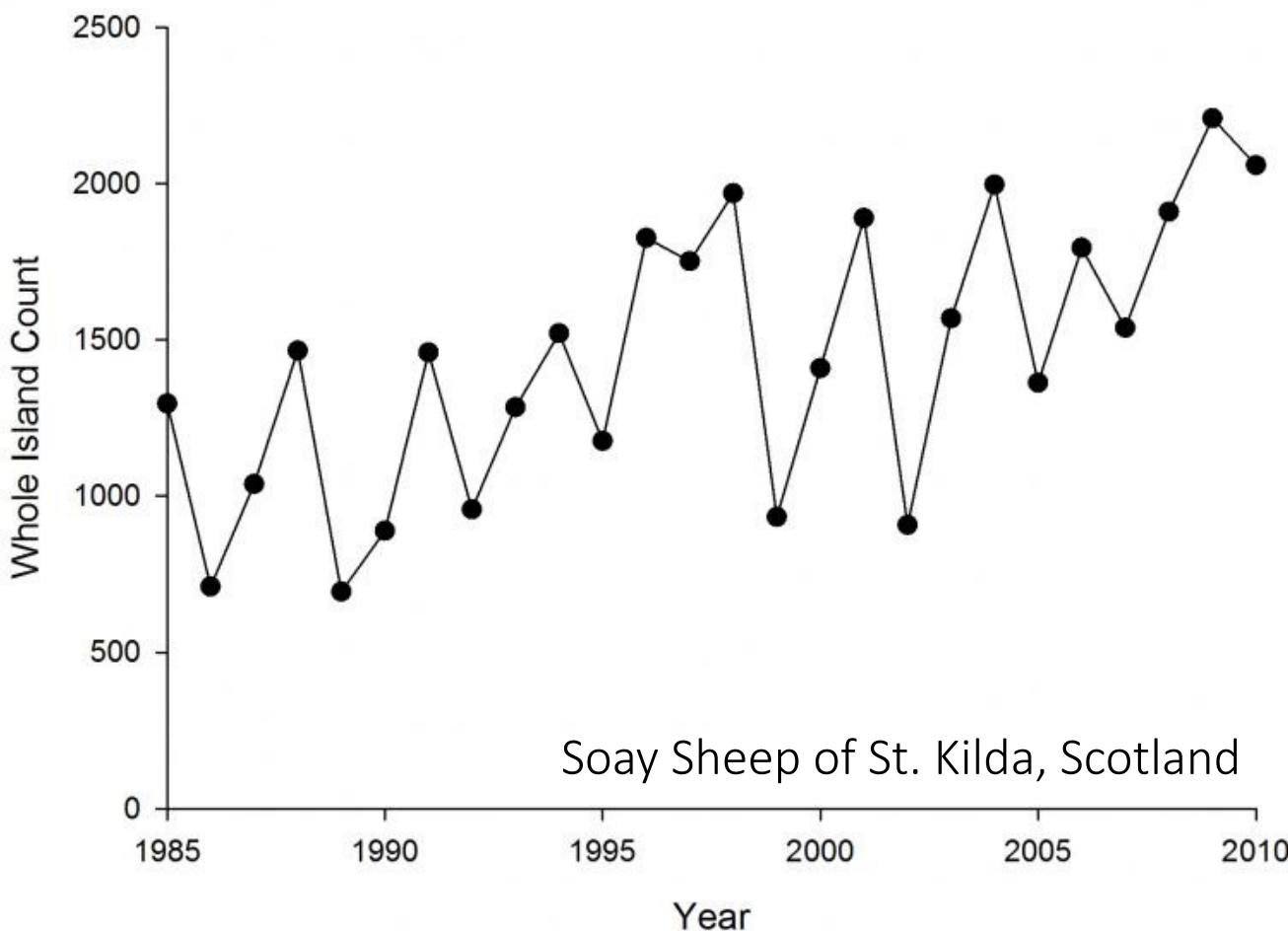
to forecast resource use

Why do we care how populations grow?



Why do we care how populations grow?

to understand past phenomena



Overcompensation and population cycles in an ungulate

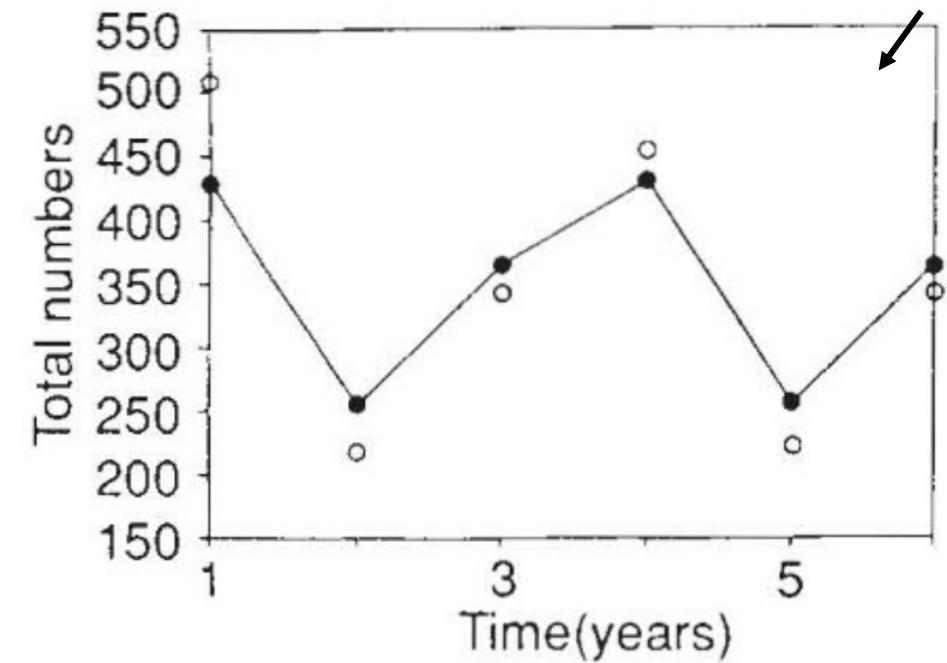
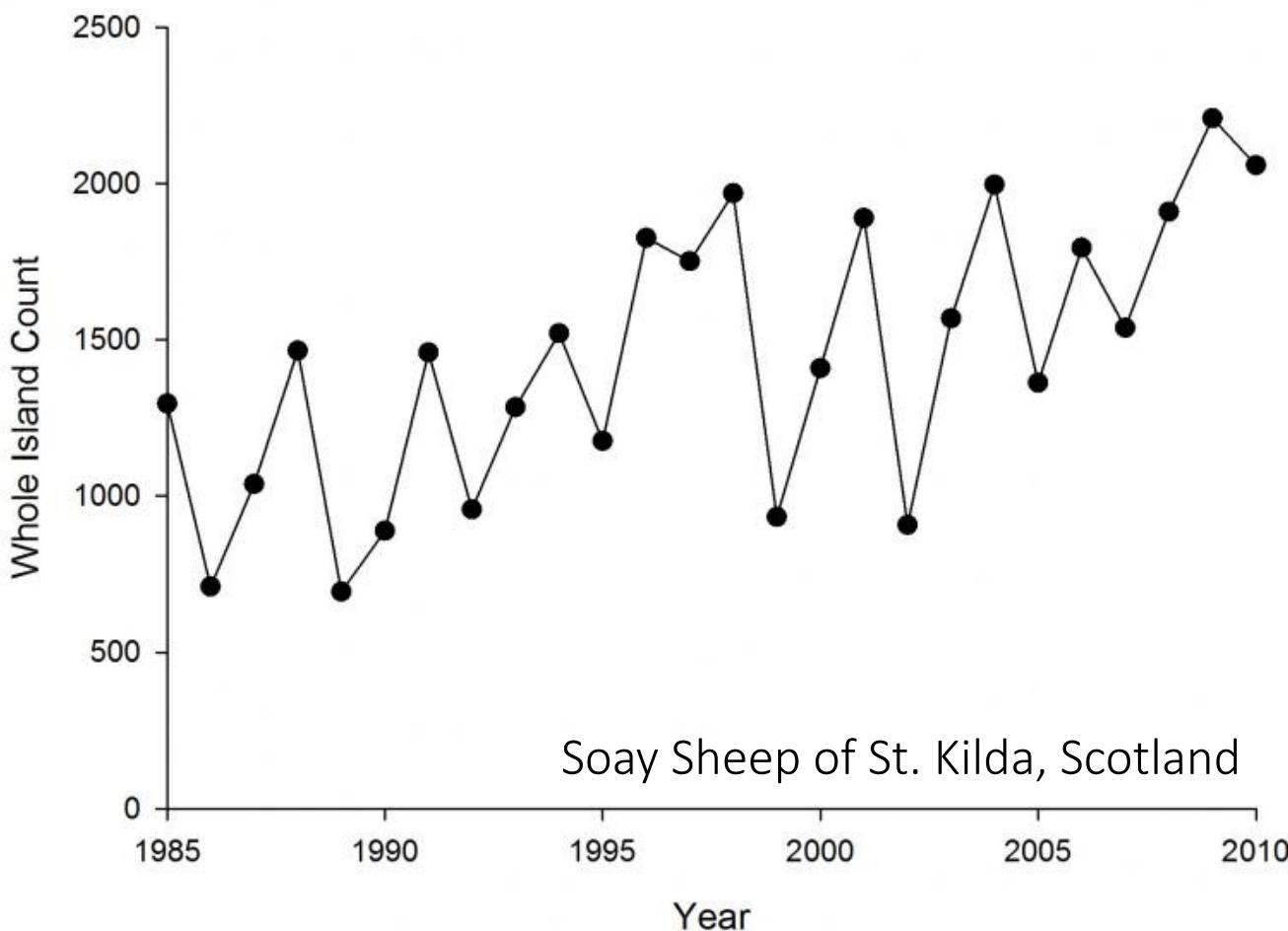
[B. T. Grenfell, O. F. Price, S. D. Albon & T. H. Glutton-Brock](#)

[Nature](#) 355, 823–826 (1992) | [Cite this article](#)

589 Accesses | 107 Citations | [Metrics](#)

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Model
compared
against
data

The simplest population model

1. Populations are divided into compartments
2. Individuals within a compartment are homogeneously mixed
3. Compartments and transition rates are determined by biological systems
4. Rates of transferring between compartments are expressed mathematically



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Madagascar
(N)



The simplest population model

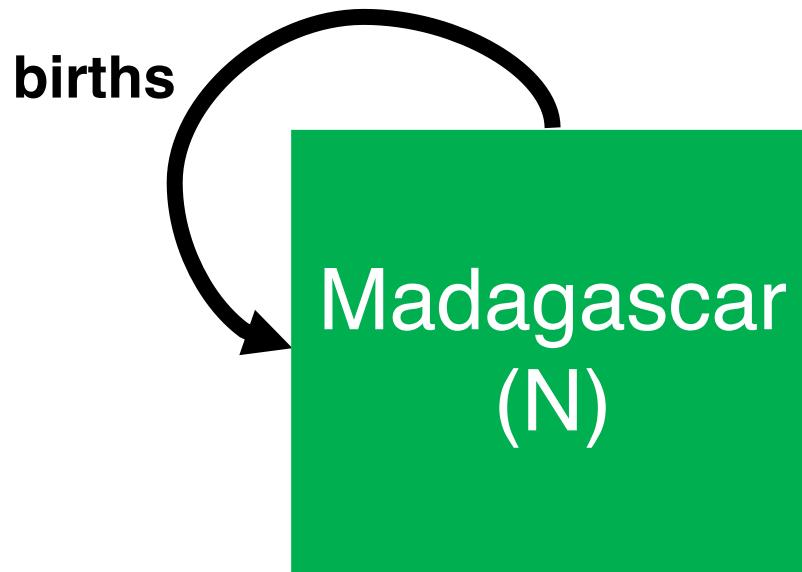
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Madagascar
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How does the population grow?



The simplest population model

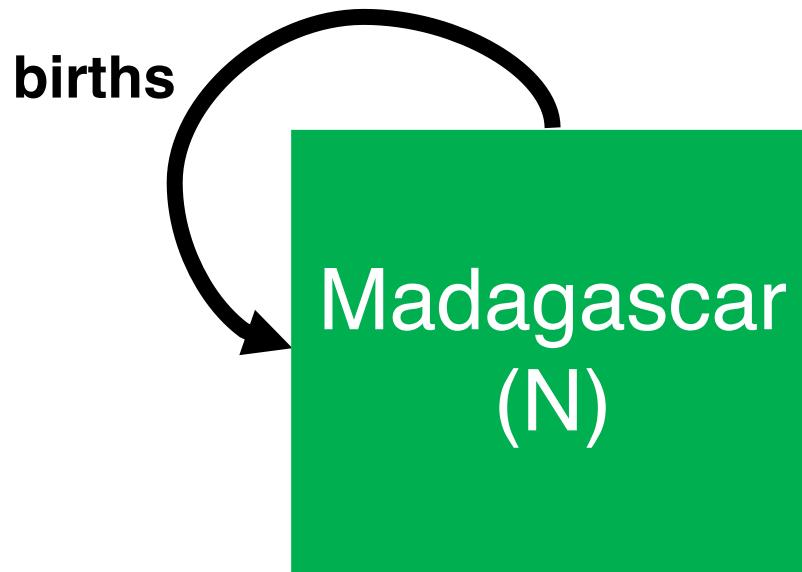


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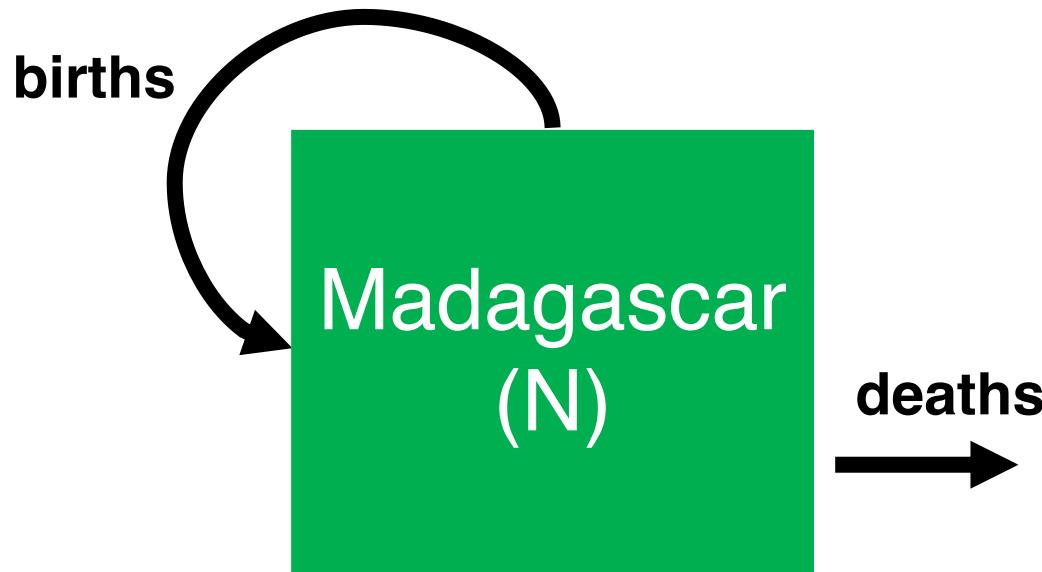


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How does the population decrease?

The simplest population model

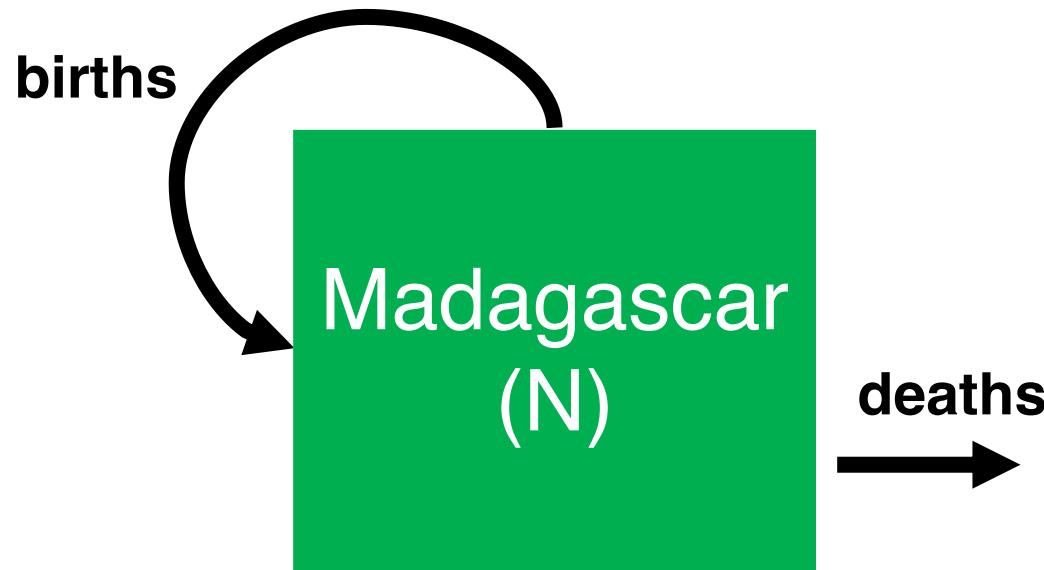


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How does the population decrease?

The simplest population model



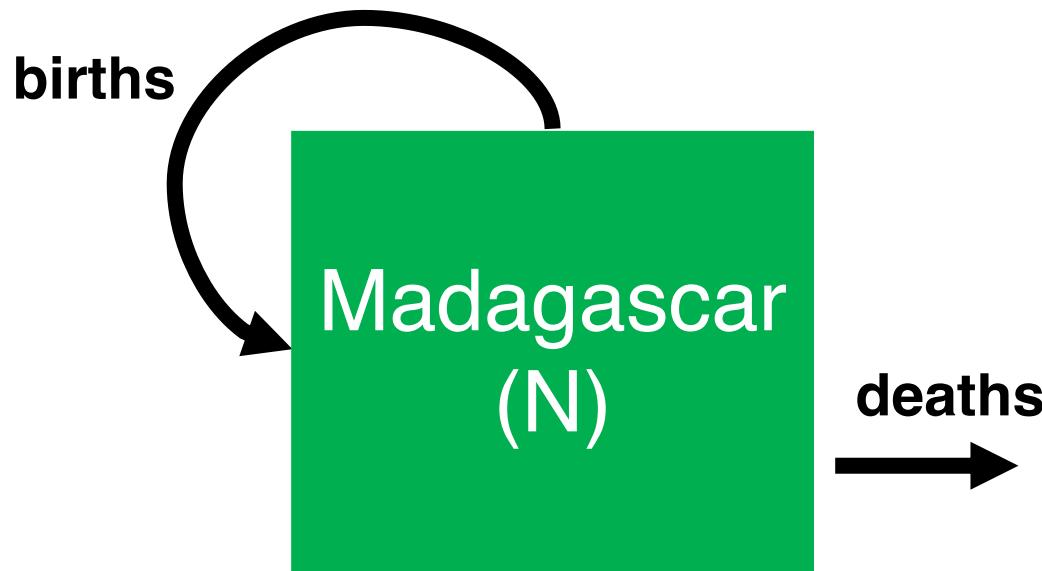
$$N_{t+1} = N_t + \text{births} * N_t - \text{deaths} * N_t$$

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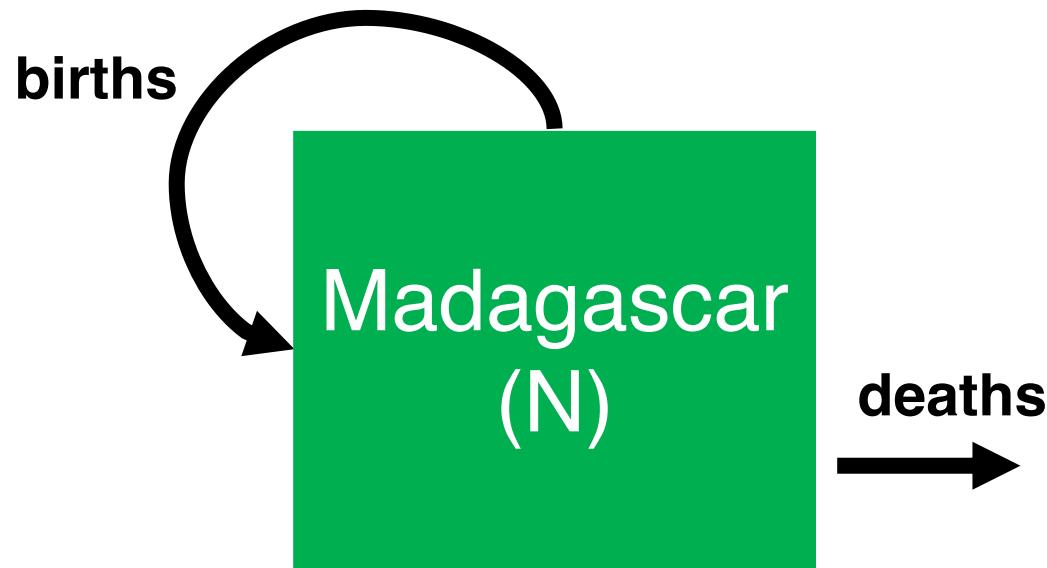


$$N_{t+1} = N_t + \text{births} * N_t - \text{deaths} * N_t$$

$$N_{t+1} = N_t + (\text{births} - \text{deaths}) * N_t$$



The simplest population model

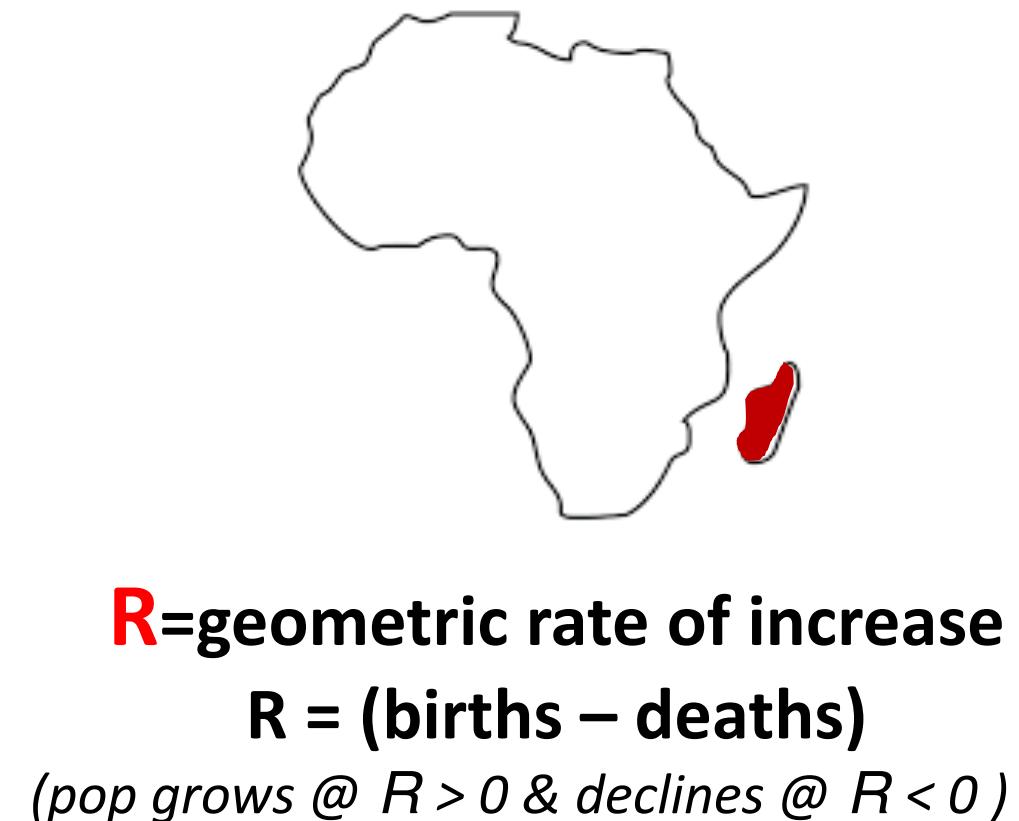


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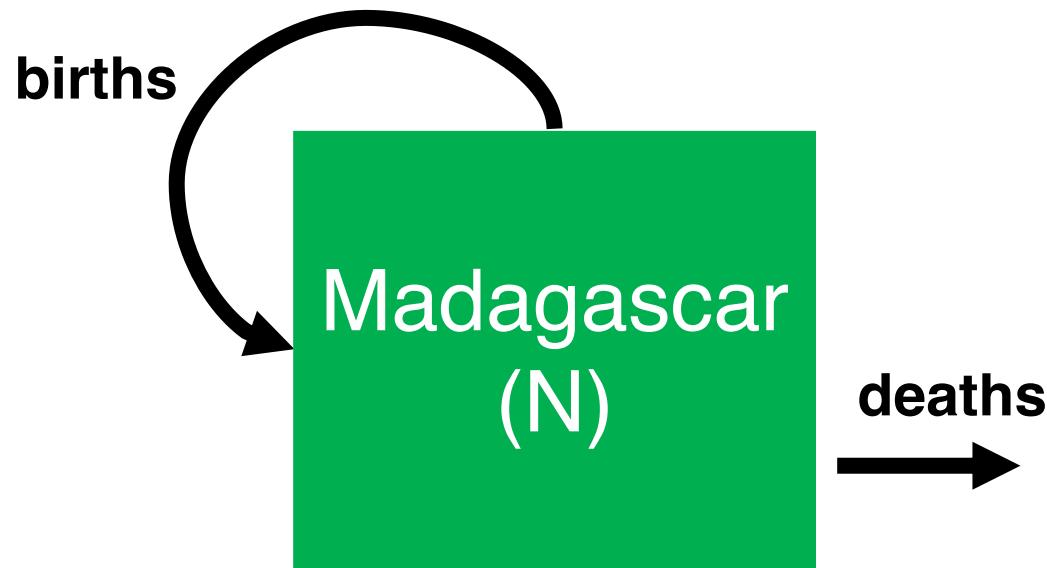
$$N_{t+1} = N_t + R * N_t$$

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$$N_{t+1} = N_t + R * N_t$$

$$N_{t+1} = (1 + R) * N_t$$

$$N_{t+1} = \lambda * N_t$$

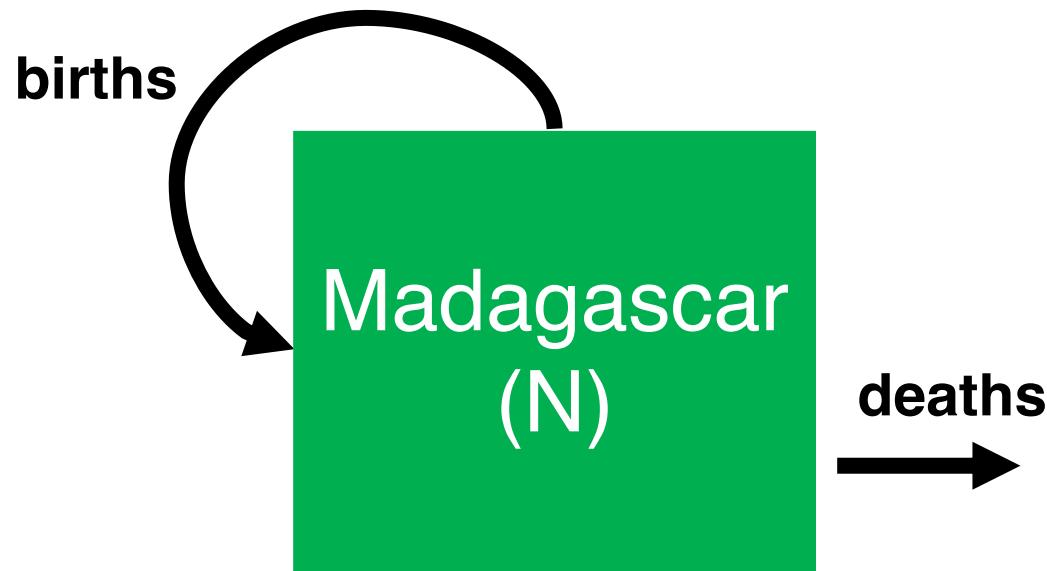


**λ = population rate of increase
(finite growth rate)**

$$\lambda = 1 + R$$

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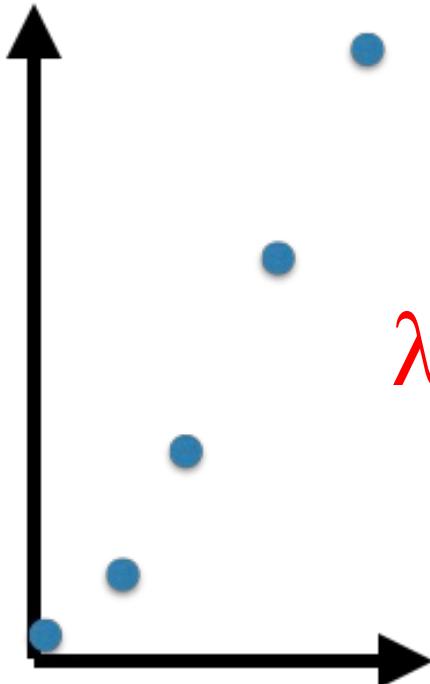


**λ = population rate of increase
(finite growth rate)**
(pop grows @ $\lambda > 1$ & declines @ $\lambda < 1$)

Geometric growth



Geometric growth is measured in discrete time



$$\lambda = N_{t+1}/N_t$$

$$N_1 = \lambda N_0$$

$$N_2 = \lambda[\lambda N_0] = \lambda^2 N_0$$

$$N_3 = \lambda^3 N_0$$

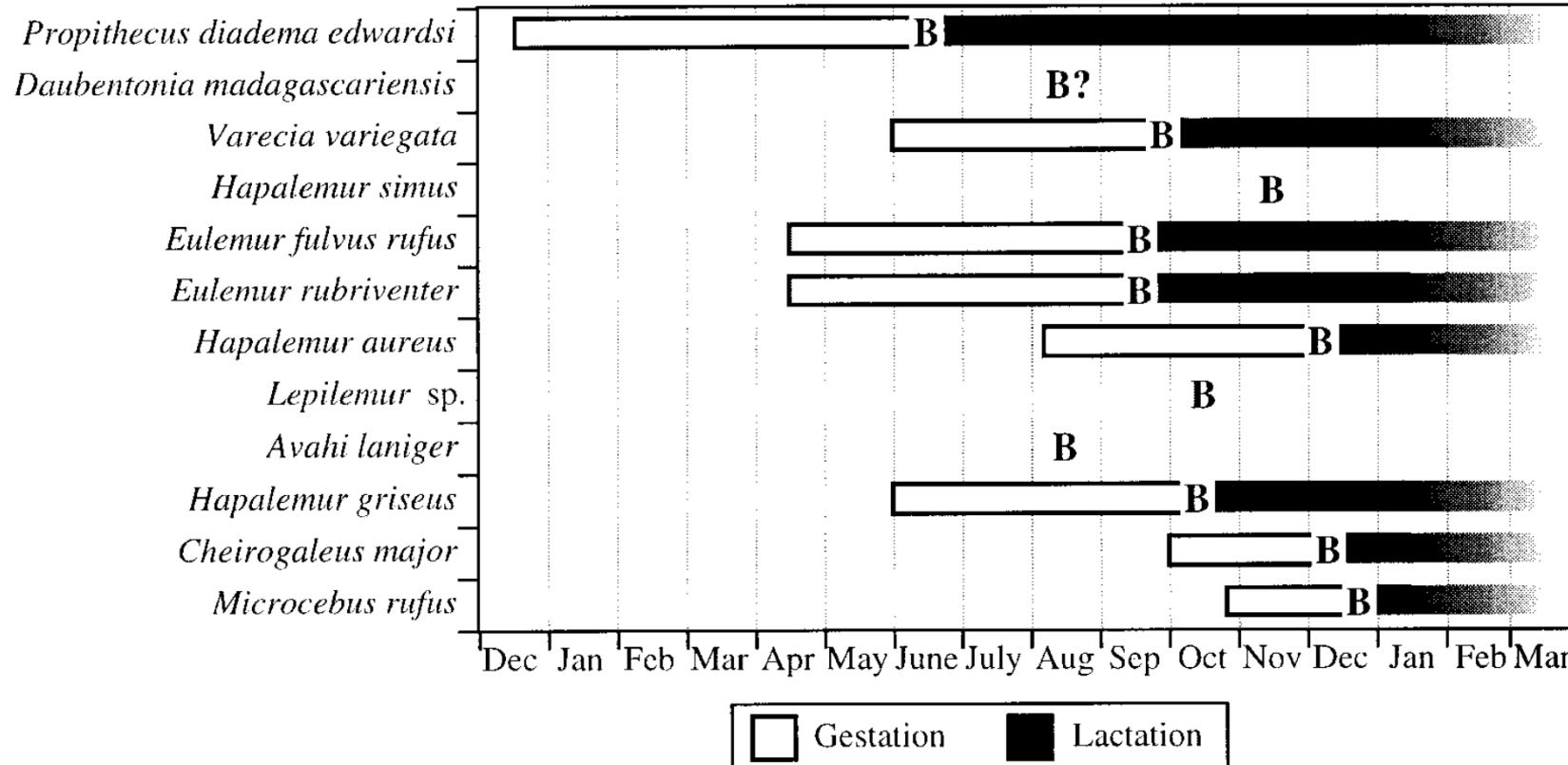
$$N_t = \lambda^t N_0$$

λ = population rate of increase

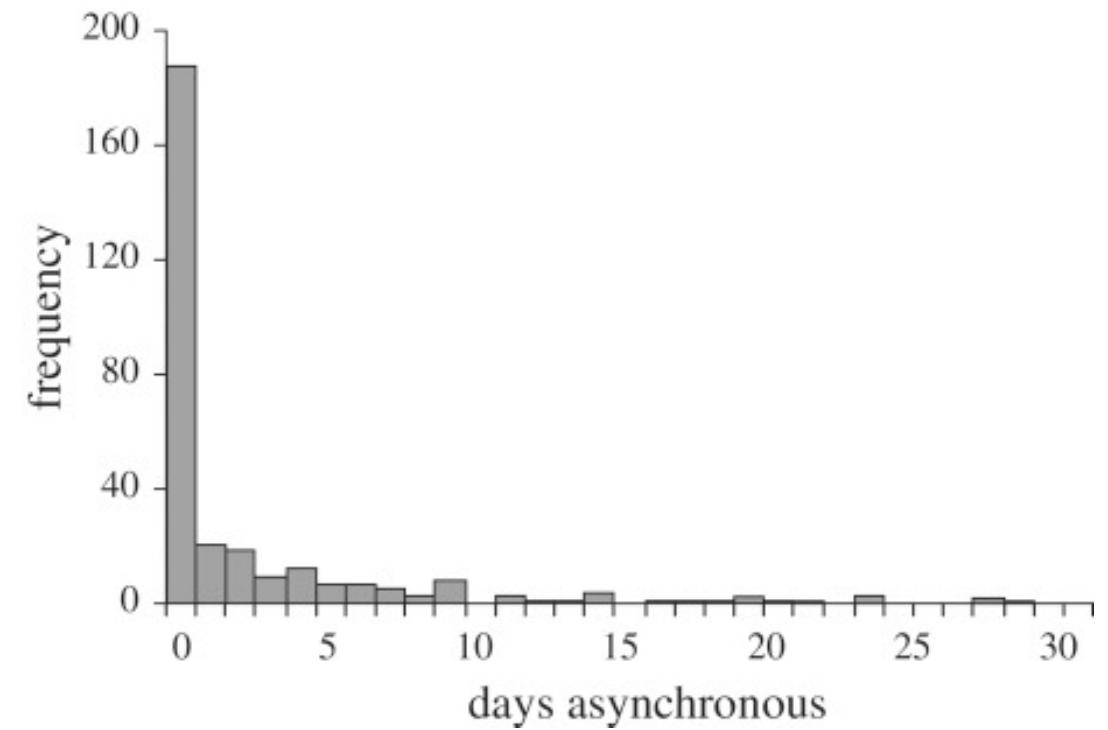
Is discrete time realistic for population growth?



Is discrete time realistic for population growth?

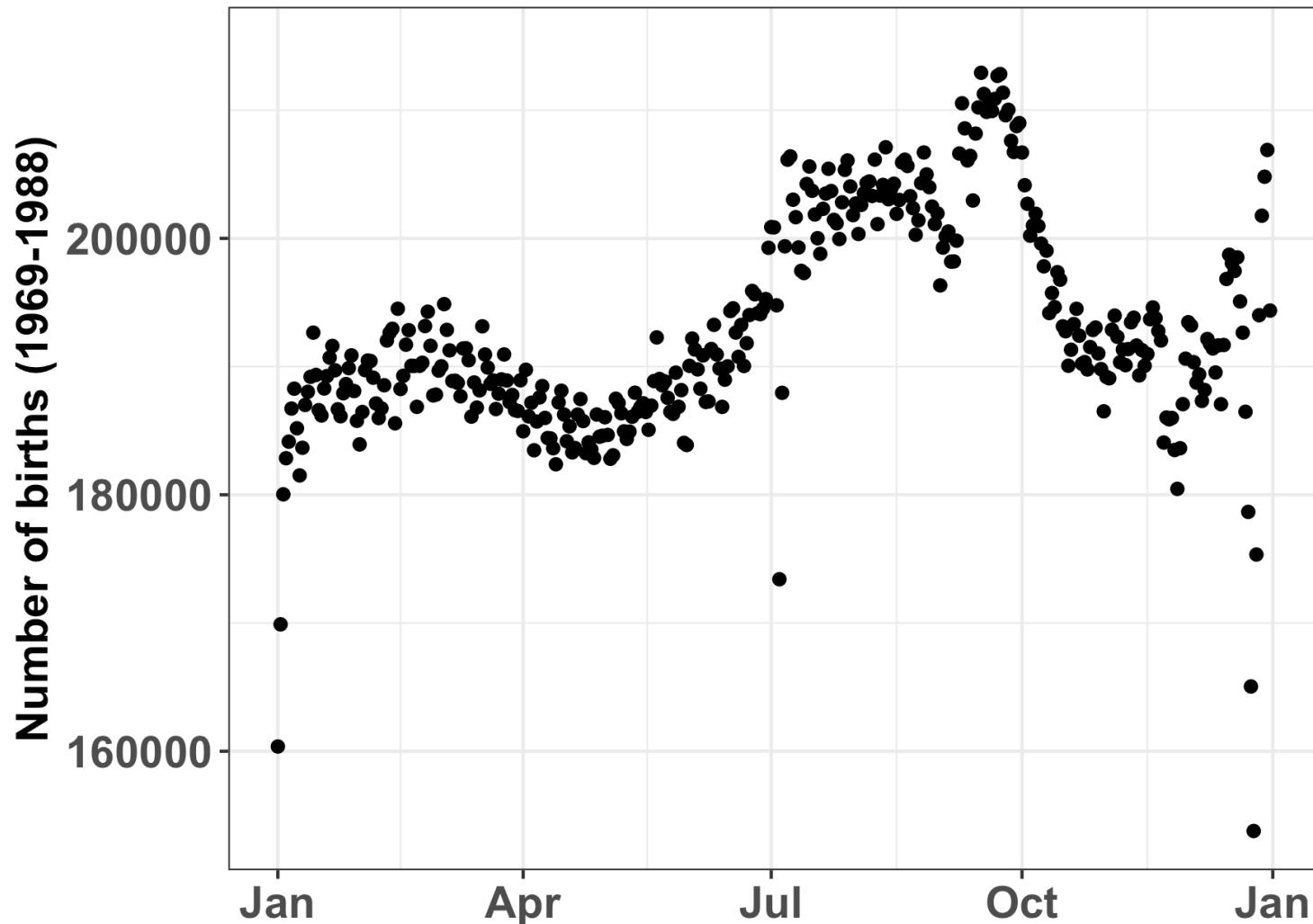


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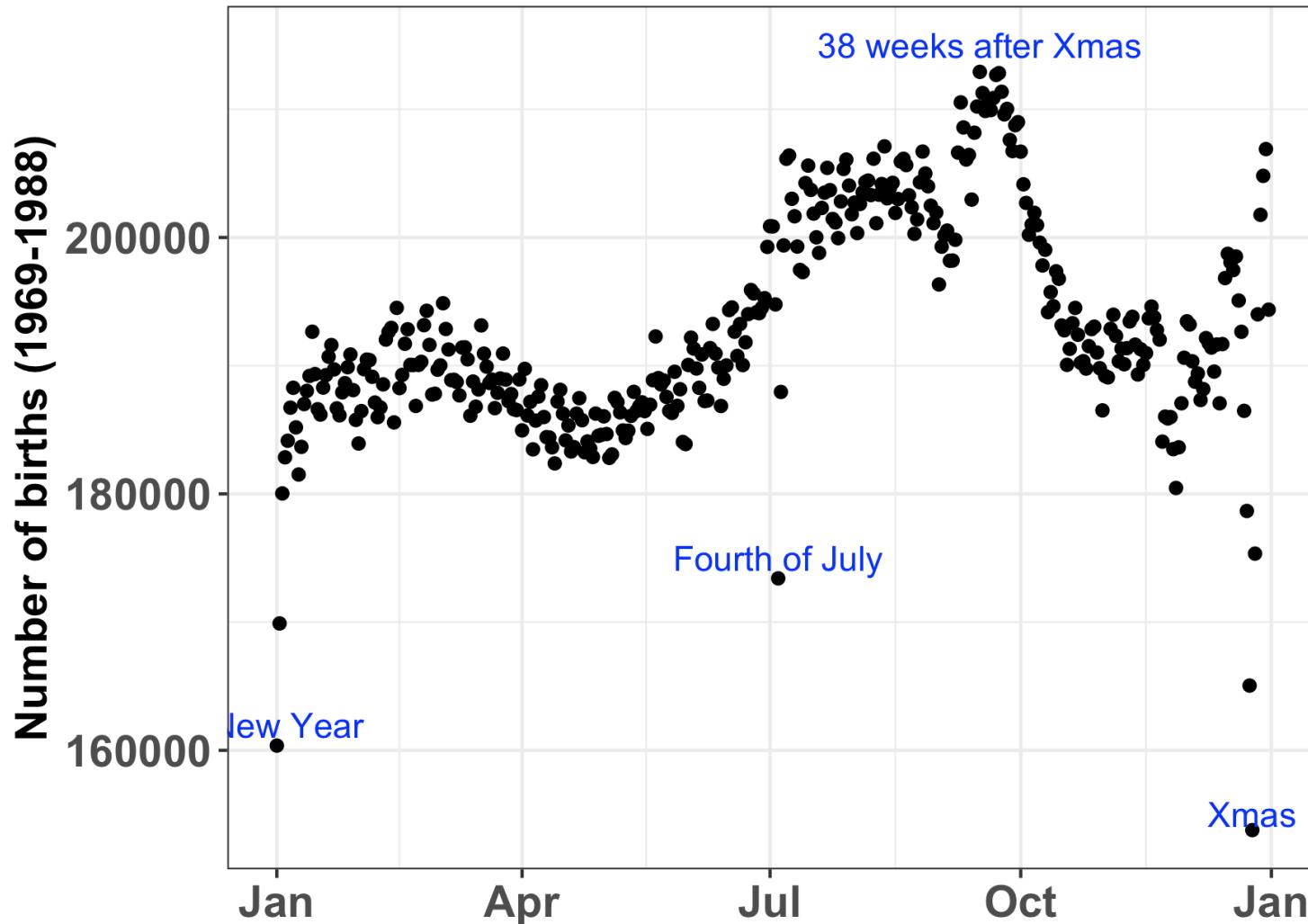
64% of banded mongoose pups are born on the same day.

Is discrete time realistic for population growth?



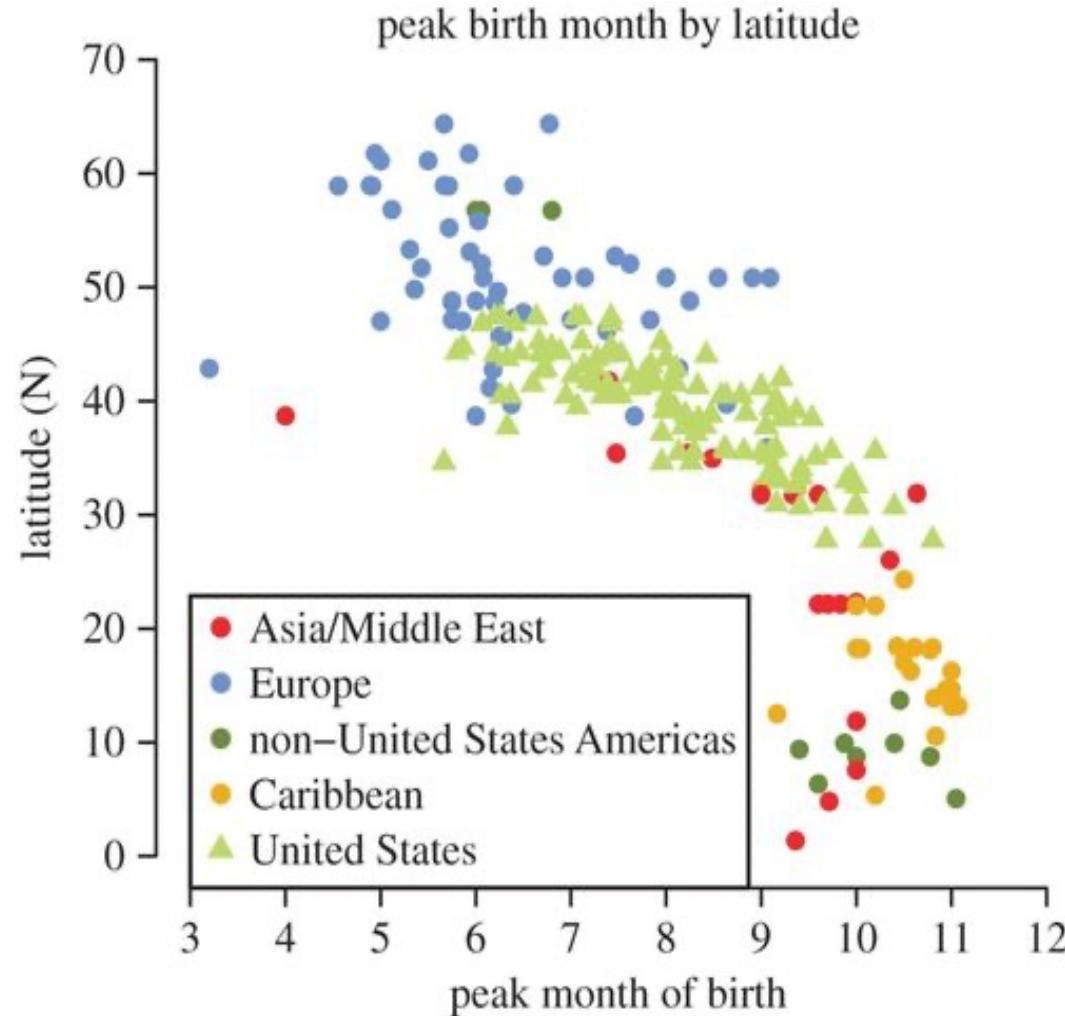
Human births by
day in the US
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Is discrete time realistic for population growth?



Human births by day in the US (1969-1988)

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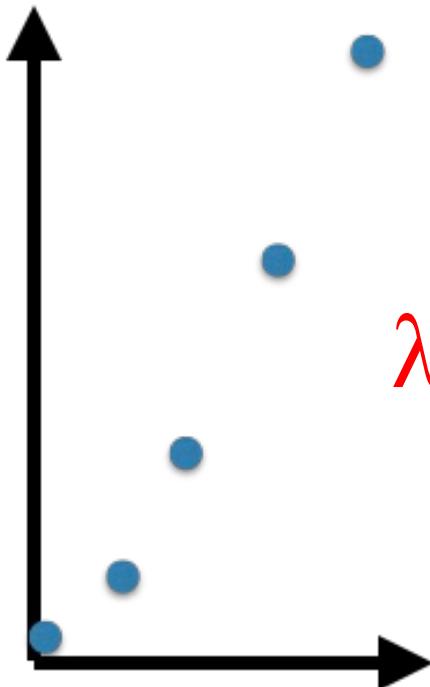


Many populations
(including human) are
better approximated by
an assumption of a
continuous birth rate

Geometric vs. exponential growth



Geometric growth



$$\lambda = N_{t+1}/N_t$$

$$N_1 = \lambda N_0$$

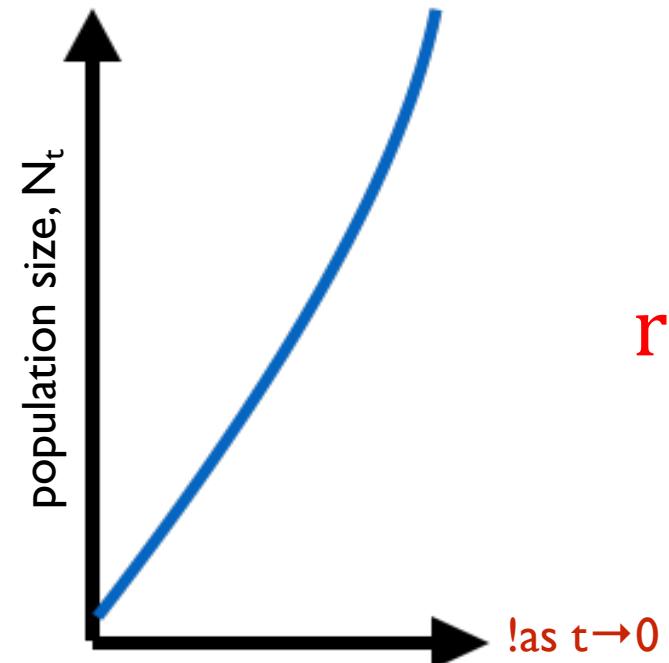
$$N_2 = \lambda[\lambda N_0] = \lambda^2 N_0$$

$$N_3 = \lambda^3 N_0$$

$$N_t = \lambda^t N_0$$

λ = population rate of increase

Exponential growth is measured in continuous time



$$r = \frac{\ln\left(\frac{N_t}{N_0}\right)}{t}$$

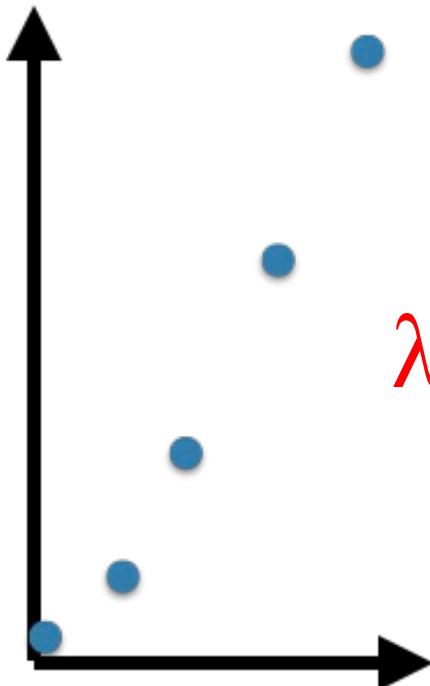
$$dN(t)/dt = rN(t)$$

r = intrinsic (instantaneous) rate of increase

Geometric vs. exponential growth



Discrete time



Continuous time

$$dN(t)/dt = rN(t)$$

$$\lambda = N_{t+1}/N_t$$

$$N_1 = \lambda N_0$$

$$N_2 = \lambda[\lambda N_0] = \lambda^2 N_0$$

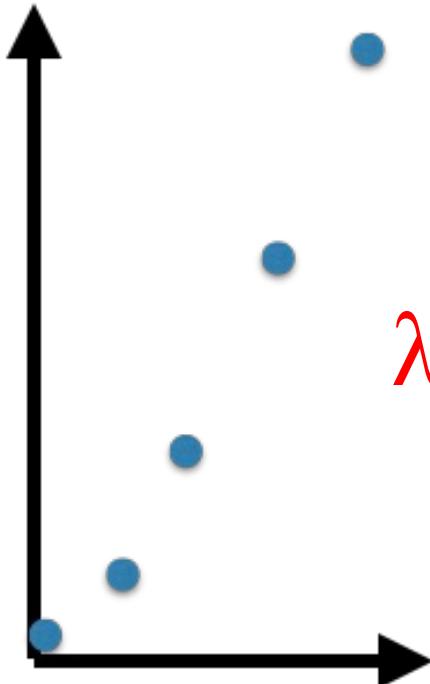
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Geometric vs. exponential growth



Discrete time



$$\lambda = N_{t+1}/N_t$$

Continuous time

$$dN(t)/dt = rN(t)$$

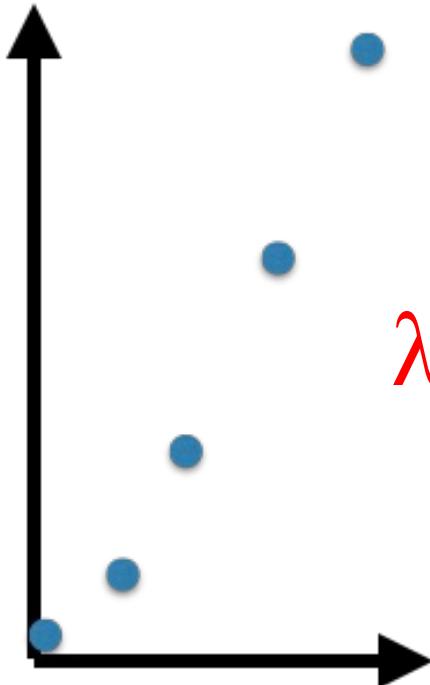
Separation of variables:
 $dN(t)/N(t) = r dt$

$$\begin{aligned}N_1 &= \lambda N_0 \\N_2 &= \lambda[\lambda N_0] = \lambda^2 N_0 \\N_3 &= \lambda^3 N_0 \\N_t &= \lambda^t N_0\end{aligned}$$

Geometric vs. exponential growth



Discrete time



$$\lambda = N_{t+1}/N_t$$

Continuous time

$$dN(t)/dt = rN(t)$$

Separation of variables:
 $dN(t)/N(t) = r dt$

Integrate both sides:
 $\int dN(t)/N(t) = \int r dt$

$$N_1 = \lambda N_0$$

$$N_2 = \lambda [\lambda N_0] = \lambda^2 N_0$$

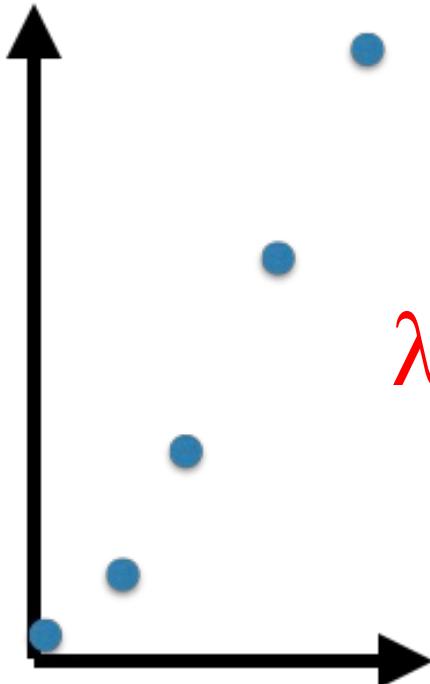
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Geometric vs. exponential growth



Discrete time



$$\lambda = N_{t+1}/N_t$$

Continuous time

$$dN(t)/dt = rN(t)$$

Separation of variables:
 $dN(t)/N(t) = r dt$

Integrate both sides:
 $\int dN(t)/N(t) = \int r dt$

By definition:
 $\log(N(t)) = rt + c$

$$N_1 = \lambda N_0$$

$$N_2 = \lambda[\lambda N_0] = \lambda^2 N_0$$

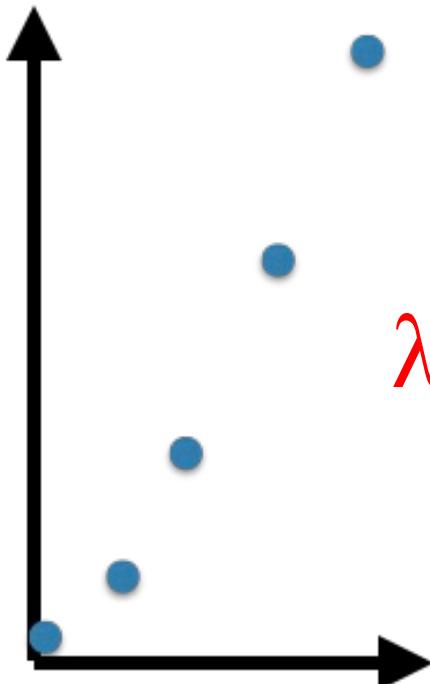
$$N_3 = \lambda^3 N_0$$

$$N_t = \lambda^t N_0$$

Geometric vs. exponential growth



Discrete time



$$\lambda = N_{t+1}/N_t$$

Continuous time

$$dN(t)/dt = rN(t)$$

Separation of variables:
 $dN(t)/N(t) = r dt$

Integrate both sides:
 $\int dN(t)/N(t) = \int r dt$

By definition:
 $\log(N(t)) = rt + c$

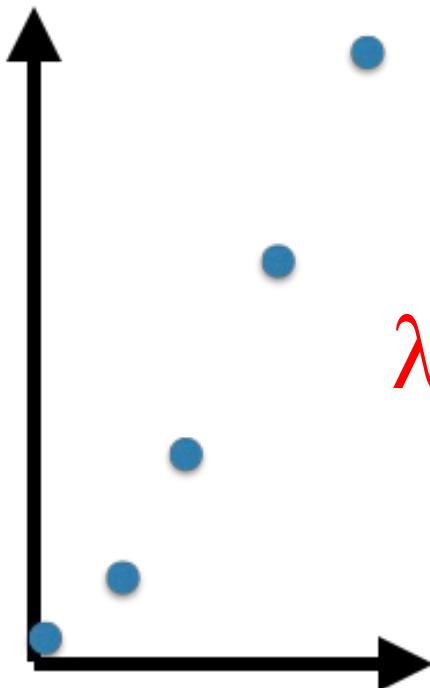
Take exponentials:
 $N(t) = e^{rt+c} = Ce^{rt}$
 $N(t) = N(0)e^{rt}$

$$\begin{aligned}N_1 &= \lambda N_0 \\N_2 &= \lambda[\lambda N_0] = \lambda^2 N_0 \\N_3 &= \lambda^3 N_0 \\N_t &= \lambda^t N_0\end{aligned}$$

Geometric vs. exponential growth

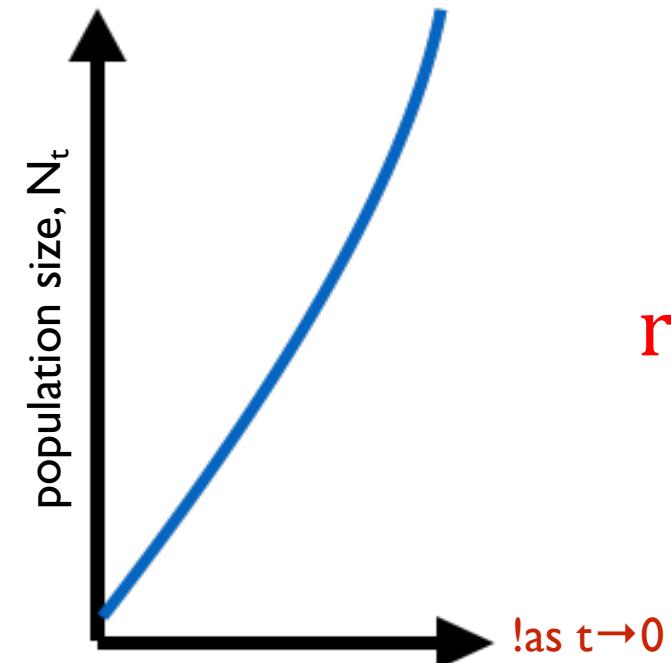


Discrete time



$$\lambda = N_{t+1}/N_t$$

Continuous time



$$r = \frac{\ln\left(\frac{N_t}{N_0}\right)}{t}$$

$$N_1 = \lambda N_0$$

$$N_2 = \lambda[\lambda N_0] = \lambda^2 N_0$$

$$N_3 = \lambda^3 N_0$$

$$N_t = \lambda^t N_0$$

λ =population rate of increase

(pop grows @ $\lambda > 1$ & declines @ $\lambda < 1$)

$$N_t = N_0 e^{rt}$$

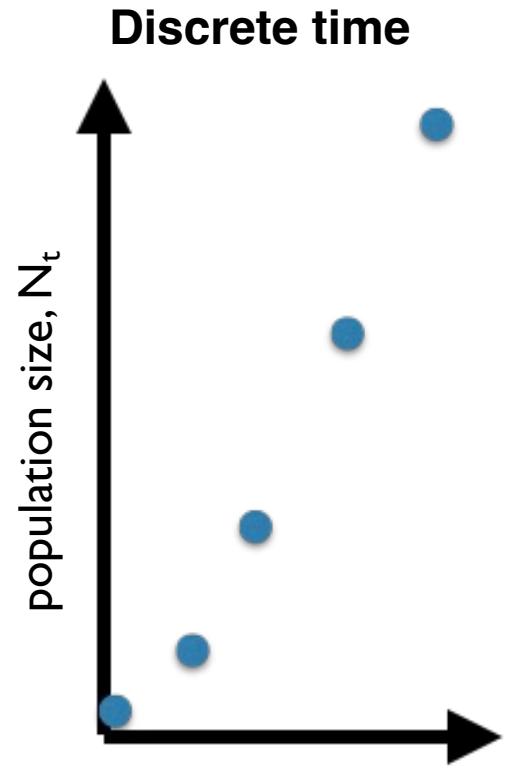
r =intrinsic (instantaneous) rate of increase

(pop grows @ $r > 0$ & declines @ $r < 0$)

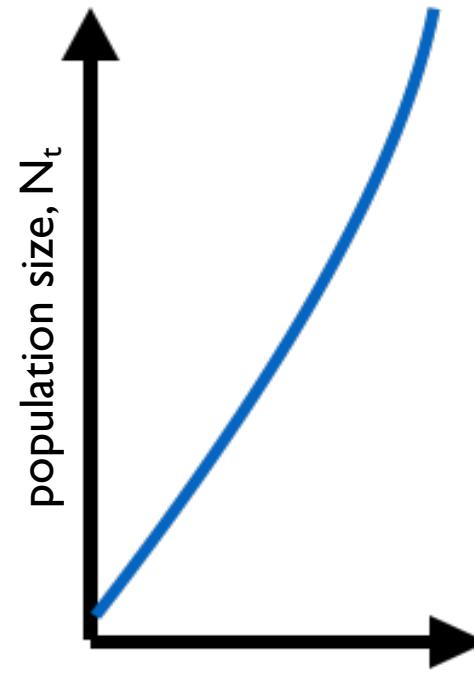
Geometric vs. exponential growth

geometric
 $N_t = \lambda^t N_0$

exponential
 $N_t = N_0 e^{rt}$



Continuous time



Geometric vs. exponential growth

geometric

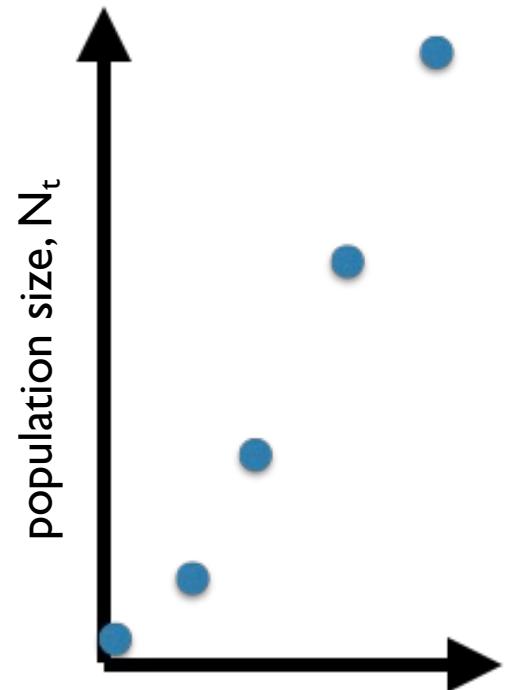
$$N_t = \lambda^t N_0$$

exponential

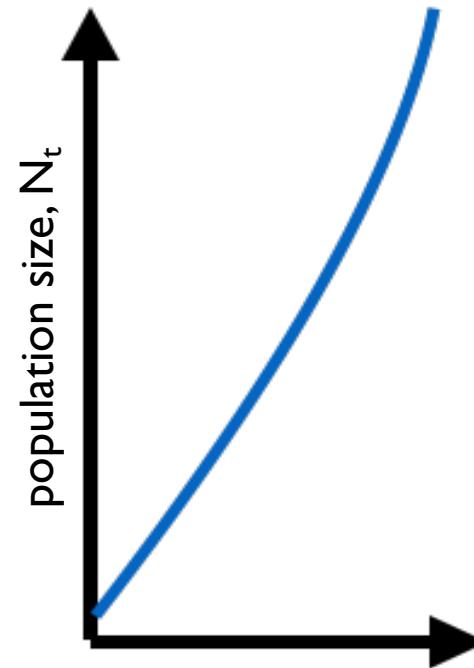
$$N_t = N_0 e^{rt}$$

$$\lambda^t N_0 = N_0 e^{rt}$$

Discrete time



Continuous time



Geometric vs. exponential growth

geometric

$$N_t = \lambda^t N_0$$

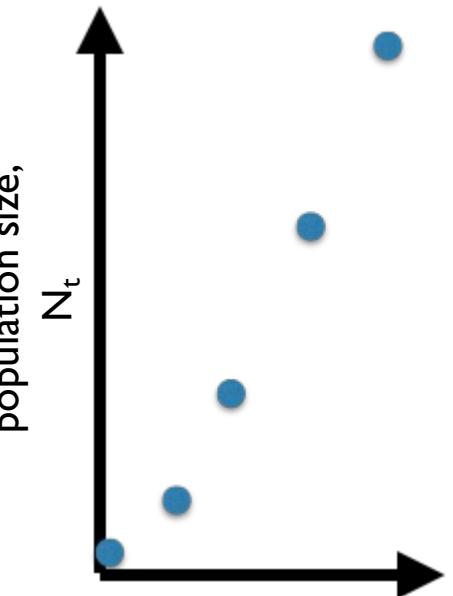
exponential

$$N_t = N_0 e^{rt}$$

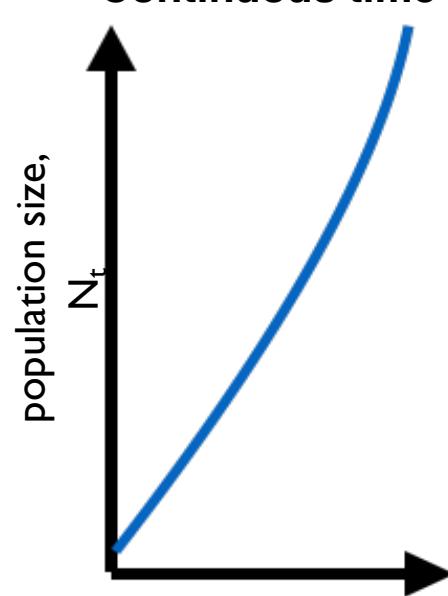
$$\lambda^t N_0 = N_0 e^{rt}$$

$$\lambda^t = e^{rt}$$

Discrete time



Continuous time



Geometric vs. exponential growth

geometric

$$N_t = \lambda^t N_0$$

exponential

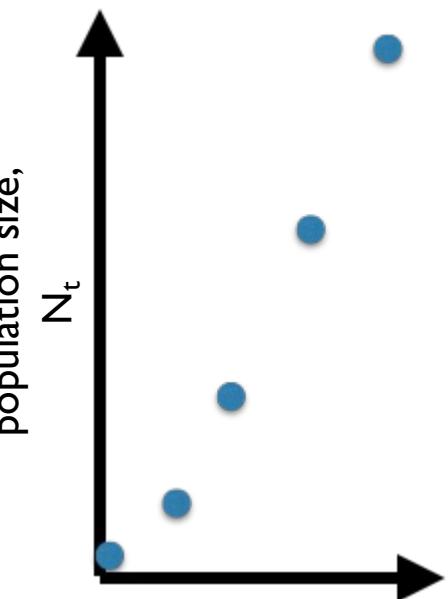
$$N_t = N_0 e^{rt}$$

$$\lambda^t N_0 = N_0 e^{rt}$$

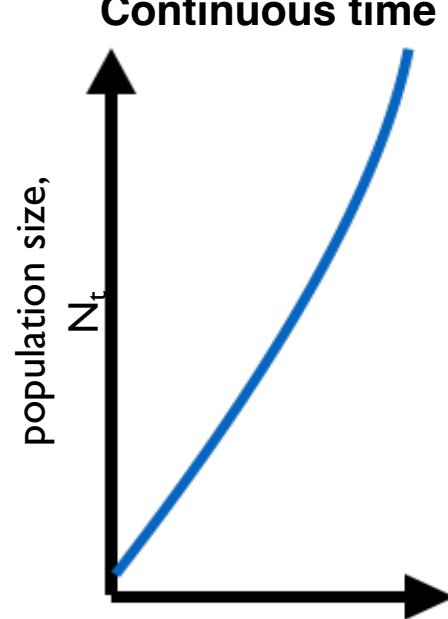
$$\lambda^t = e^{rt}$$

$$\lambda = e^r$$

Discrete time



Continuous time



Geometric vs. exponential growth

geometric

$$N_t = \lambda^t N_0$$

exponential

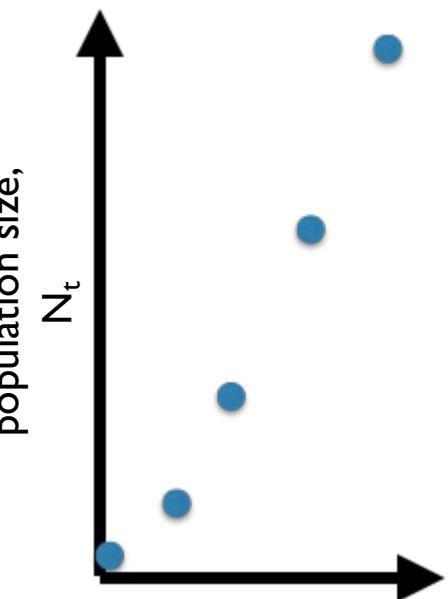
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$$\lambda^t N_0 = N_0 e^{rt}$$

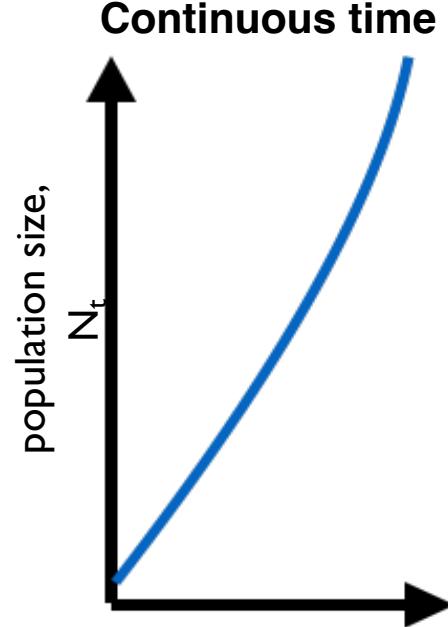
$$\lambda^t = e^{rt}$$

$$\lambda = e^r$$

Discrete time



Continuous time



Continuous models can be discretized.

Discrete models can be approximated in continuous time.

Geometric vs. exponential growth

geometric

$$N_t = \lambda^t N_0$$

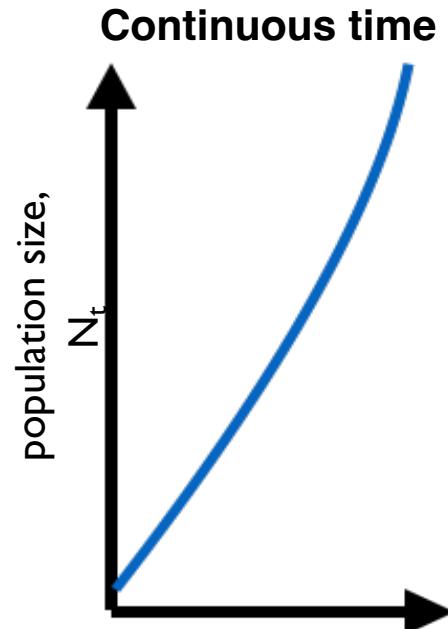
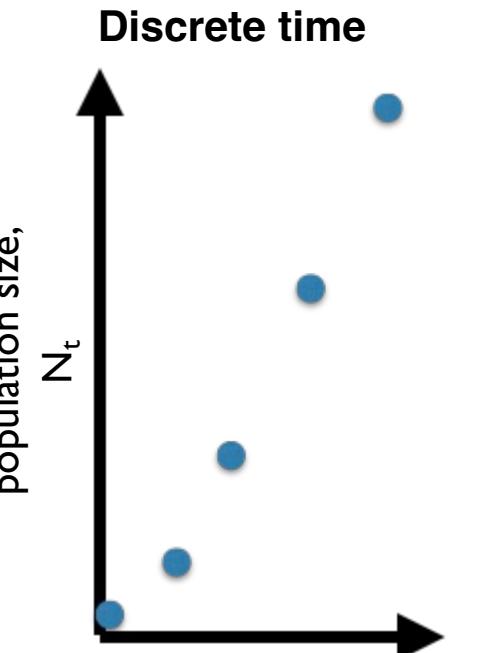
exponential

$$N_t = N_0 e^{rt}$$

$$\lambda^t N_0 = N_0 e^{rt}$$

$$\lambda^t = e^{rt}$$

$$\lambda = e^r$$



Continuous models can be discretized.

Discrete models can be approximated in continuous time.

How to choose what to do?

Geometric vs. exponential growth

geometric

$$N_t = \lambda^t N_0$$

exponential

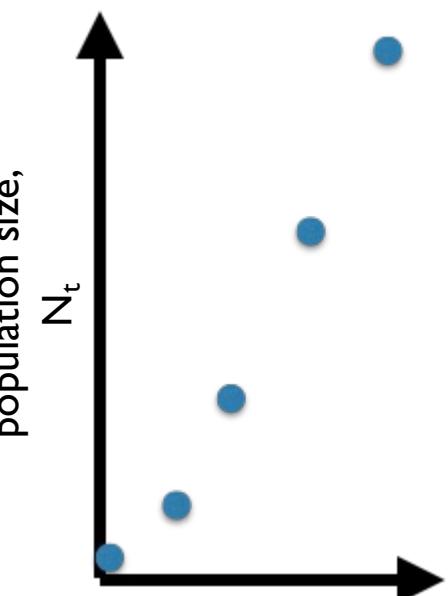
$$N_t = N_0 e^{rt}$$

$$\lambda^t N_0 = N_0 e^{rt}$$

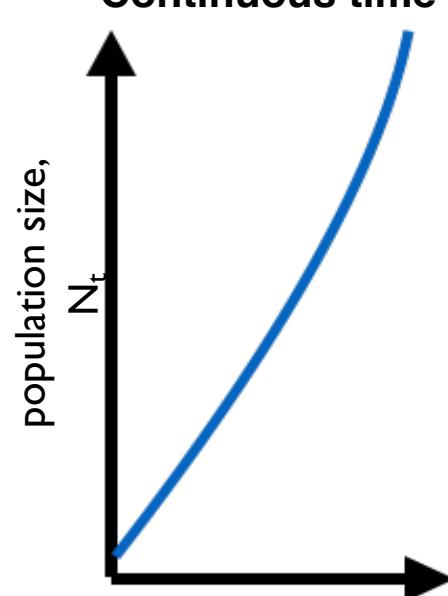
$$\lambda^t = e^{rt}$$

$$\lambda = e^r$$

Discrete time



Continuous time



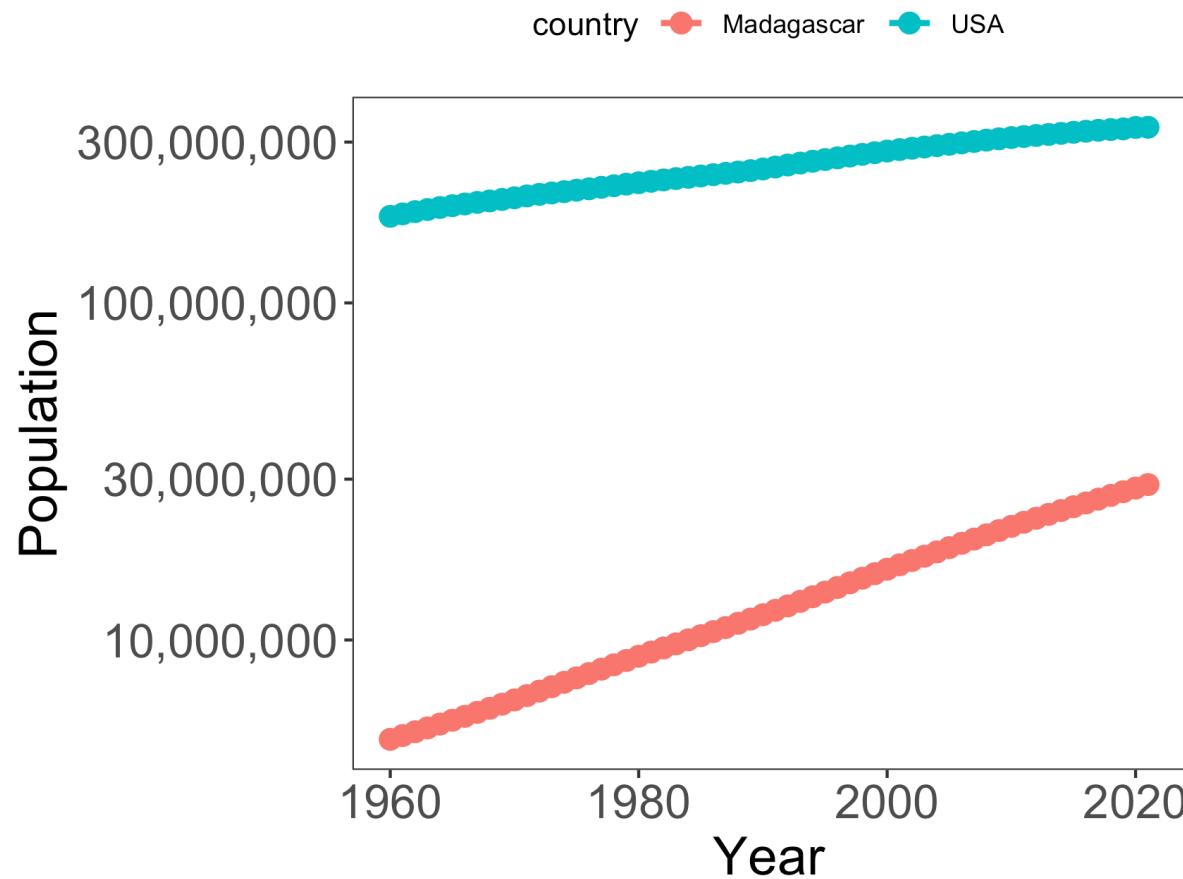
Continuous models can be discretized.

Discrete models can be approximated in continuous time.

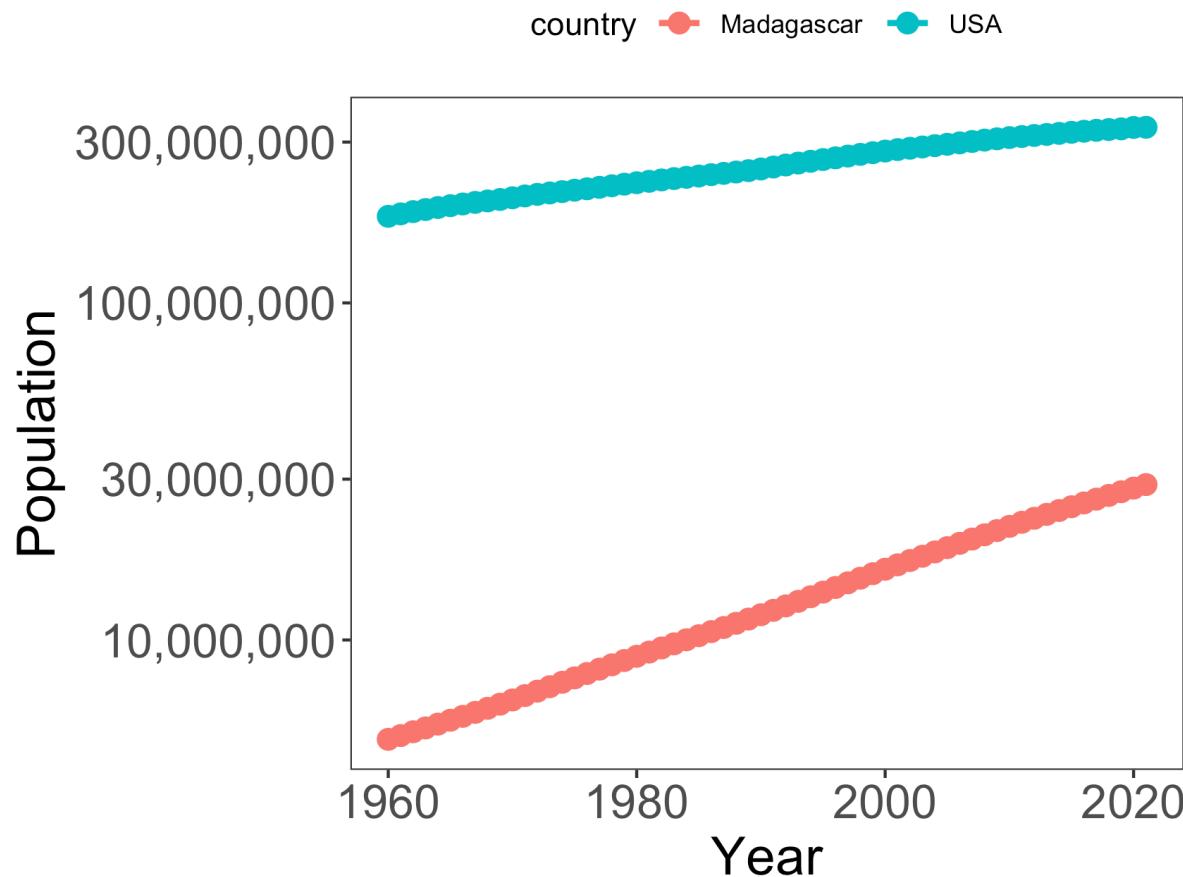
How to choose what to do?

The answer depends on the data and the question at hand!

Geometric vs. exponential growth



Geometric vs. exponential growth

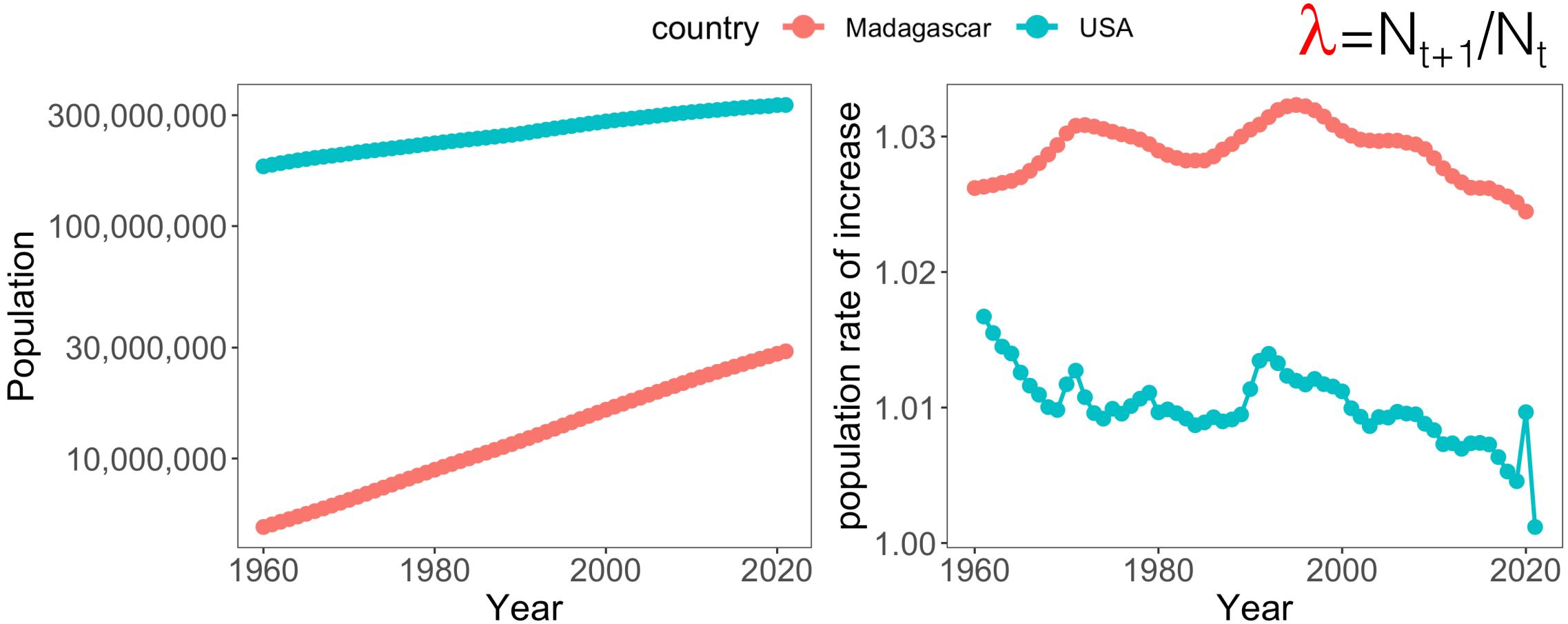


$$\lambda = N_{t+1}/N_t$$

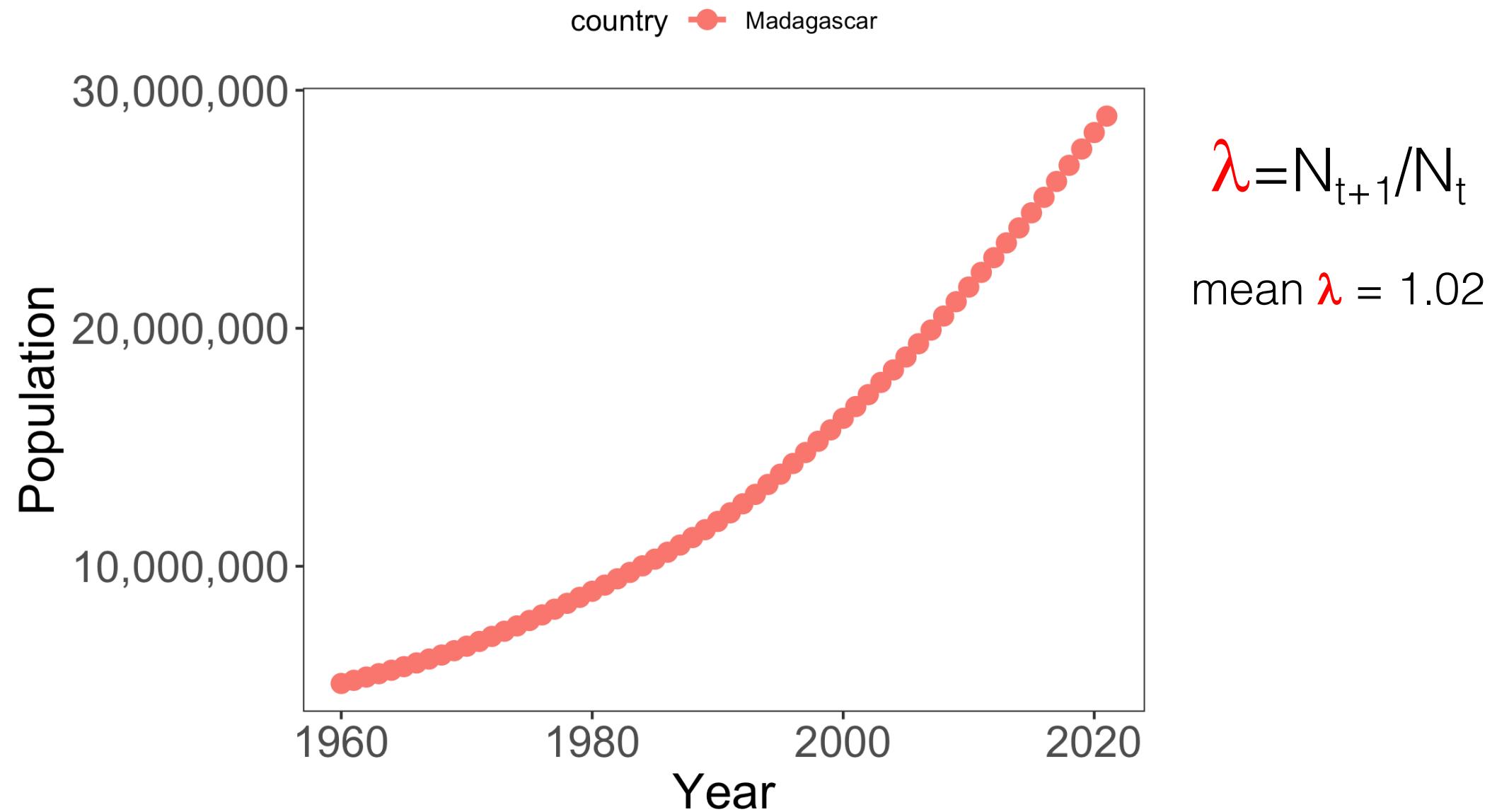
where $t = 1$ year

Which country has the higher growth rate?

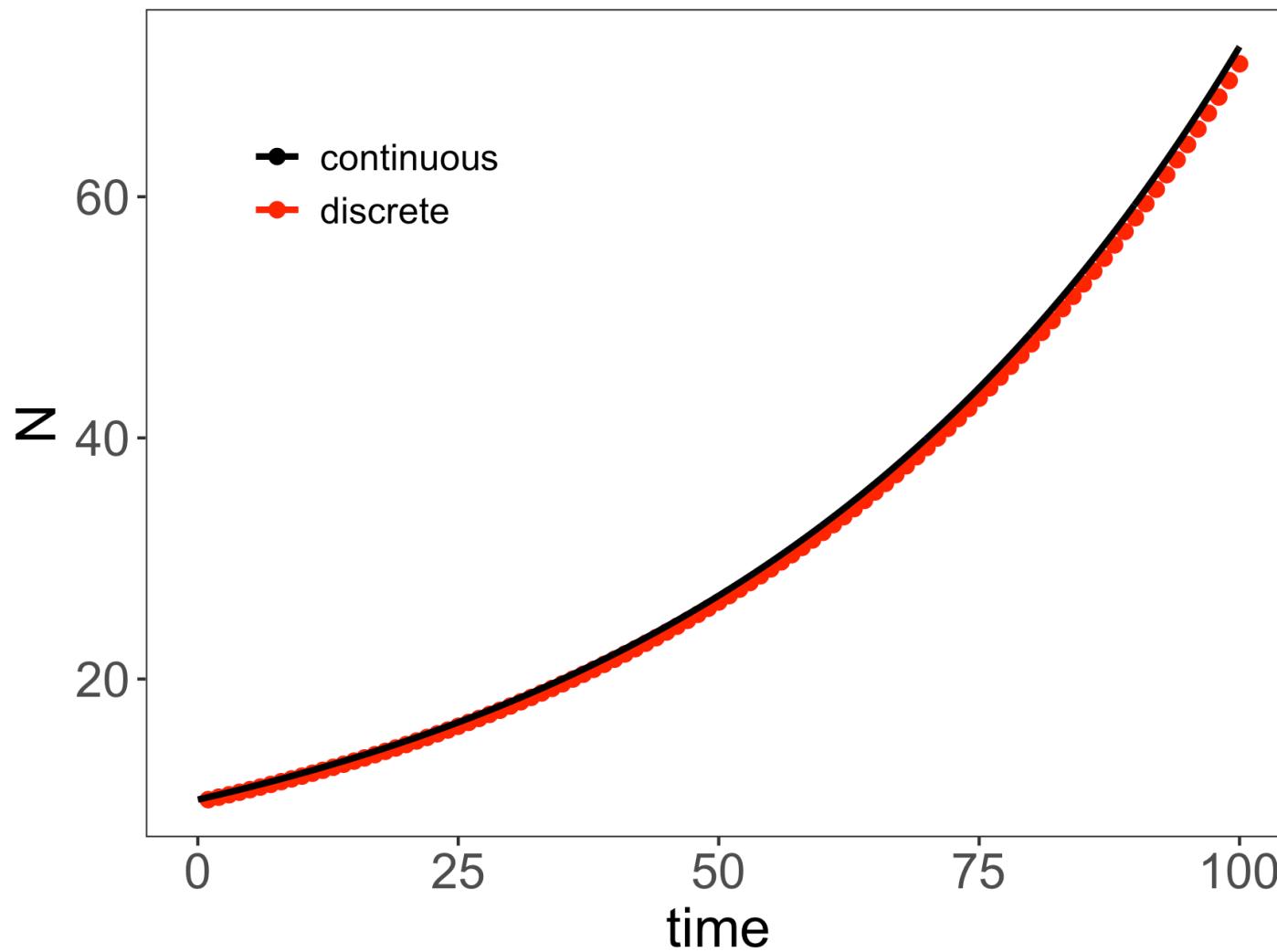
Geometric vs. exponential growth



Geometric growth approximation of Madagascar's population



Projecting population under geometric vs. exponential growth

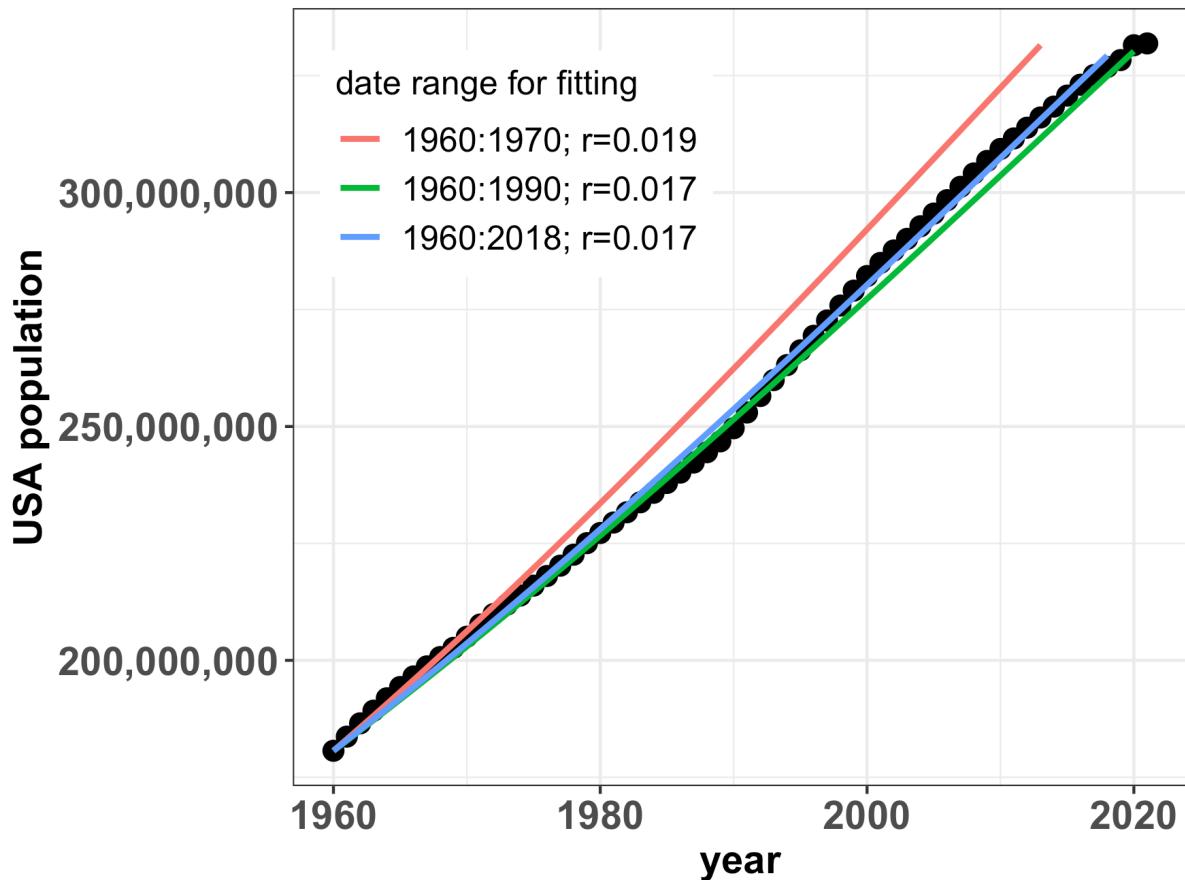


Geometric: $\lambda = 1.02$

Exponential: $r = \log(1.02) = 0.02$

Models are similar over
short time horizons
and/or when discrete
timesteps are small!

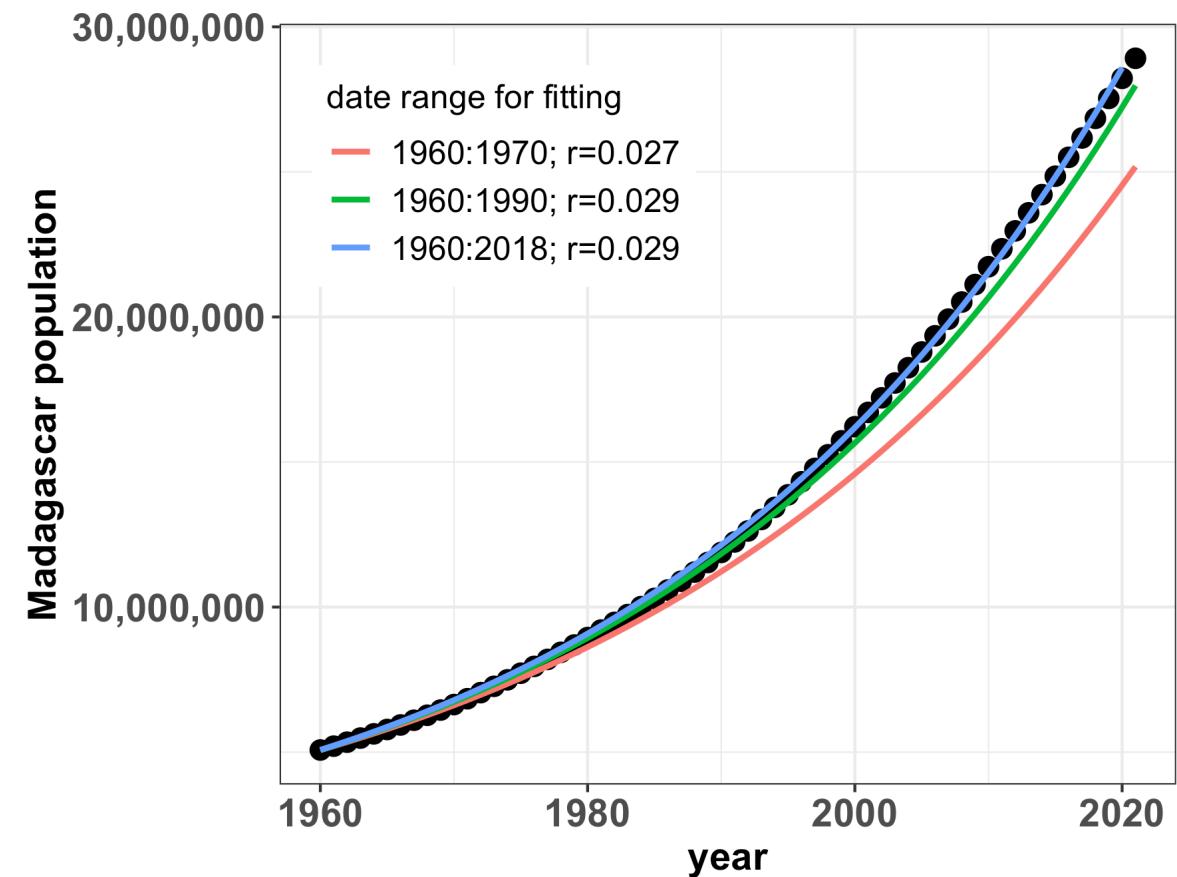
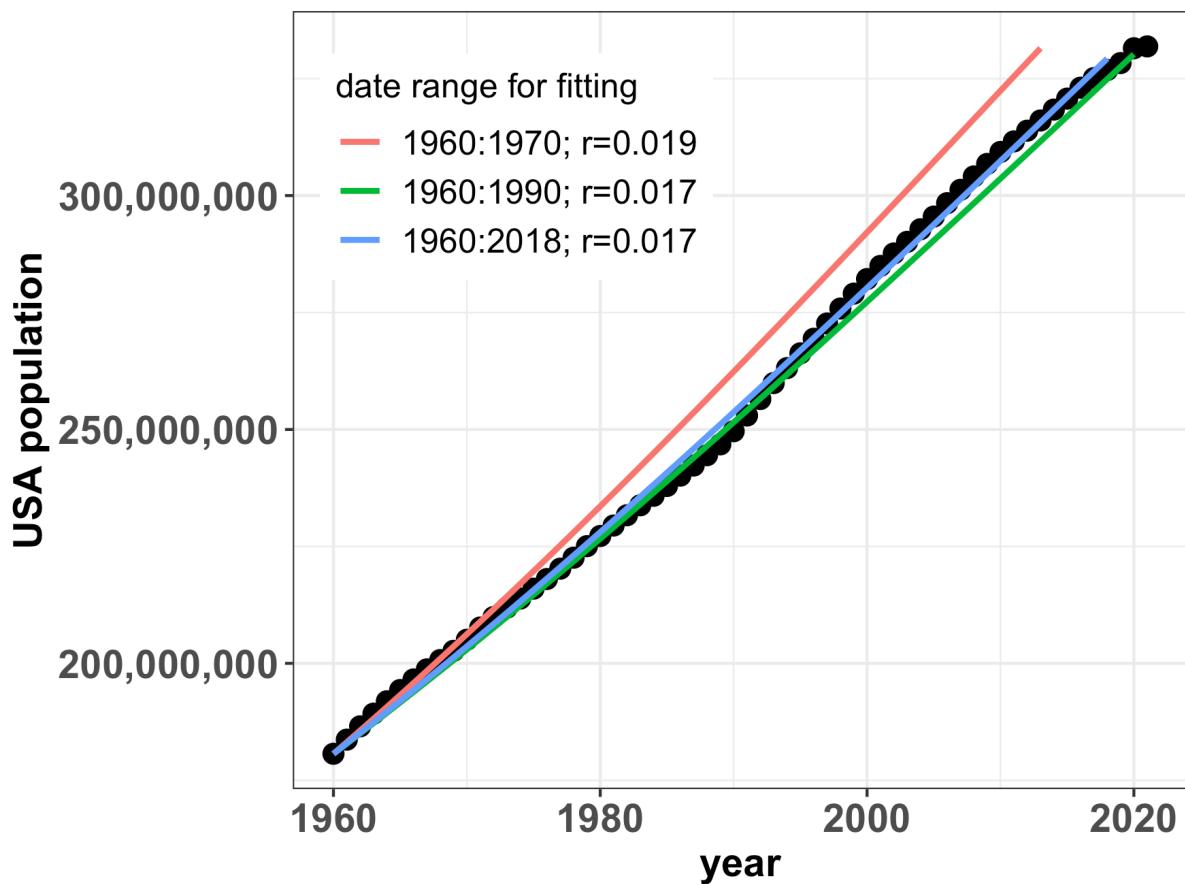
We can estimate growth rates by ‘fitting’ a model to data



US growth rates slowed over the time period!

Model fits to data from earlier years **overestimate** current population growth rates

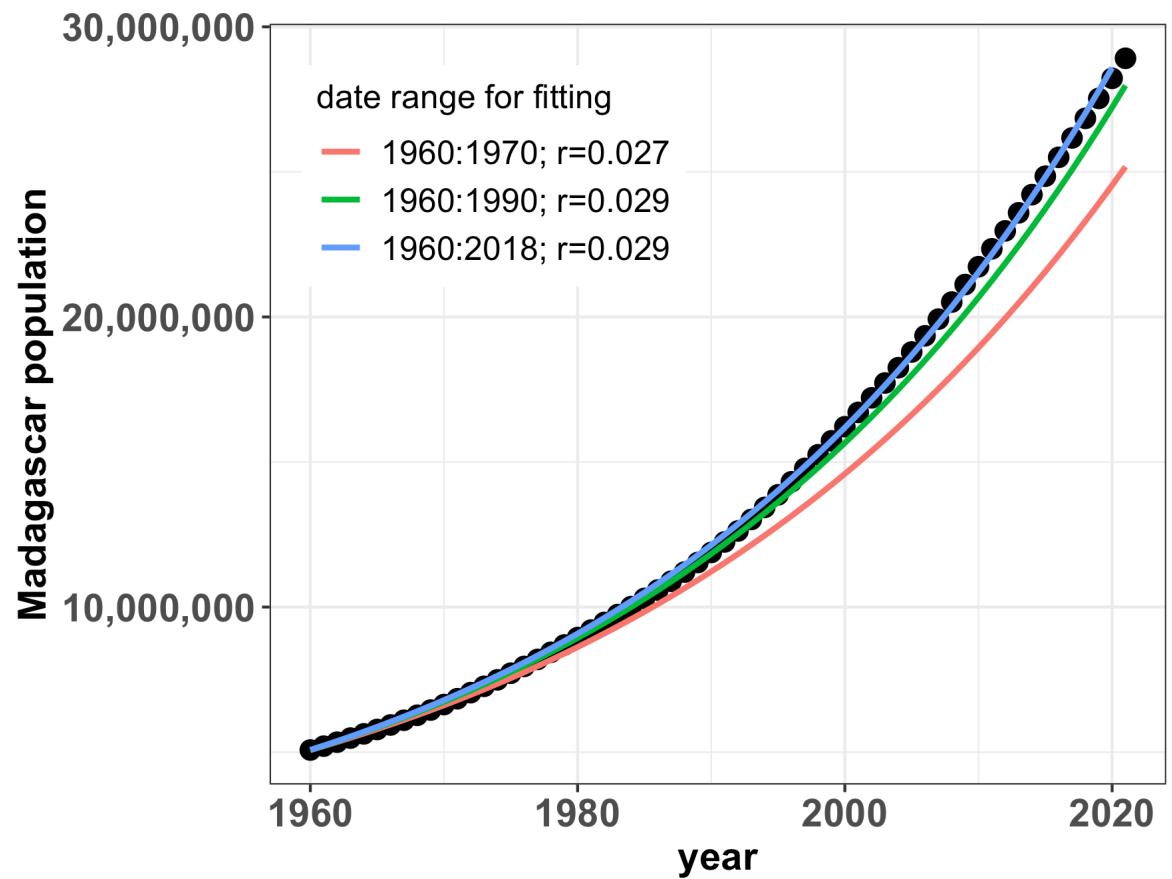
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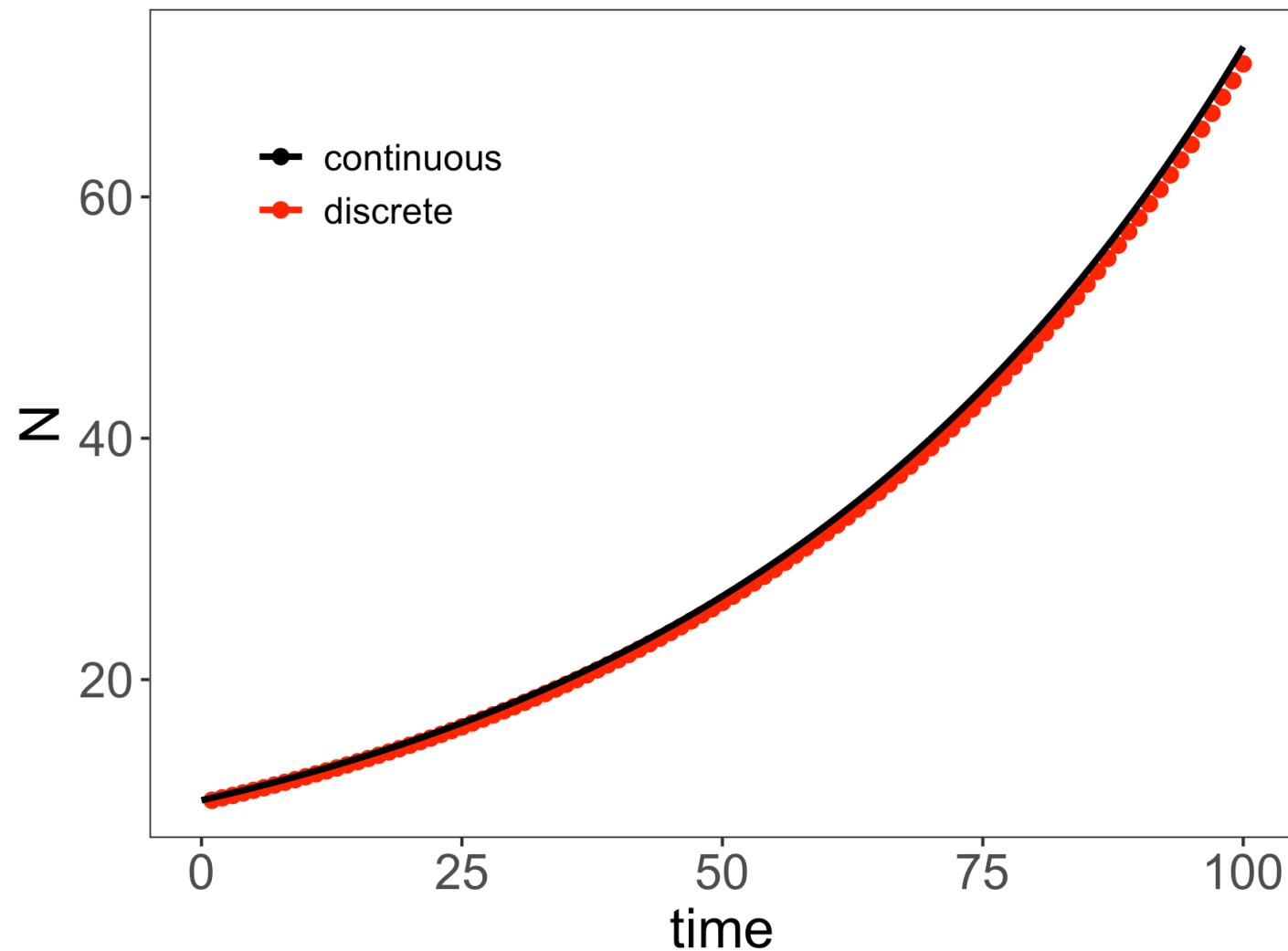
We can estimate growth rates by ‘fitting’ a model to data

Madagascar growth rates
accelerated over the time
period!

Model fits to data from earlier
years **underestimate** current
population growth rates



Both geometric and exponential growth are **unchecked**.



Malthus proposed some limits to population growth

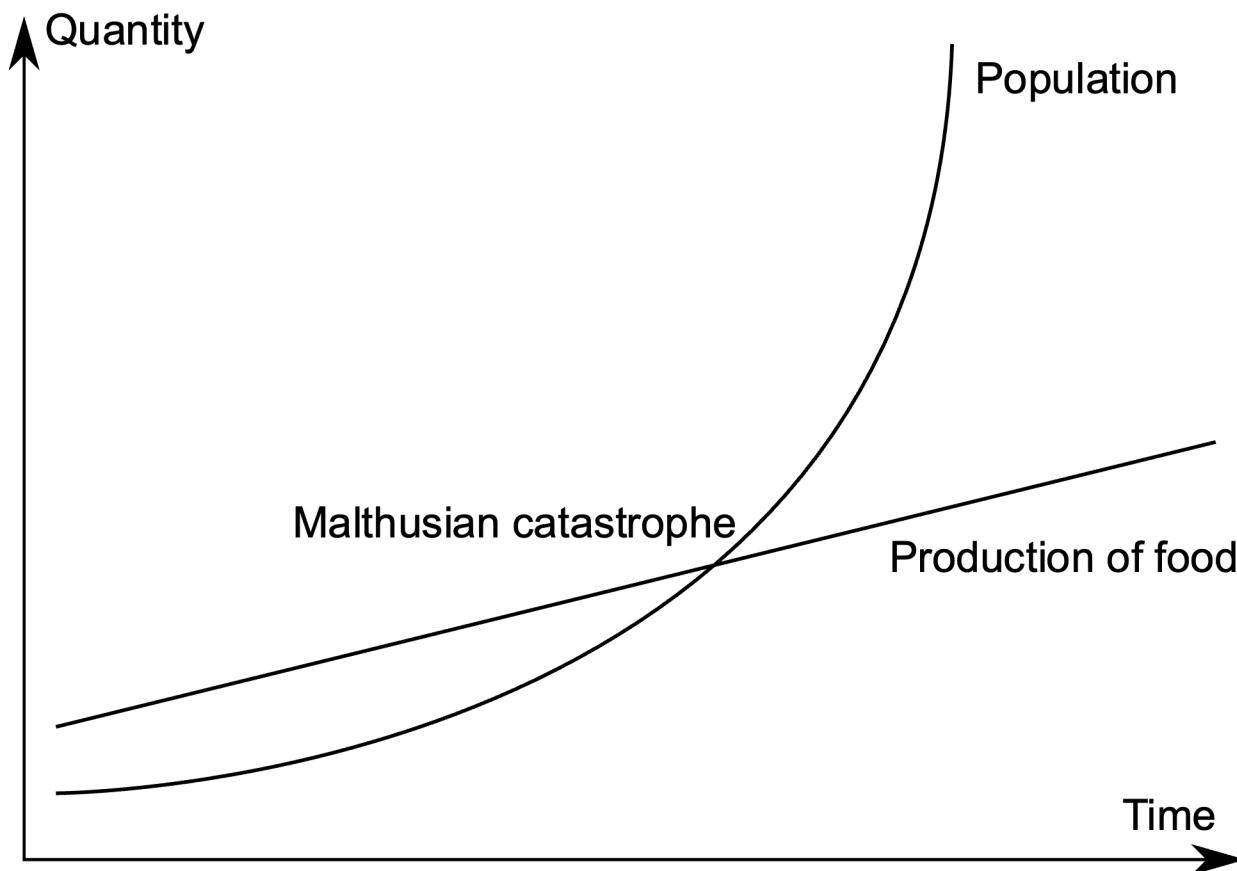
[. . .] the power of population is indefinitely greater than the power in the earth to produce subsistence for man. Population, when unchecked, increases in a geometrical ratio. Subsistence increases only in an arithmetical ratio. A slight acquaintance with numbers will shew the immensity of the first power in comparison of the second. By that law of our nature which makes food necessary to the life of man, the effects of these two unequal powers must be kept equal. This implies a strong and constantly operating check on population from the difficulty of subsistence. This difficulty must fall somewhere; and must necessarily be severely felt by a large portion of mankind."

- Thomas Malthus (1798)

An Essay on the Principle of Population as it Effects the Future Improvement of Society, With Remarks on the Speculations of Mr Godwin, Mr. Condorcet and Other Writers



Malthus proposed some limits to population growth

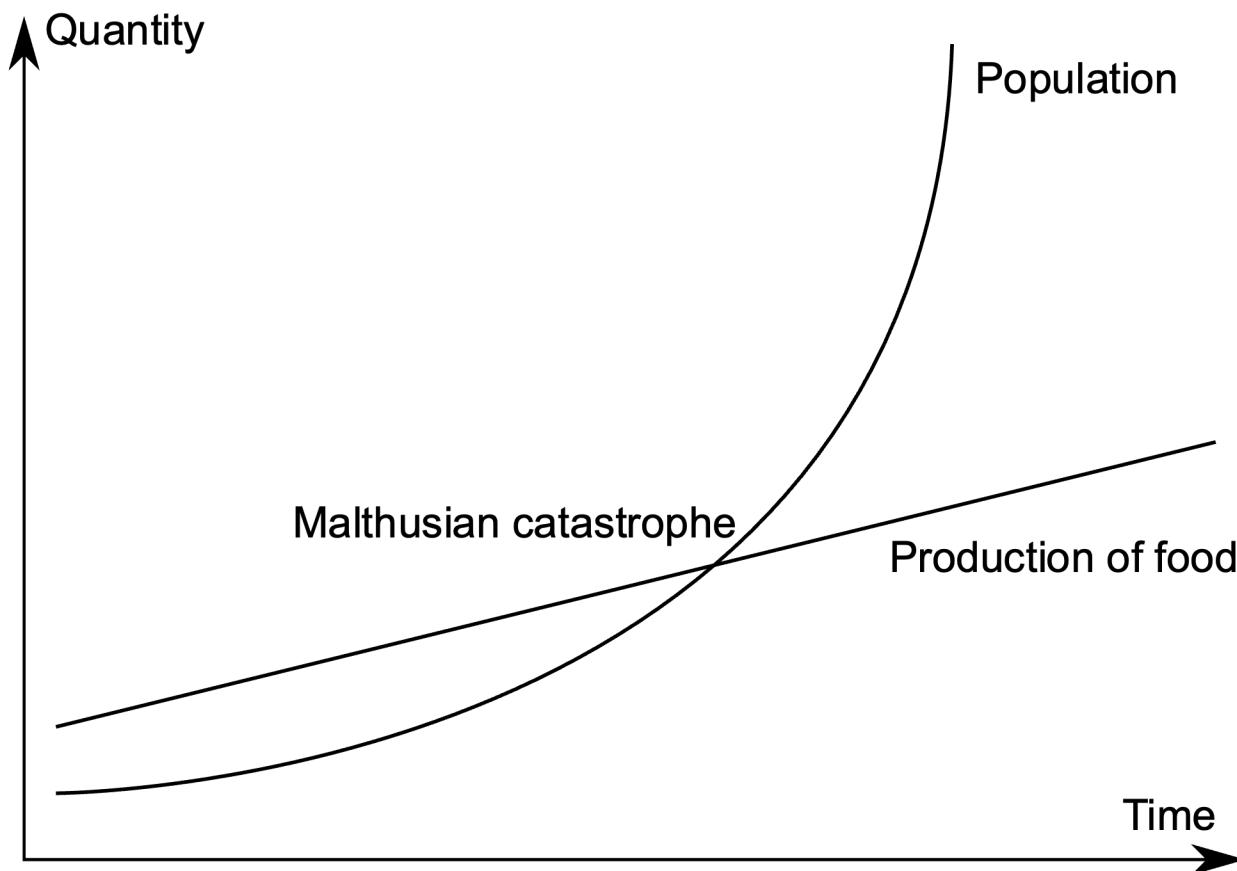


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Problem!
No basis for
assumption of
arithmetical ratio
for food.



Logistic growth equation

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

“We shall not insist on the hypothesis of geometric progression, given that it can hold only in very special circumstances; for example, when a fertile territory of almost unlimited size happens to be inhabited by people...”

- Pierre-Francois Verhulst (1838)

Logistic growth equation

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

↑ ↑

intrinsic growth rate **carrying capacity**

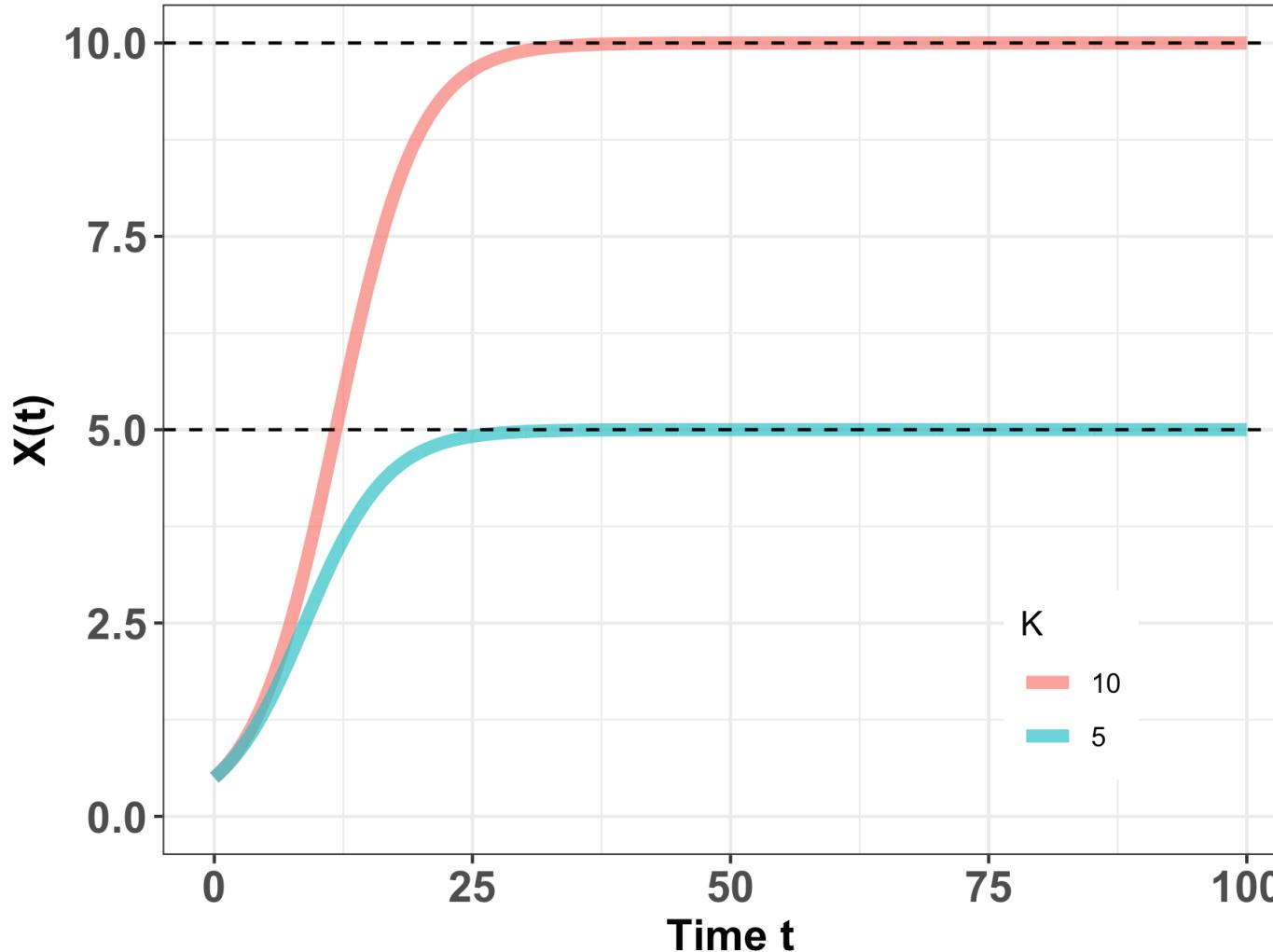
"We shall not insist on the hypothesis of geometric progression, given that it can hold only in very special circumstances; for example, when a fertile territory of almost unlimited size happens to be inhabited by people..."

- Pierre-Francois Verhulst (1838)

Population growth slows as abundance approaches **carrying capacity**.
Population growth is **density-dependent**.

Logistic growth equation

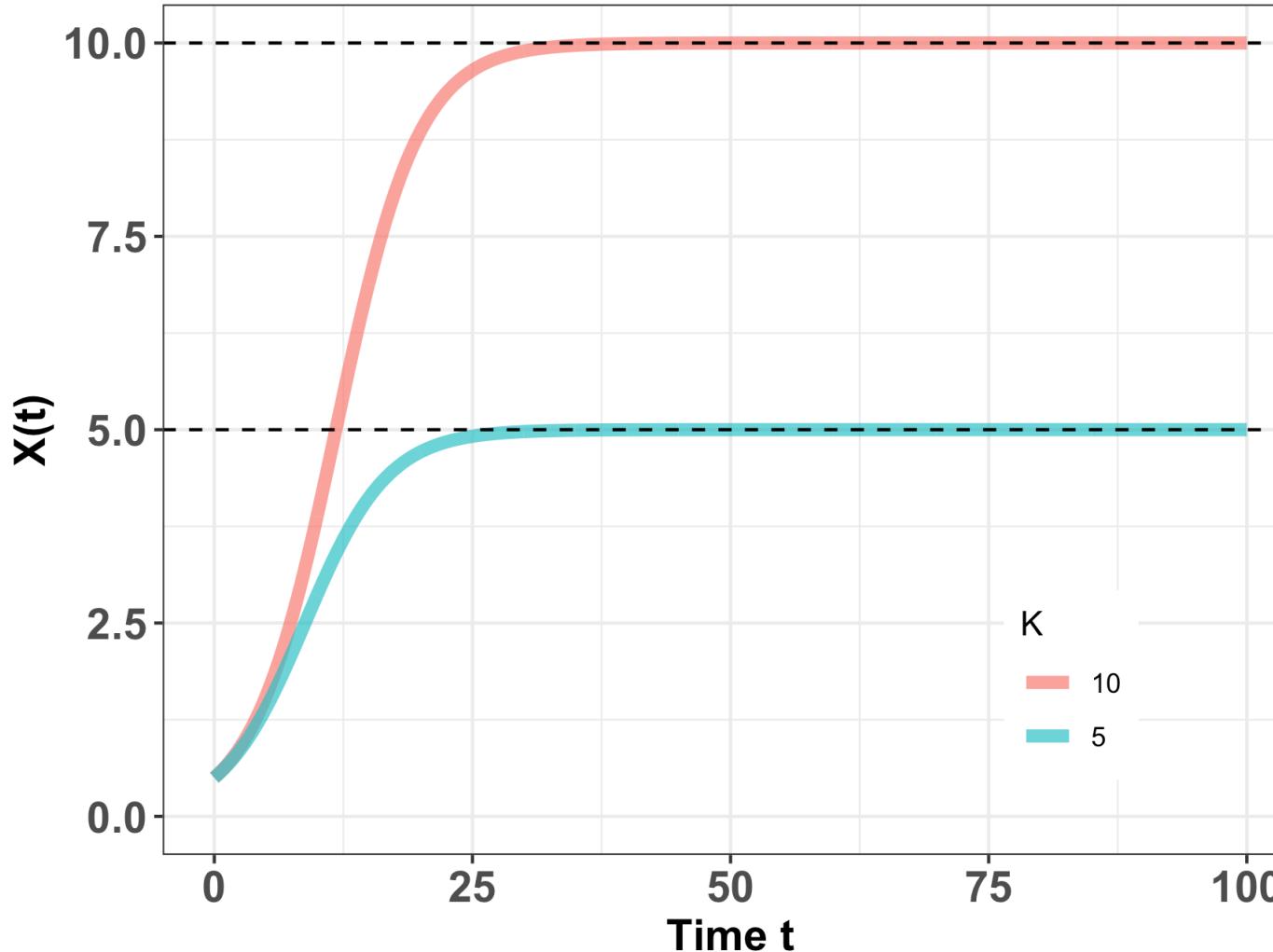
$$\frac{dN}{dt} = rN \left(1 - \frac{N}{K}\right)$$



Population growth slows to 0 as N approaches K , or – in other words – as the total population size approaches **carrying capacity**.

Logistic growth equation

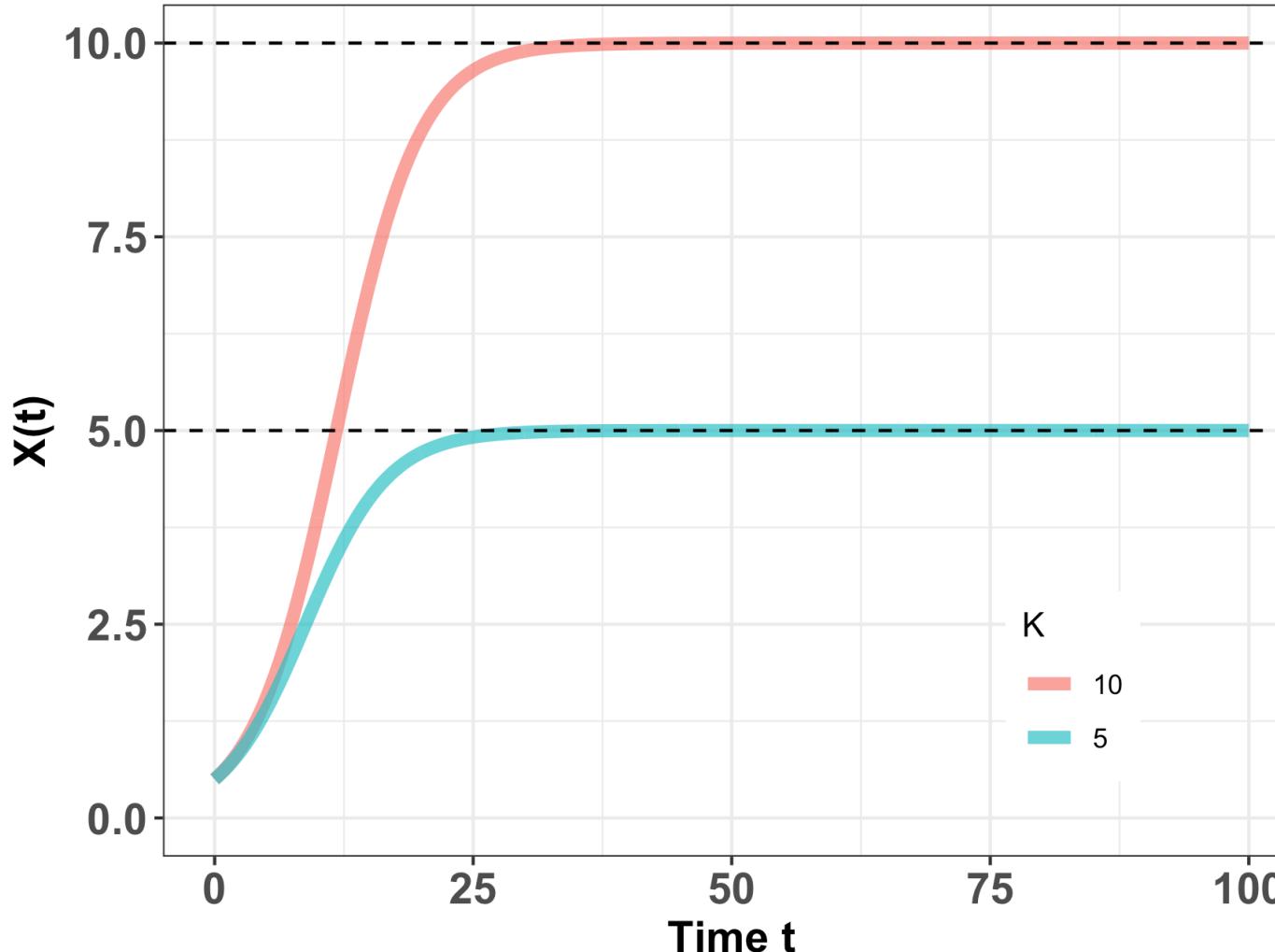
$$\frac{dN}{dt} = rN \left(1 - \frac{N}{K}\right)$$



Carrying capacity=
maximum population size
an environment can
sustain indefinitely.

Logistic growth equation

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

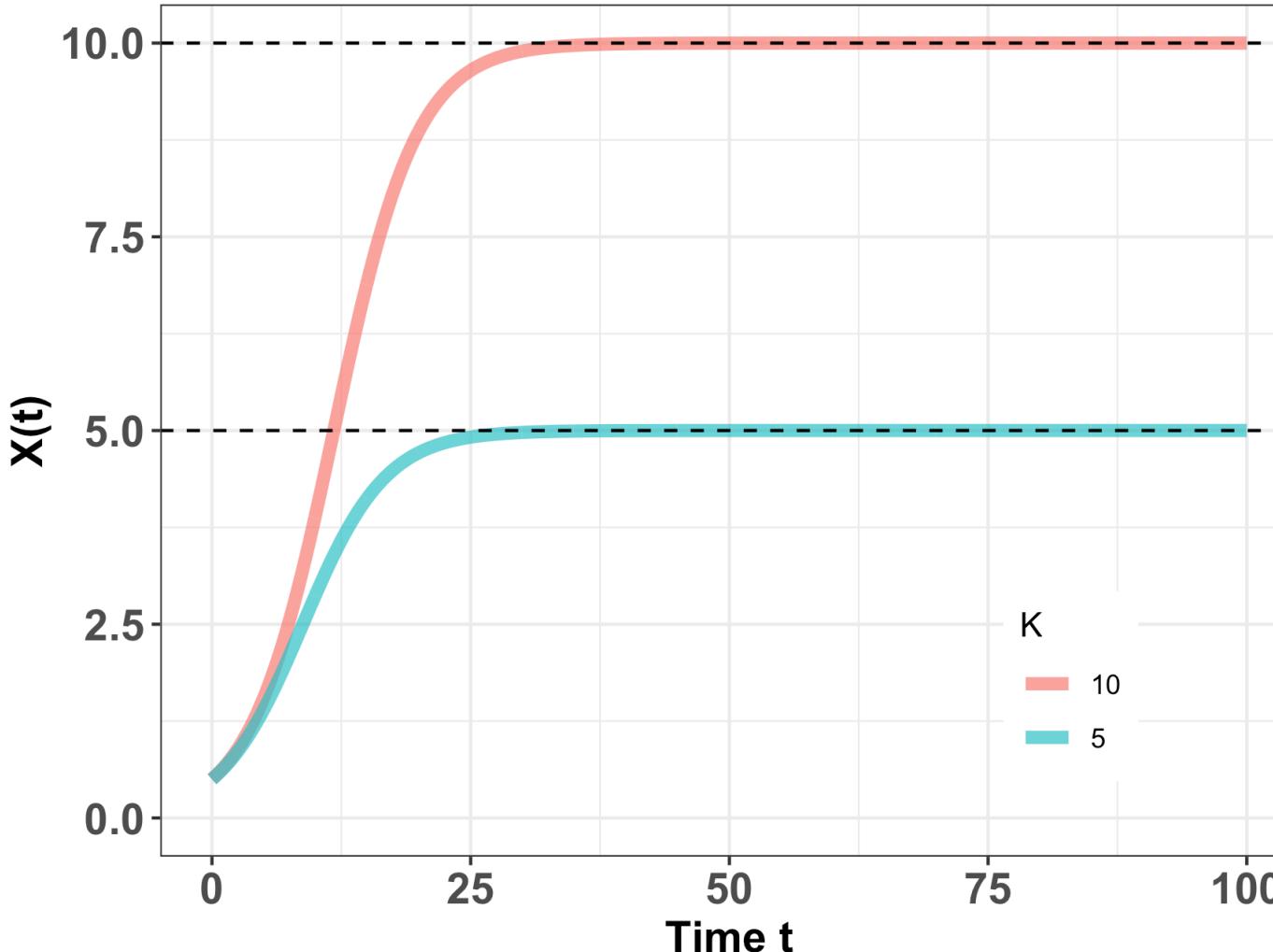


Carrying capacity=
maximum population size
an environment can
sustain indefinitely.

Ecology = organisms
interacting with each other
and the **environment**

Logistic growth equation

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



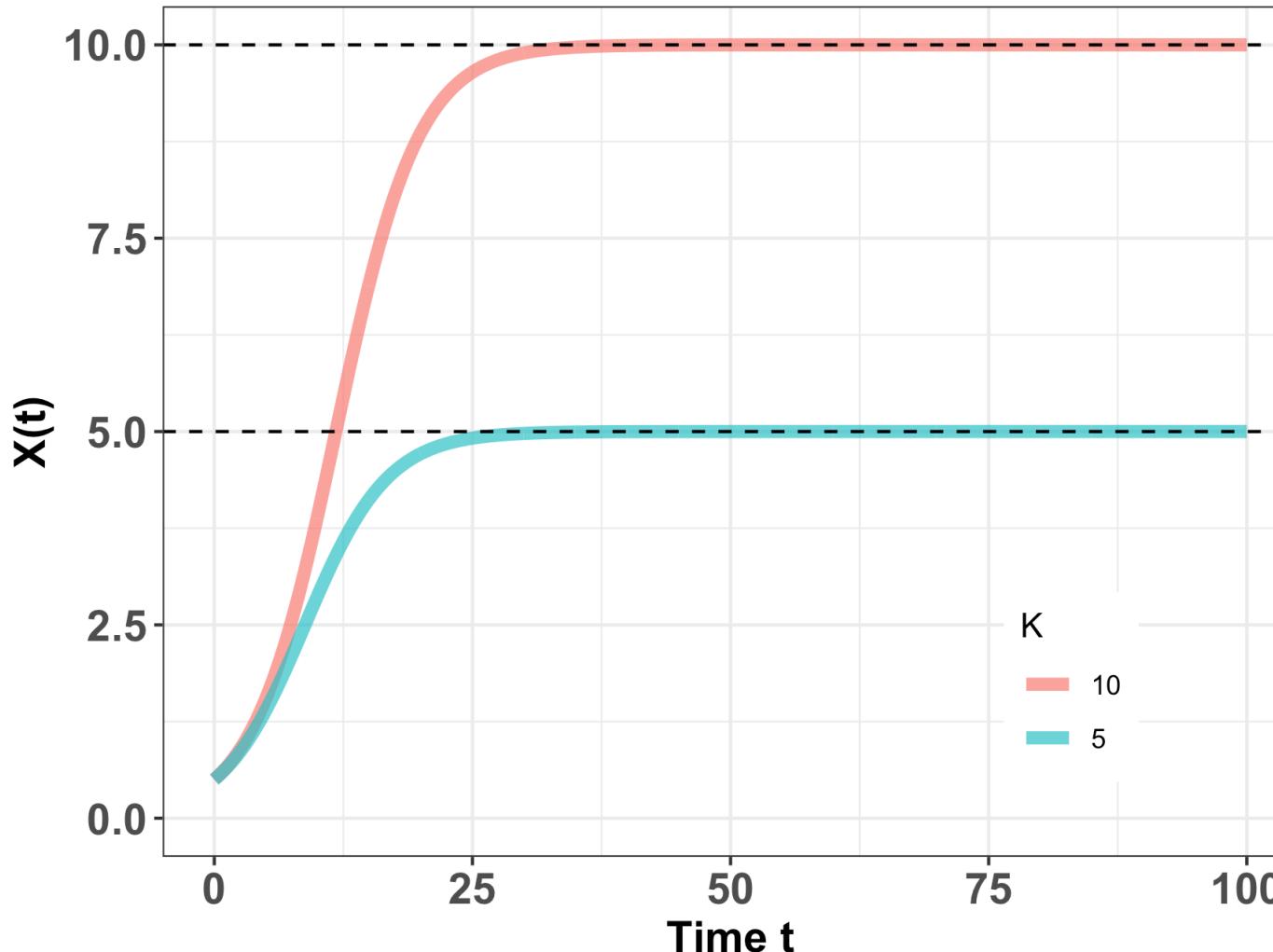
Carrying capacity=
maximum population size
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Ecology = organisms
interacting with each other
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K can change!

Logistic growth equation

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



Carrying capacity=
maximum population size
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Ecology = organisms
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K can change!

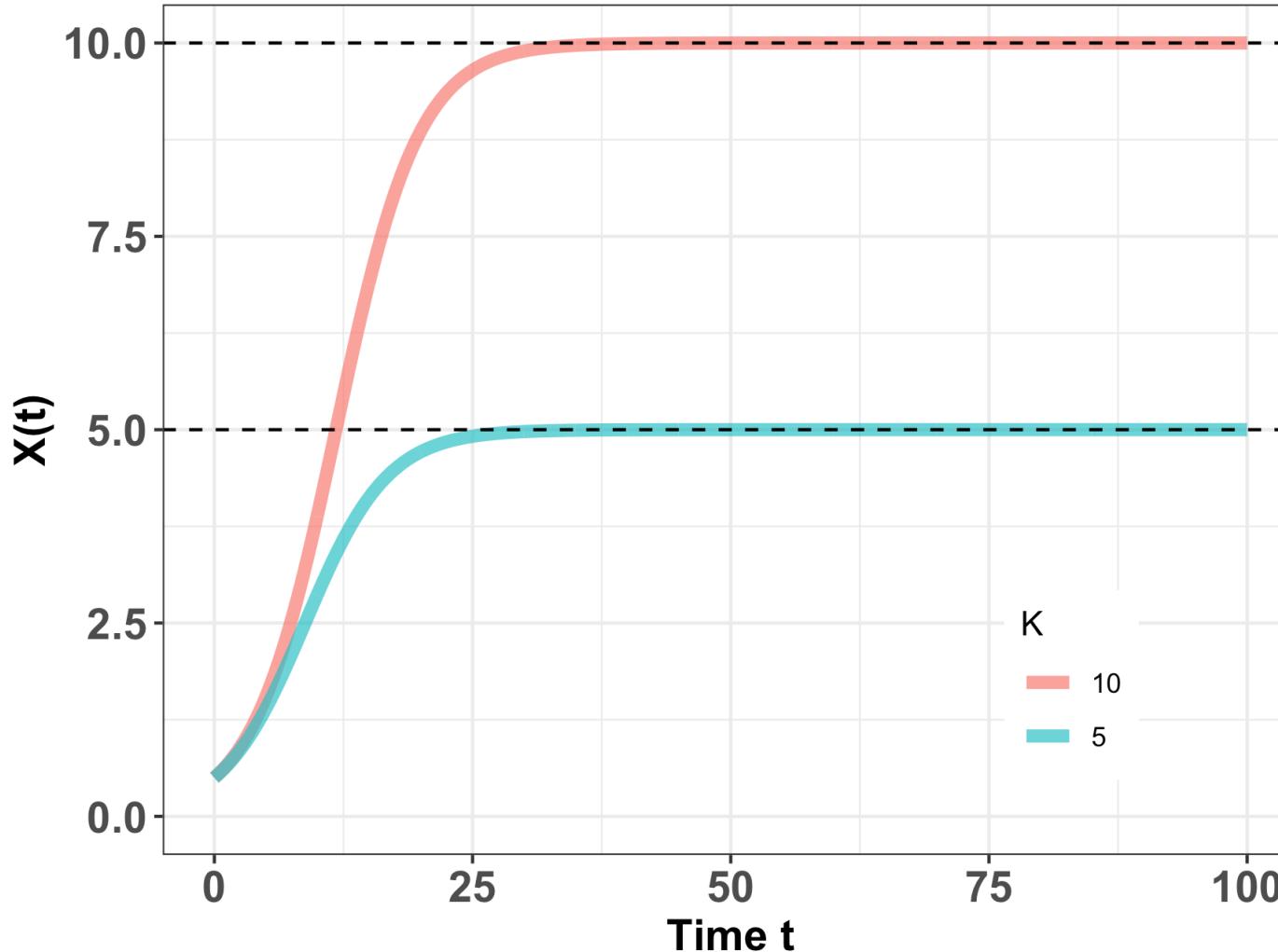
'r' vs. **'K'**-selected species

Logistic growth and equilibrium

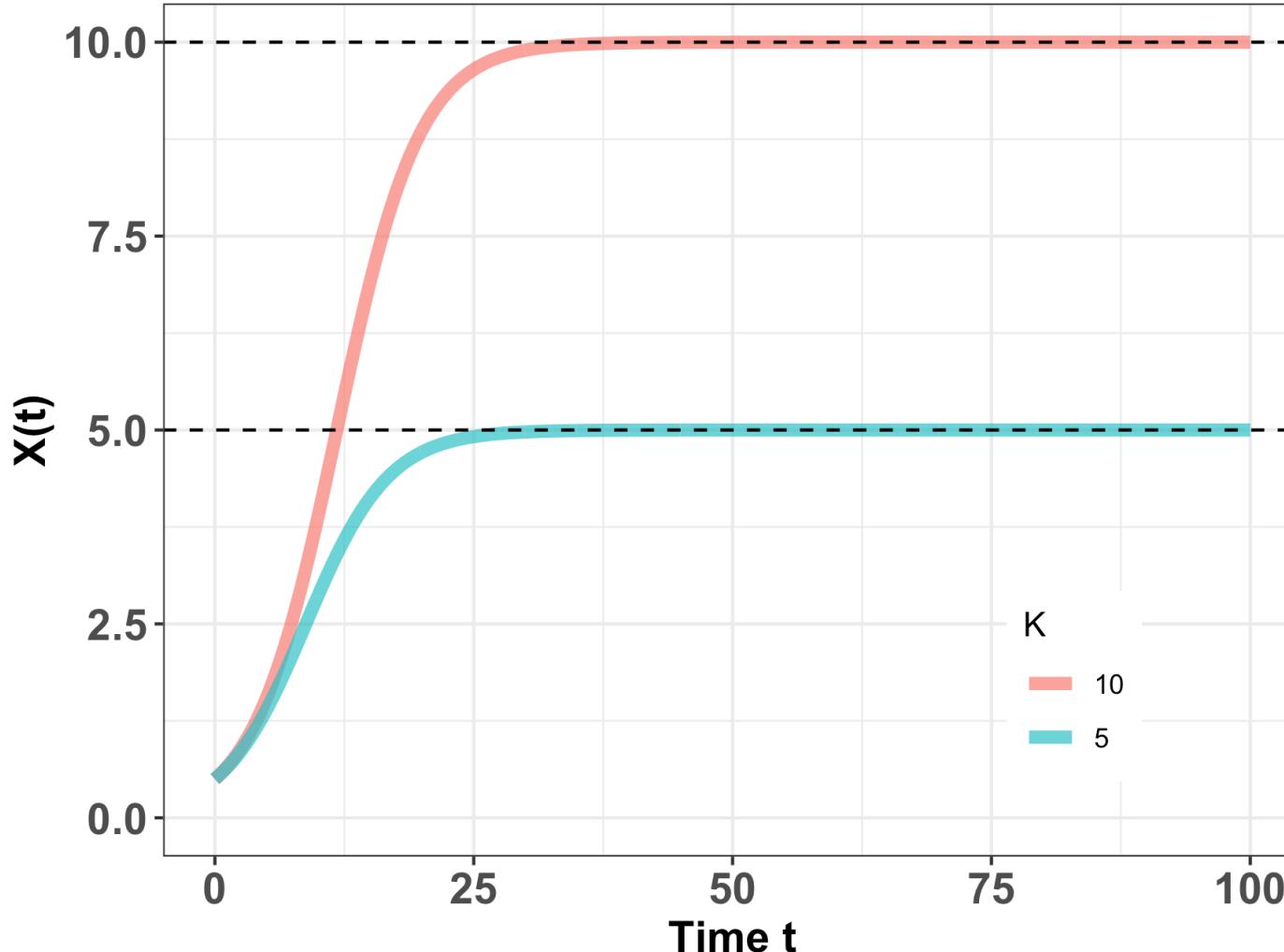
$$\frac{dN}{dt} = rN \left(1 - \frac{N}{K}\right)$$

$$\frac{dN}{dt} = 0$$

When population size is not changing, the population is said to be at **equilibrium**.



Logistic growth and equilibrium



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

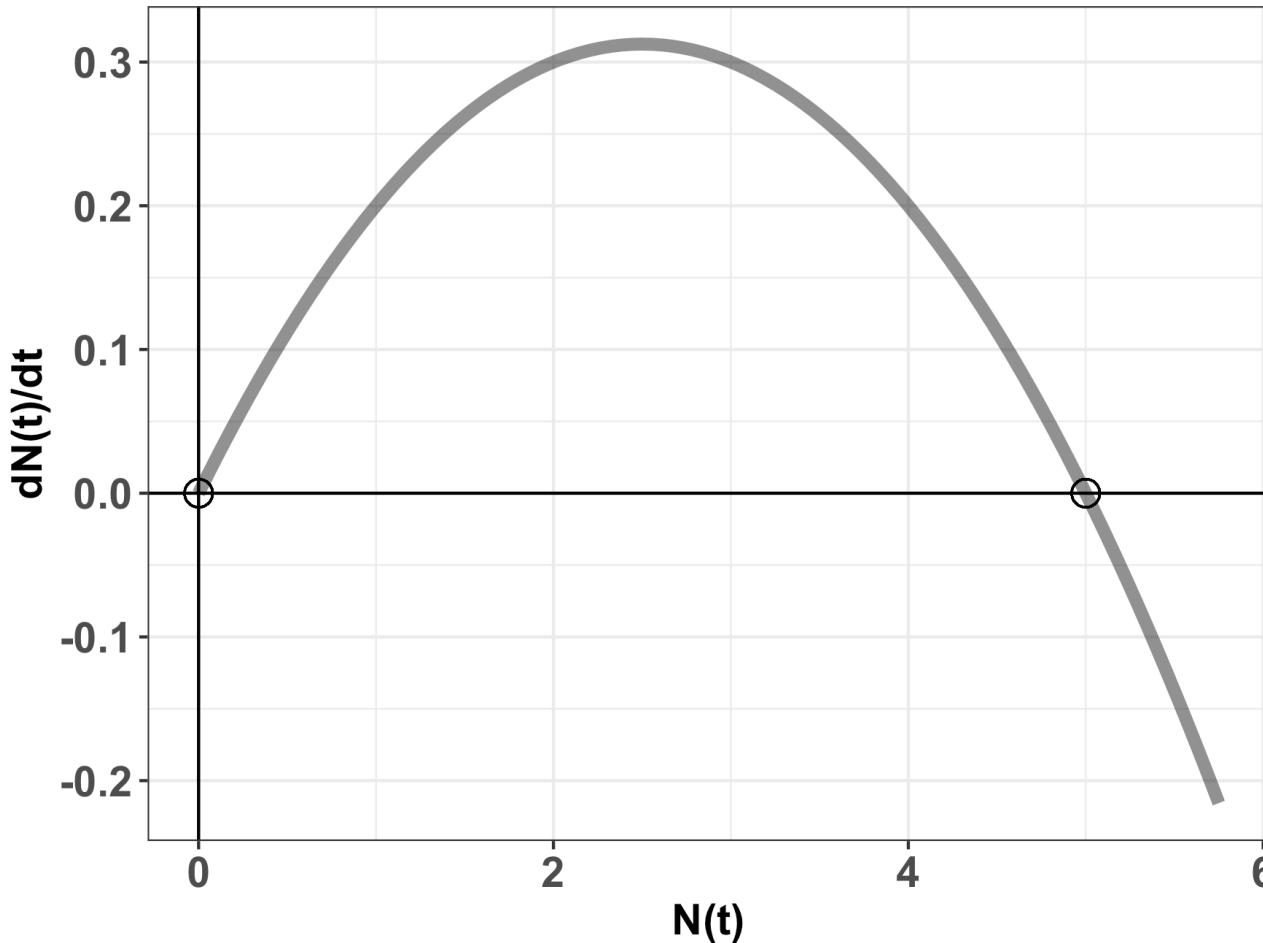
$$\frac{dN}{dt} = 0$$

$$0 = rN \left(1 - \frac{N}{K}\right)$$

$$N = K$$

A little algebra shows that the population at carrying capacity is at **equilibrium**.

Logistic growth and equilibrium



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

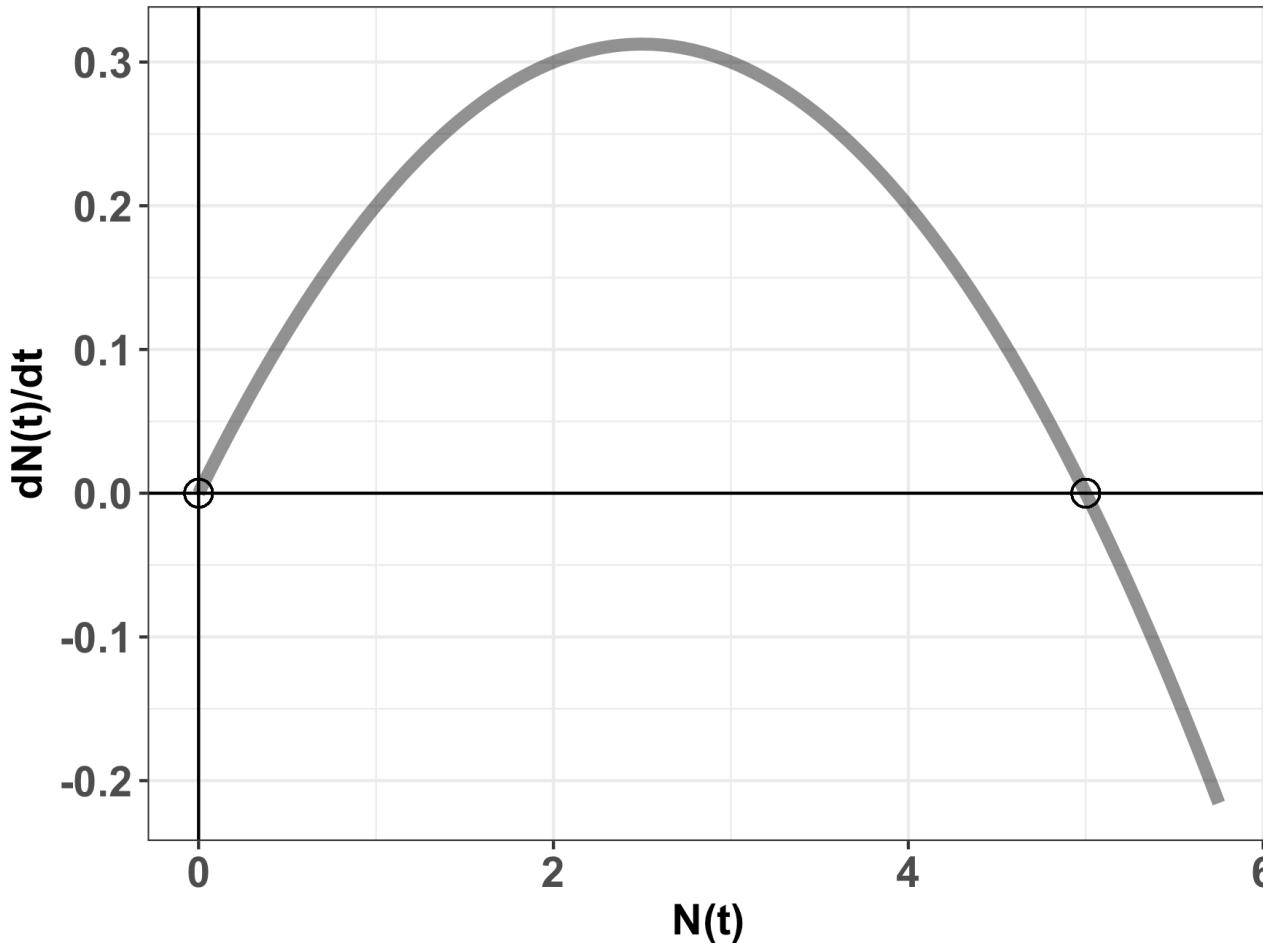
$$\frac{dN}{dt} = 0$$

$$0 = rN \left(1 - \frac{N}{K}\right)$$

$N = K$ or
 $N = 0$

logistic
growth
equilibria

Logistic growth and equilibrium



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

$$\frac{dN}{dt} = 0$$

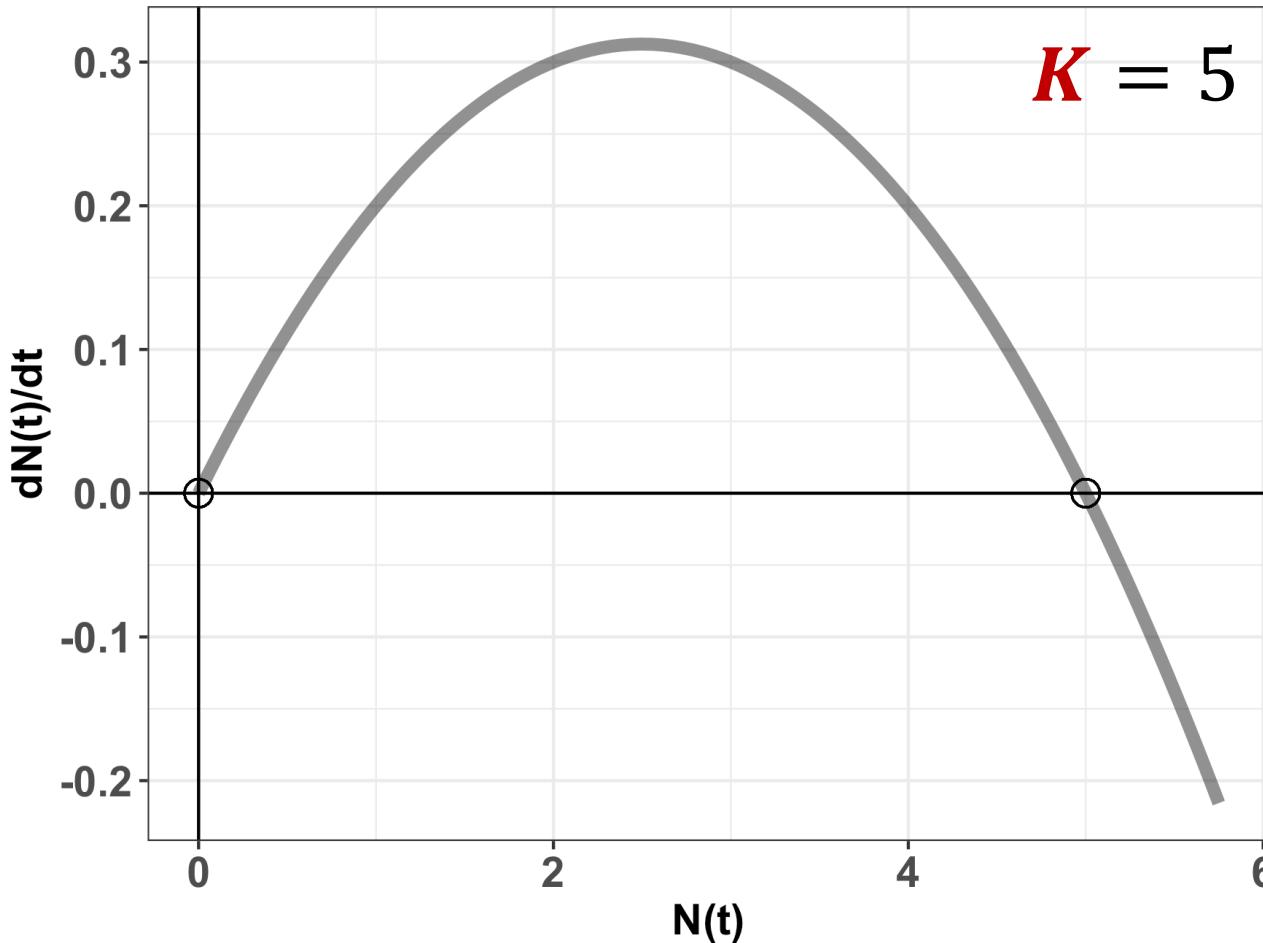
$$0 = rN \left(1 - \frac{N}{K}\right)$$

$N = K$ or
 $N = 0$

logistic
growth
equilibria

What is **K**?

Logistic growth and equilibrium



What is \mathbf{K} ?

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

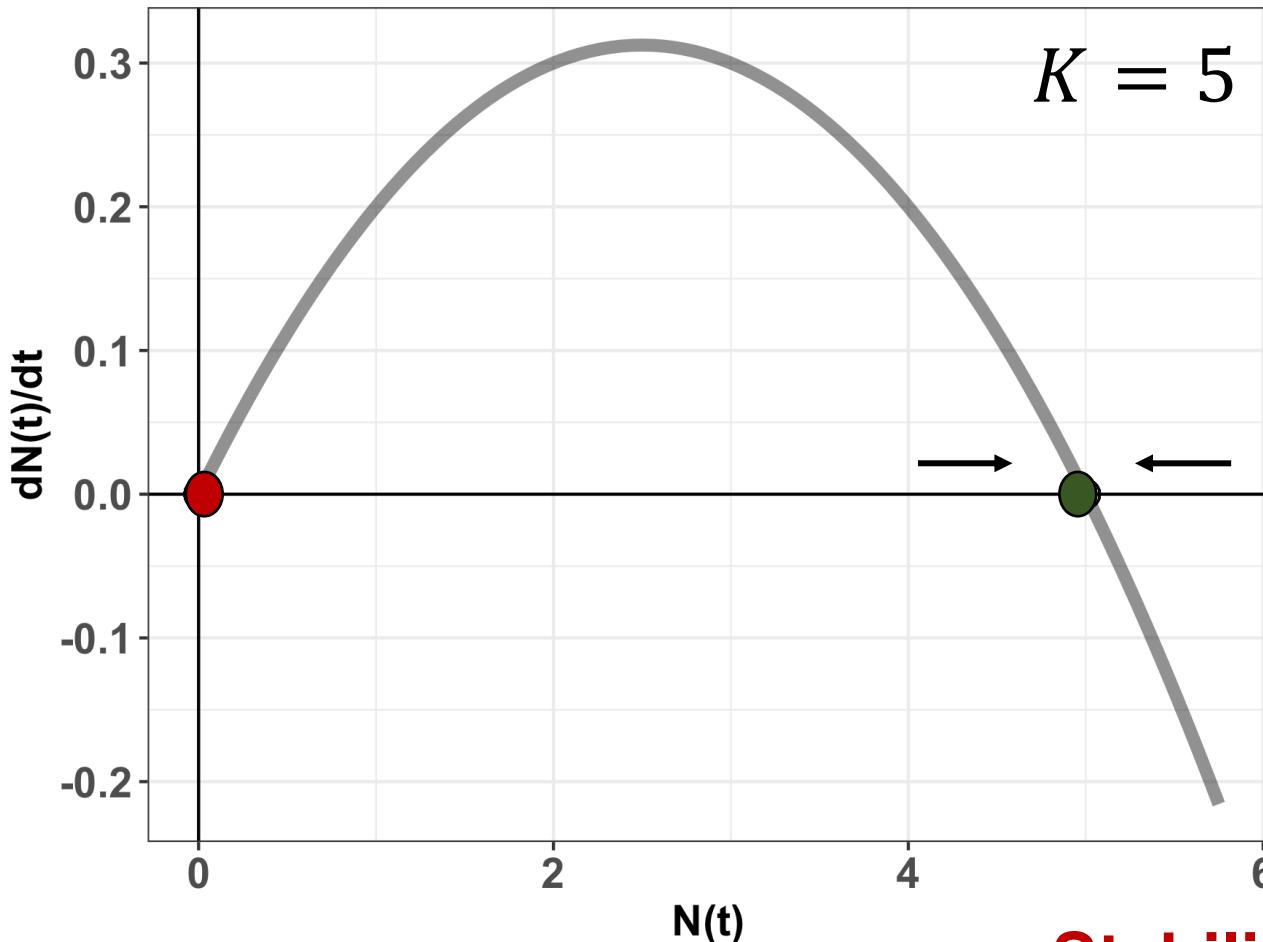
$$\frac{dN}{dt} = 0$$

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Logistic growth and equilibrium



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

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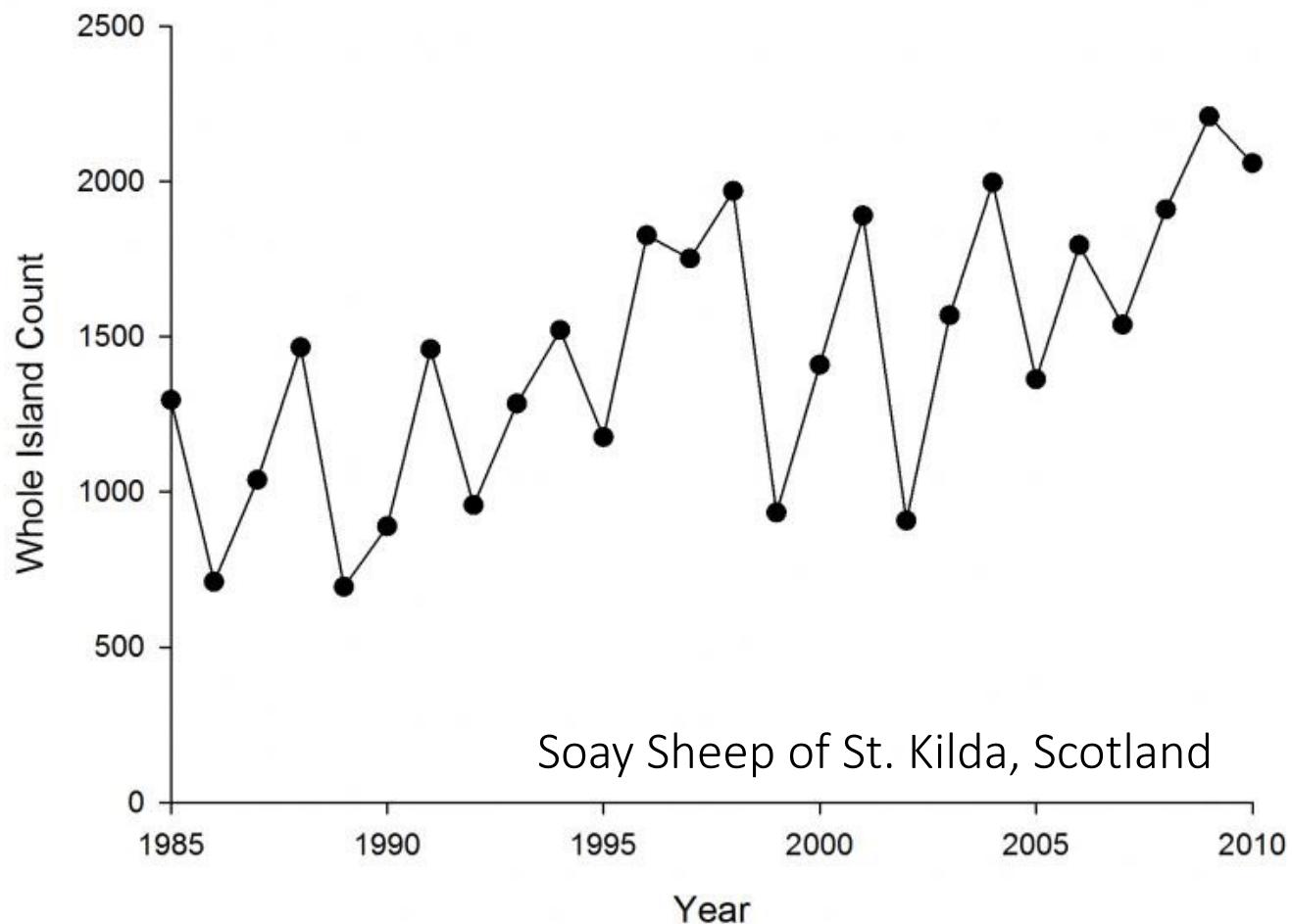
$$0 = rN \left(1 - \frac{N}{K}\right)$$

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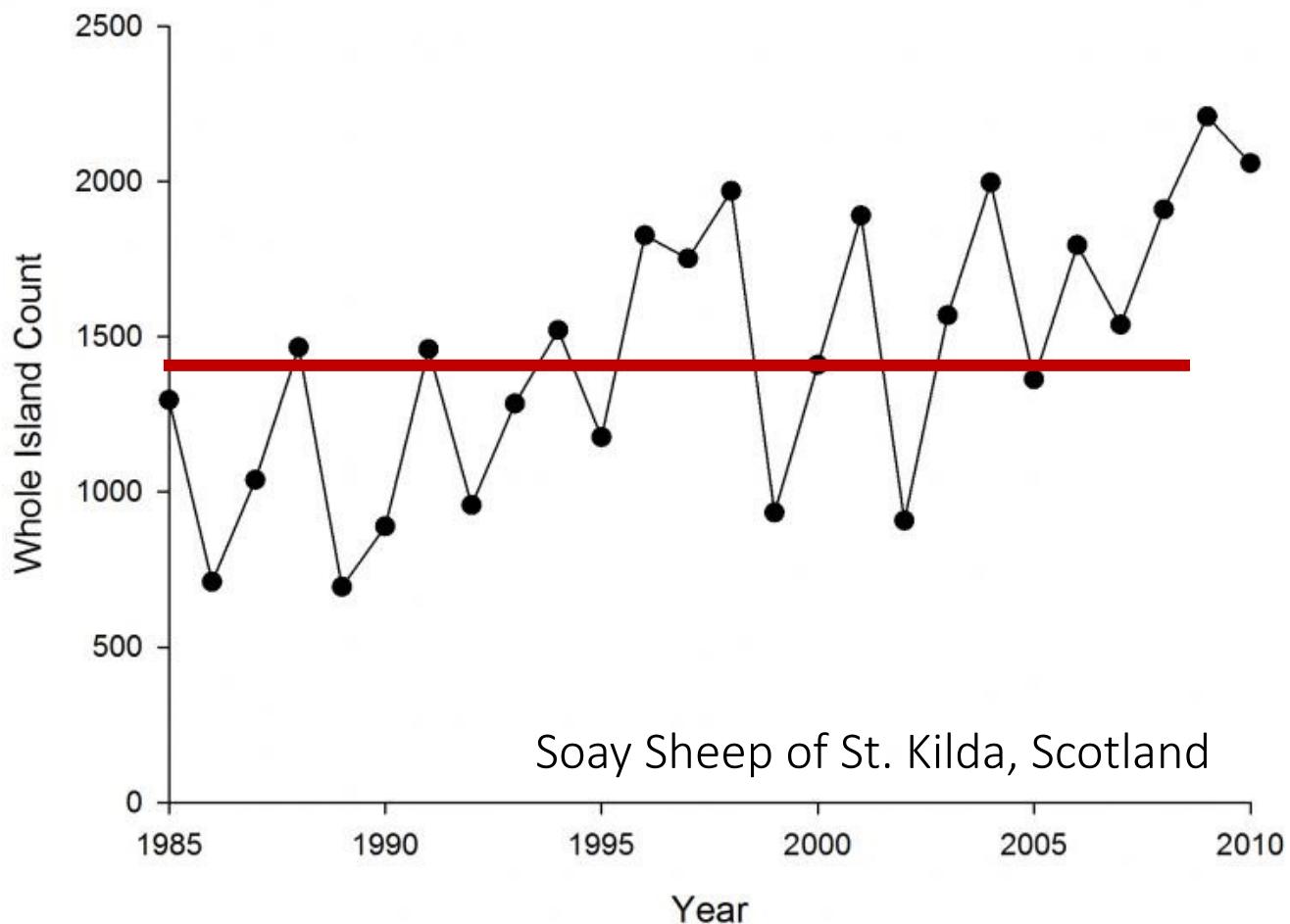
logistic
growth
equilibria

Stability: If the population is perturbed, will it return to equilibrium?

Many populations will fluctuate above or below carrying capacity.

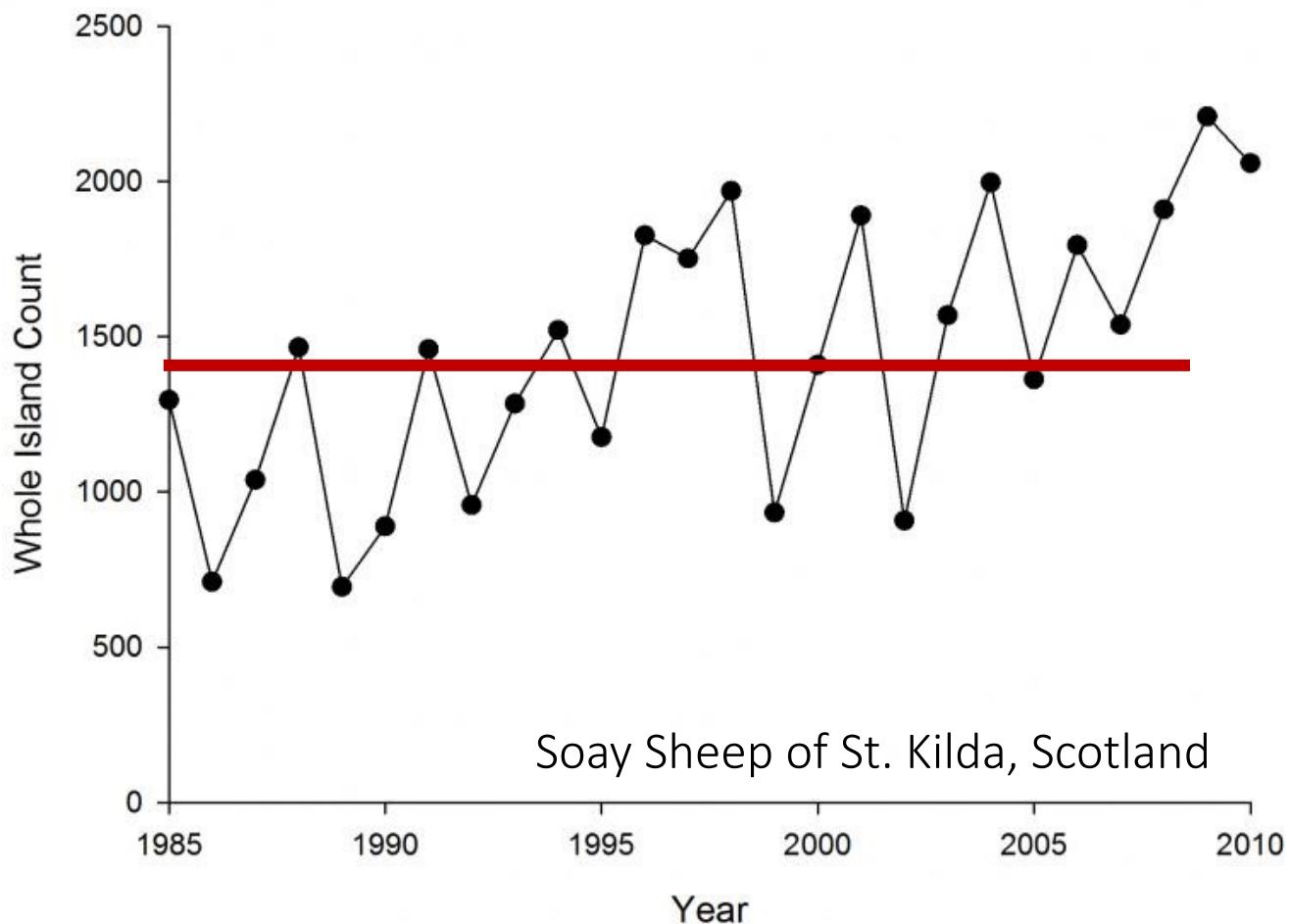


Many populations will fluctuate above or below carrying capacity.



But they can still be stable populations if they return to **equilibrium**.

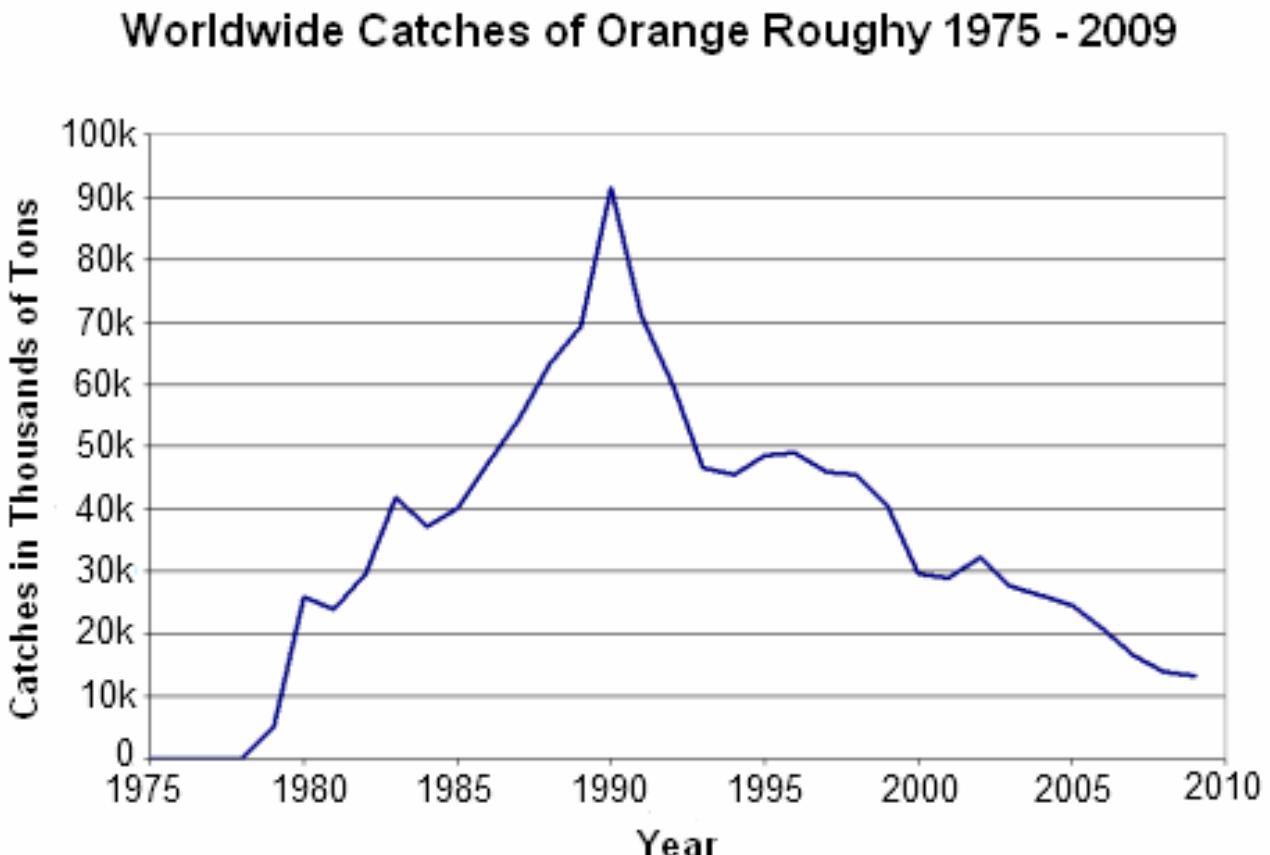
Many populations will fluctuate above or below carrying capacity.



But they can still be stable populations if they return to **equilibrium**.

In some cases, it is not possible to recover.

Many populations will fluctuate above or below carrying capacity.



Source: FAO (Fisheries and Agriculture Organisation of the United Nations) Fisheries and Aquaculture Information and Statistics Service. © L. Baumont



But they can still be stable populations if they return to **equilibrium**.

In some cases, it is not possible to recover.

Logistic growth still does not describe human populations well.

