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Fundamentals of Ecology

Week 5, Ecology Lecture 2

Cara Brook

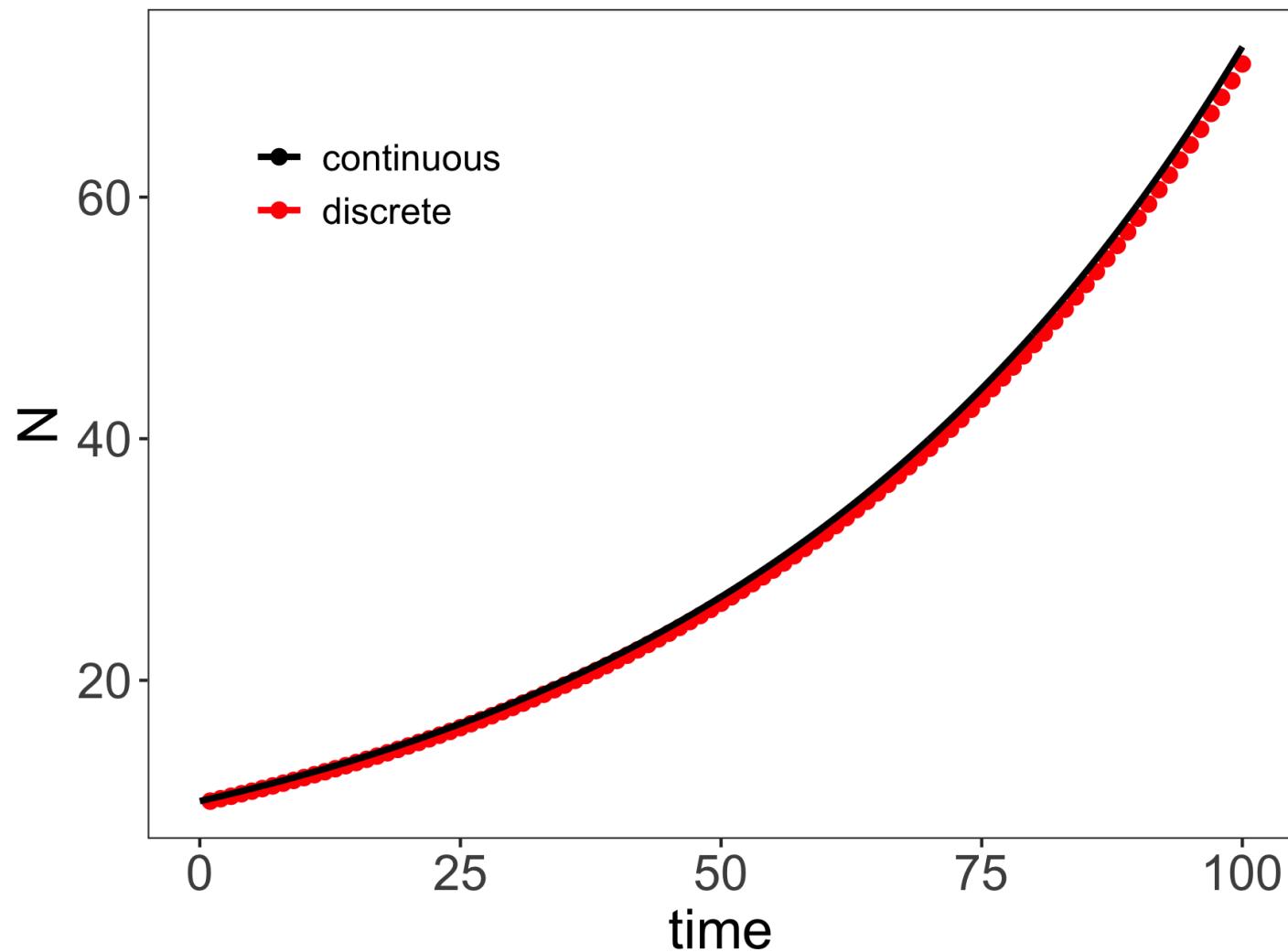
February 6, 2025

Learning objectives from Lecture 1

You should be able to:

- Define ecology as a science
- Distinguish a statistical model (pattern) from a population model (process)
- Construct a simple box plot for a population model
- Distinguish geometric and exponential growth – and know when to apply which model to which kinds of data
- Understand what it means to ‘fit’ a model to data
- Interpret whether growth is slowing, accelerating, or constant from lines ‘fit’ to different time points

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



Malthus proposed some limits to population growth

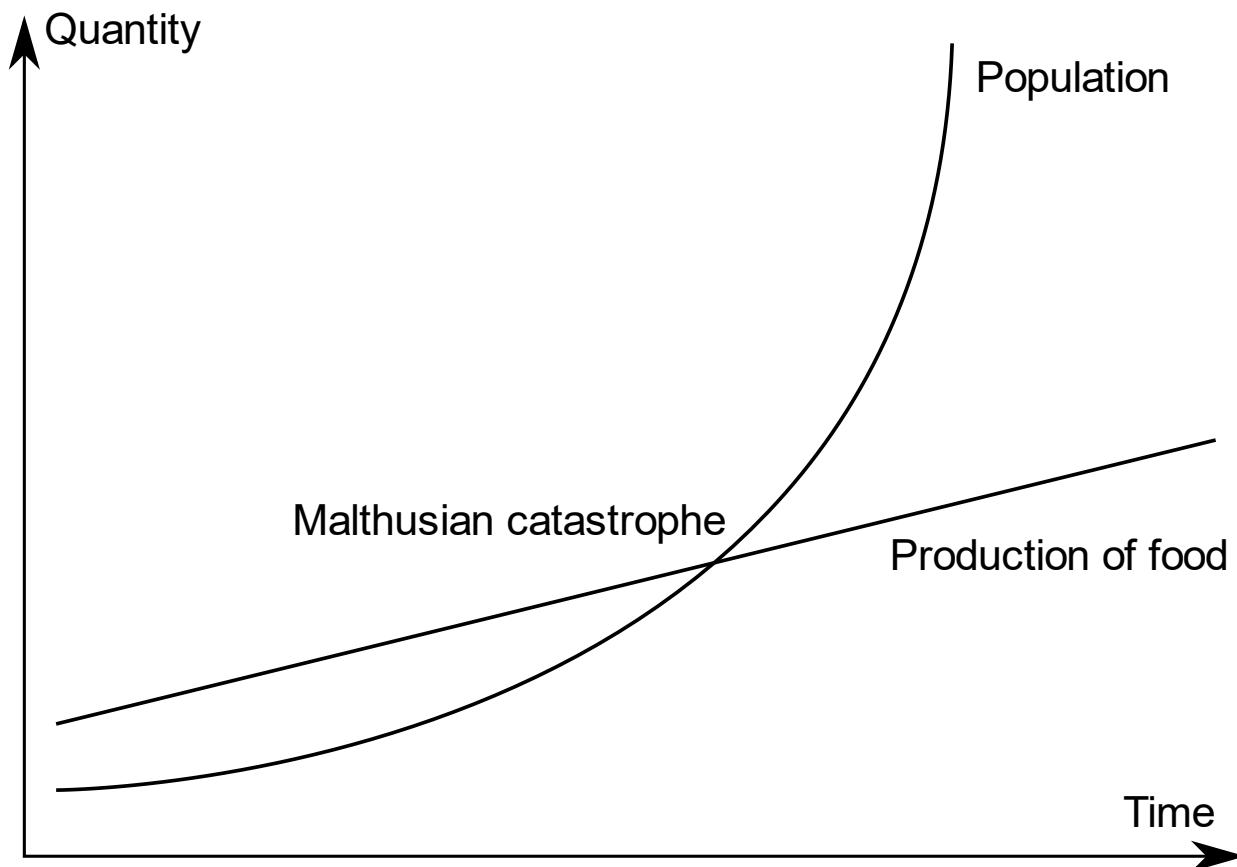
[. . .] the power of population is indefinitely greater than the power in the earth to produce subsistence for man. Population, when unchecked, increases in a geometrical ratio. Subsistence increases only in an arithmetical ratio. A slight acquaintance with numbers will shew the immensity of the first 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

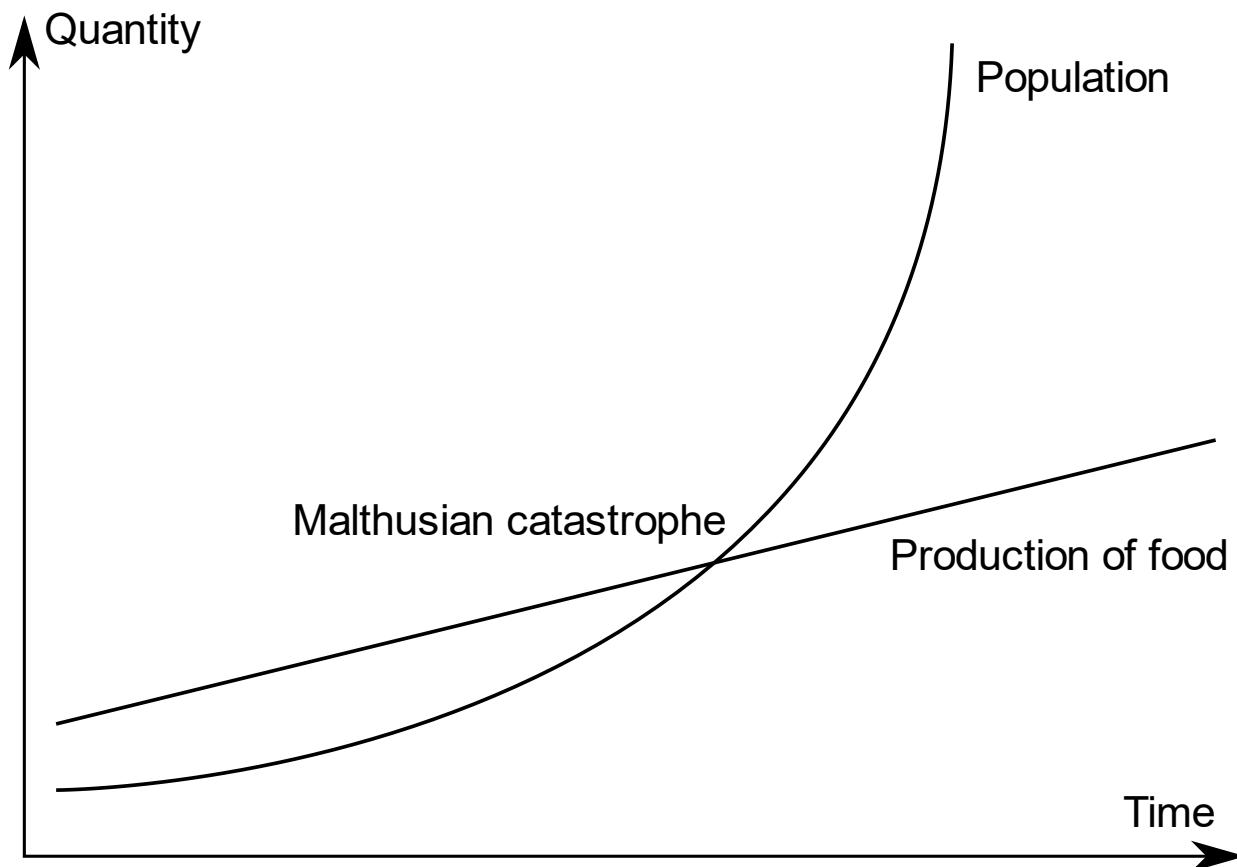


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Malthus proposed some limits to population growth



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

- 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*



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

change in population
abundance per unit time

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

↑ ↑

population size

intrinsic growth **carrying capacity**
rate

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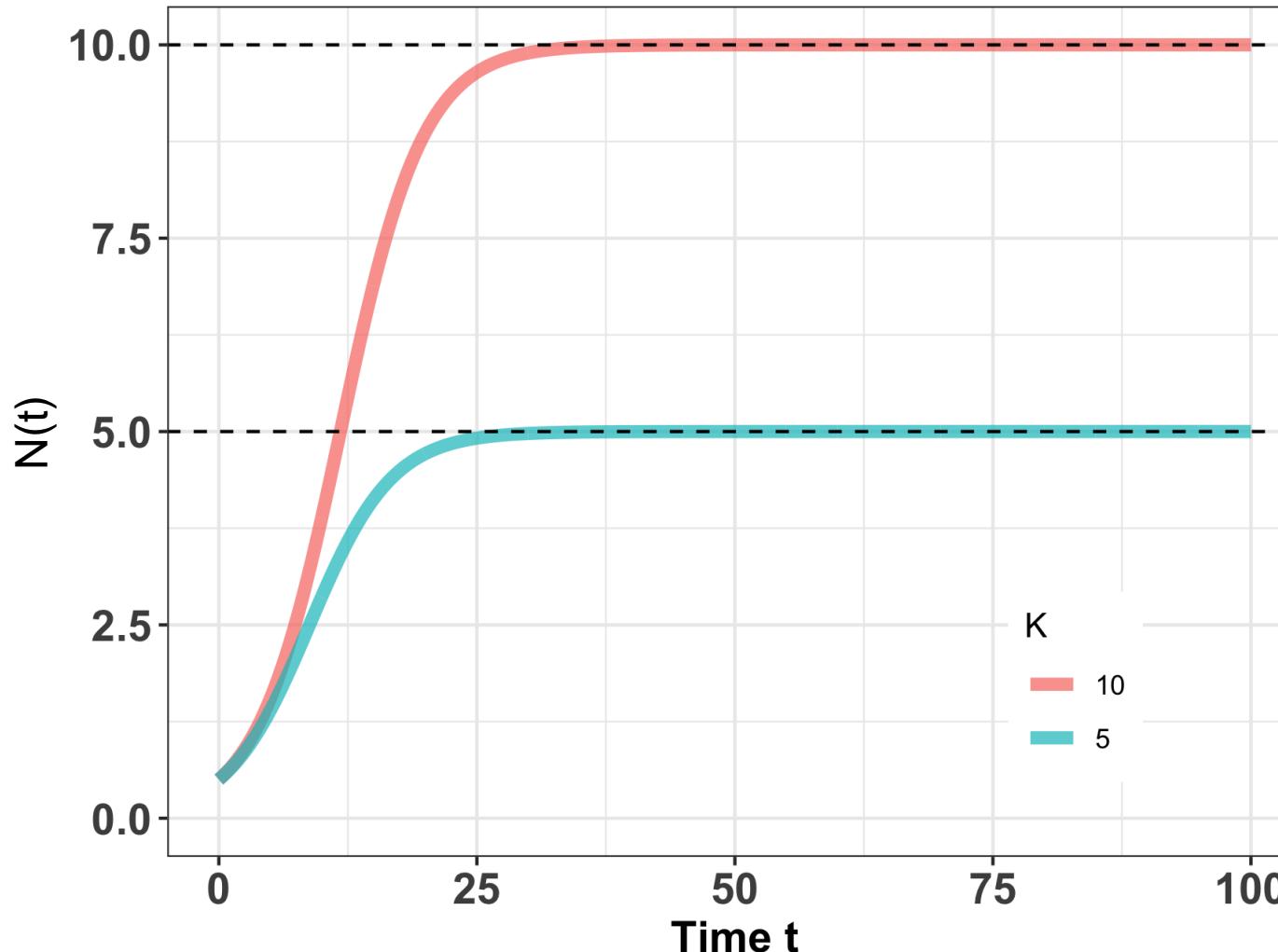
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Population growth slows as abundance (**N**)
approaches **carrying capacity (K)**.

Population growth is **density-dependent**.

Logistic growth equation

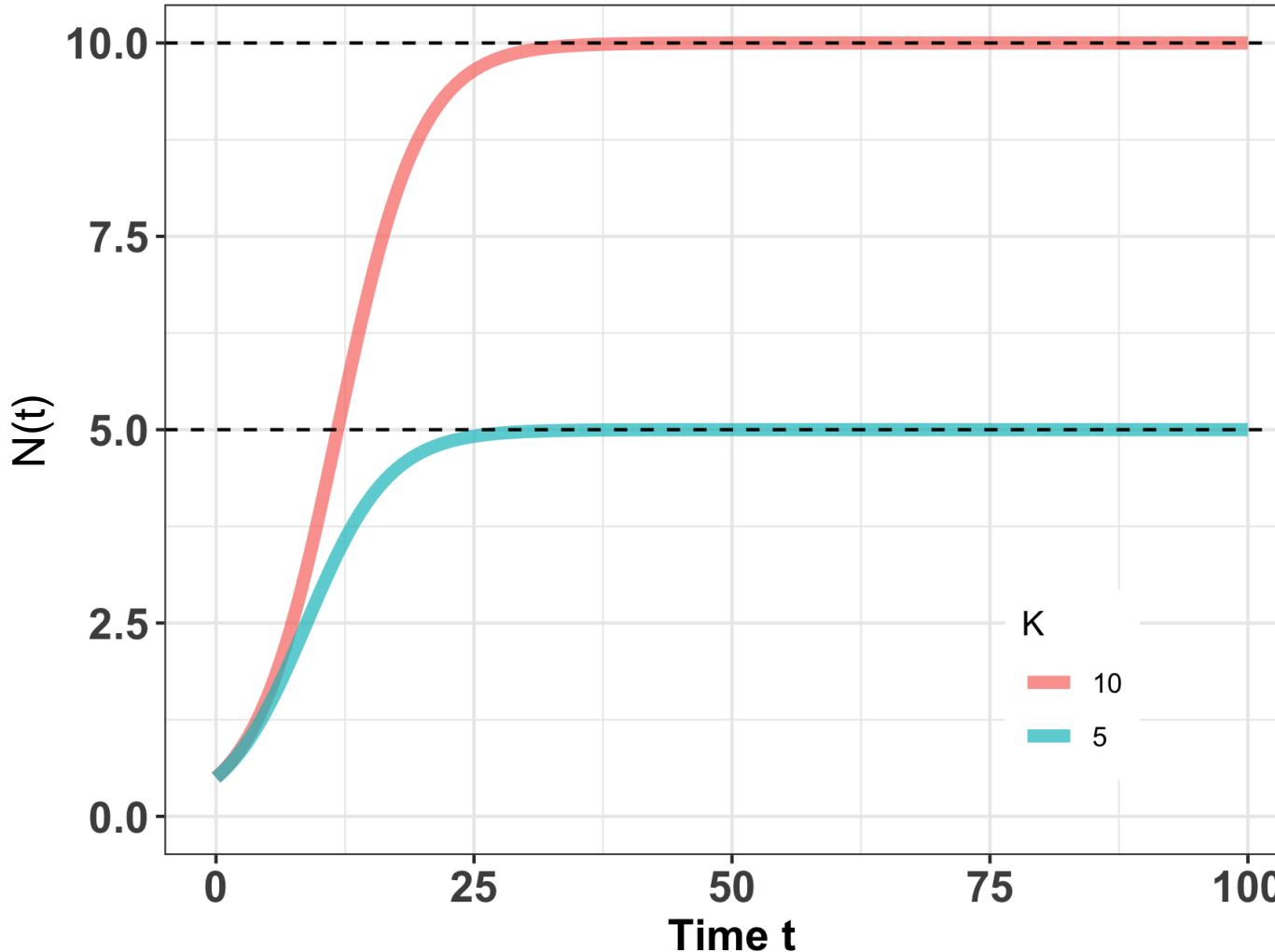
$$\frac{dN}{dt} = rN \left(1 - \frac{N}{K}\right)$$



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

Logistic growth equation

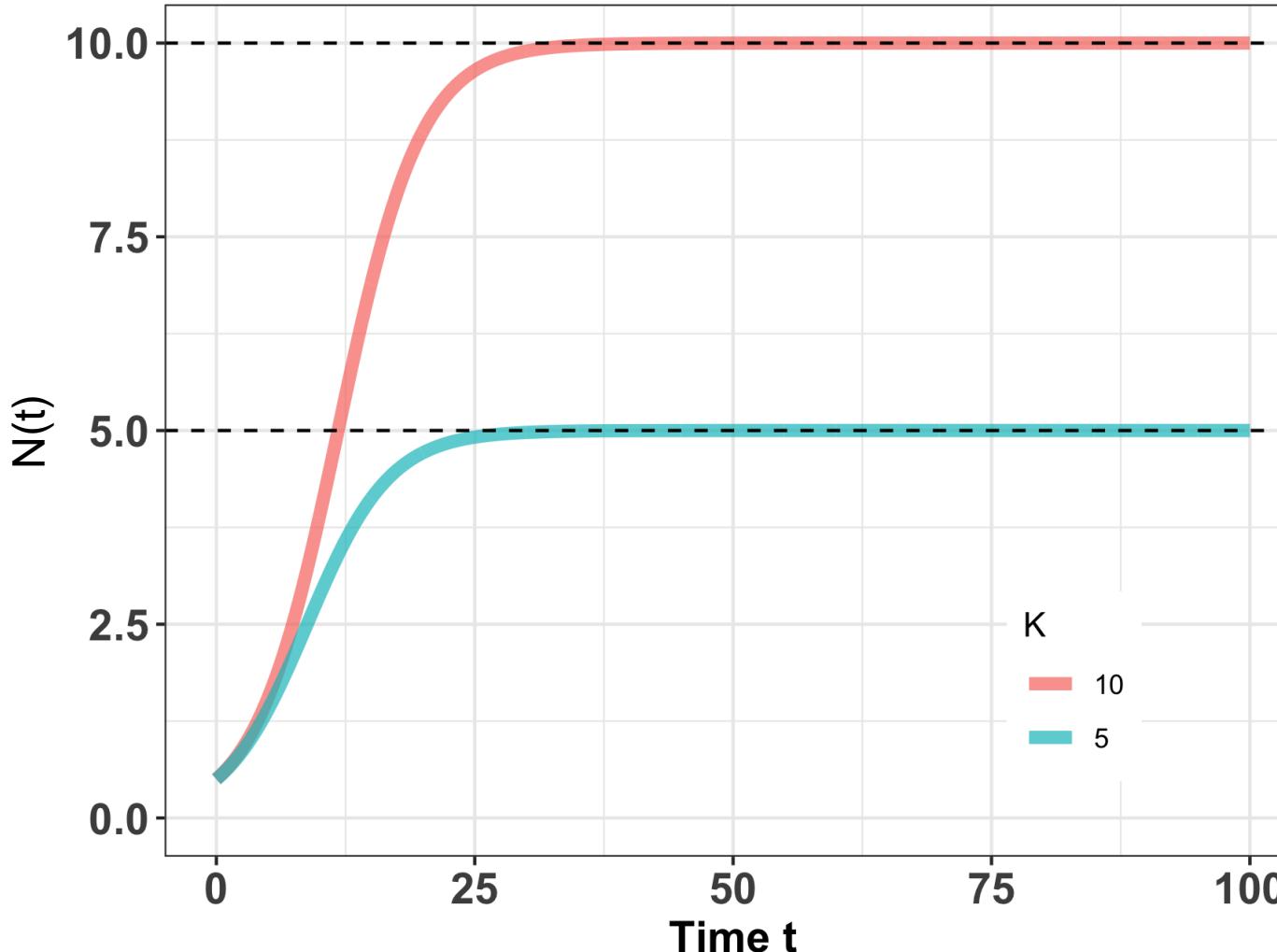
$$\frac{dN}{dt} = rN \left(1 - \frac{N}{K}\right)$$



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

Logistic growth equation

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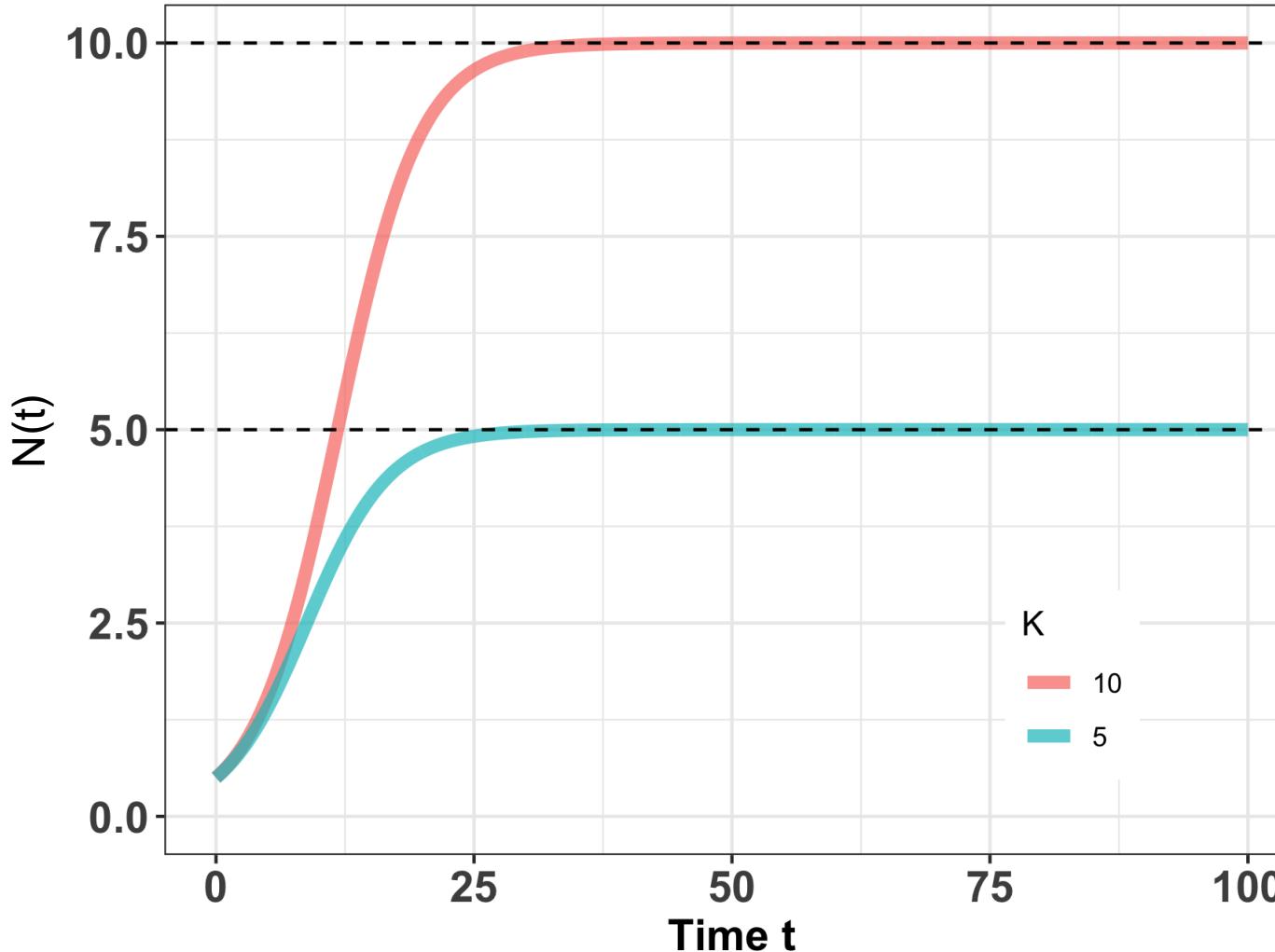


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Ecology = organisms
interacting with each other
and the **environment**

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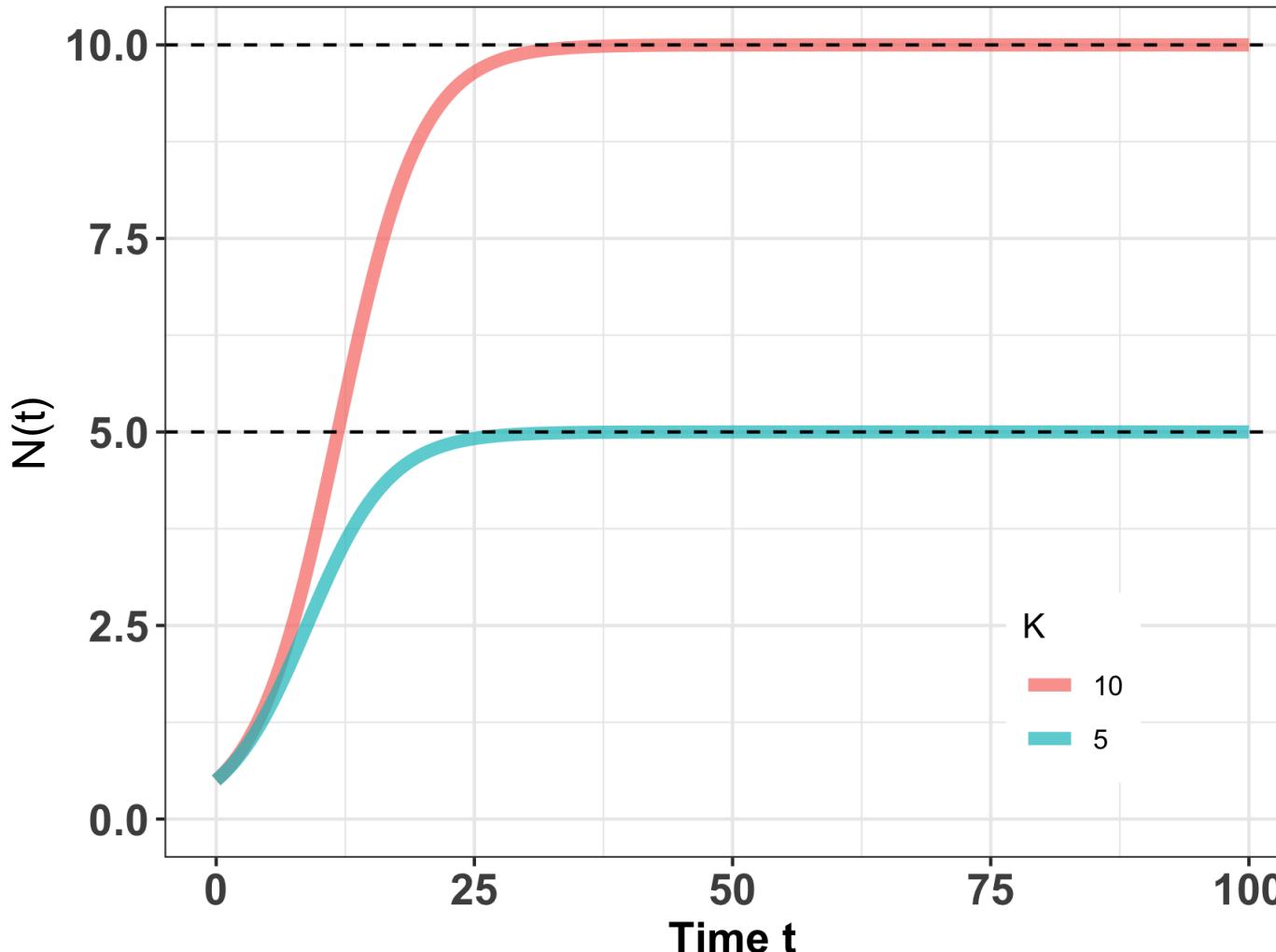
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K can change!

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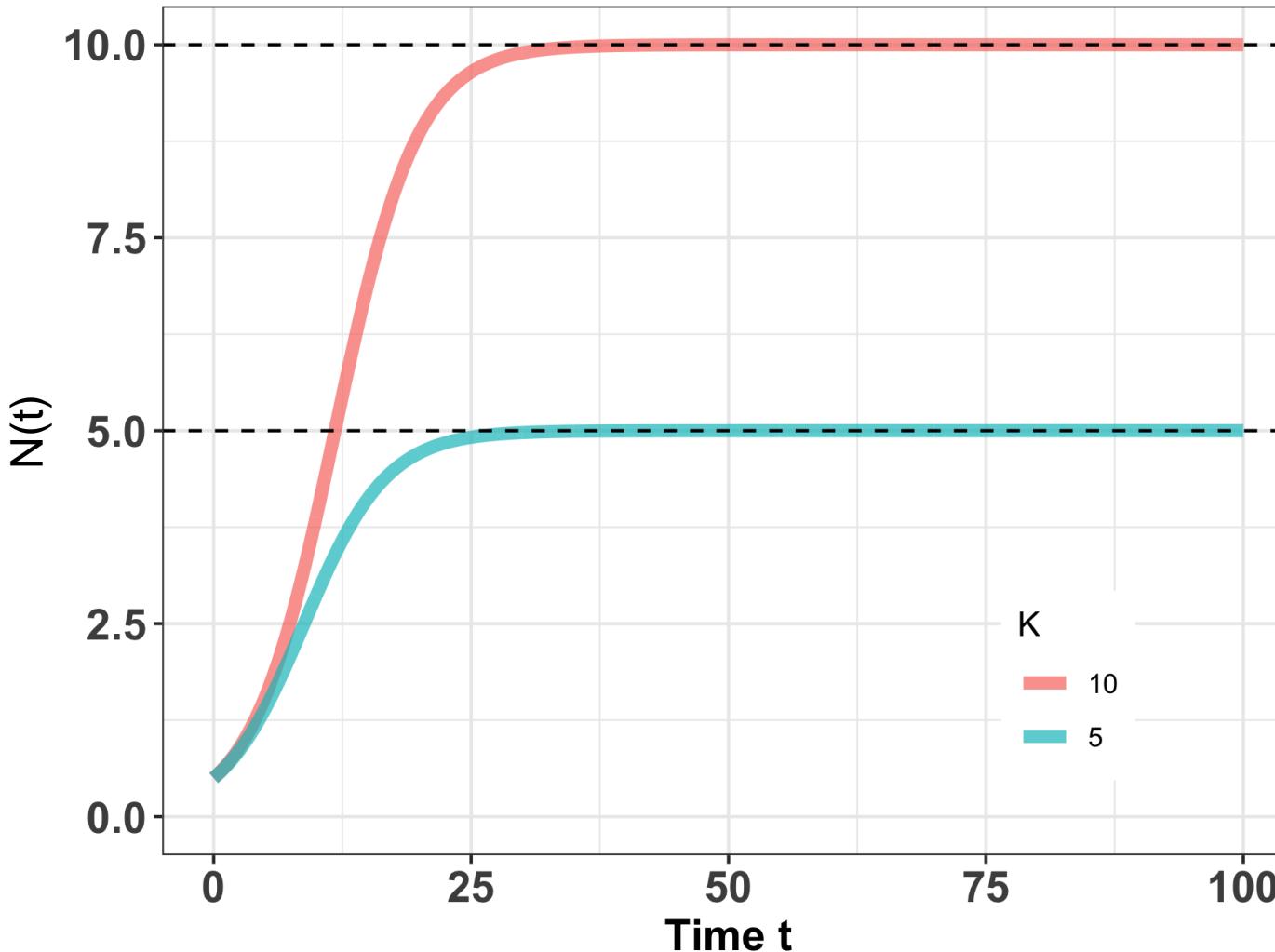
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K can change!

'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**.

Many populations will fluctuate above or below carrying capacity.

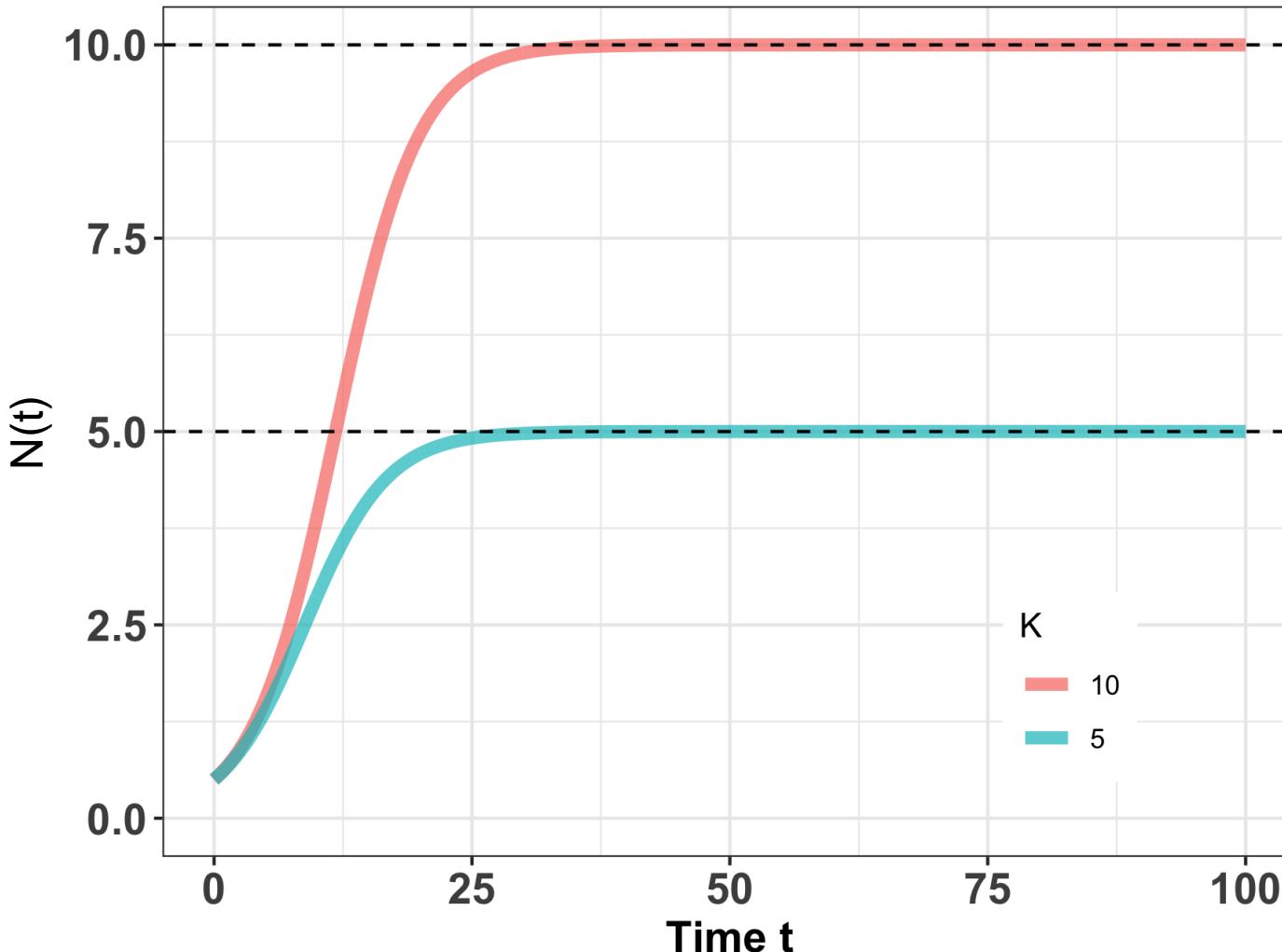


Many populations will fluctuate above or below carrying capacity.



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

Logistic growth and equilibrium



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

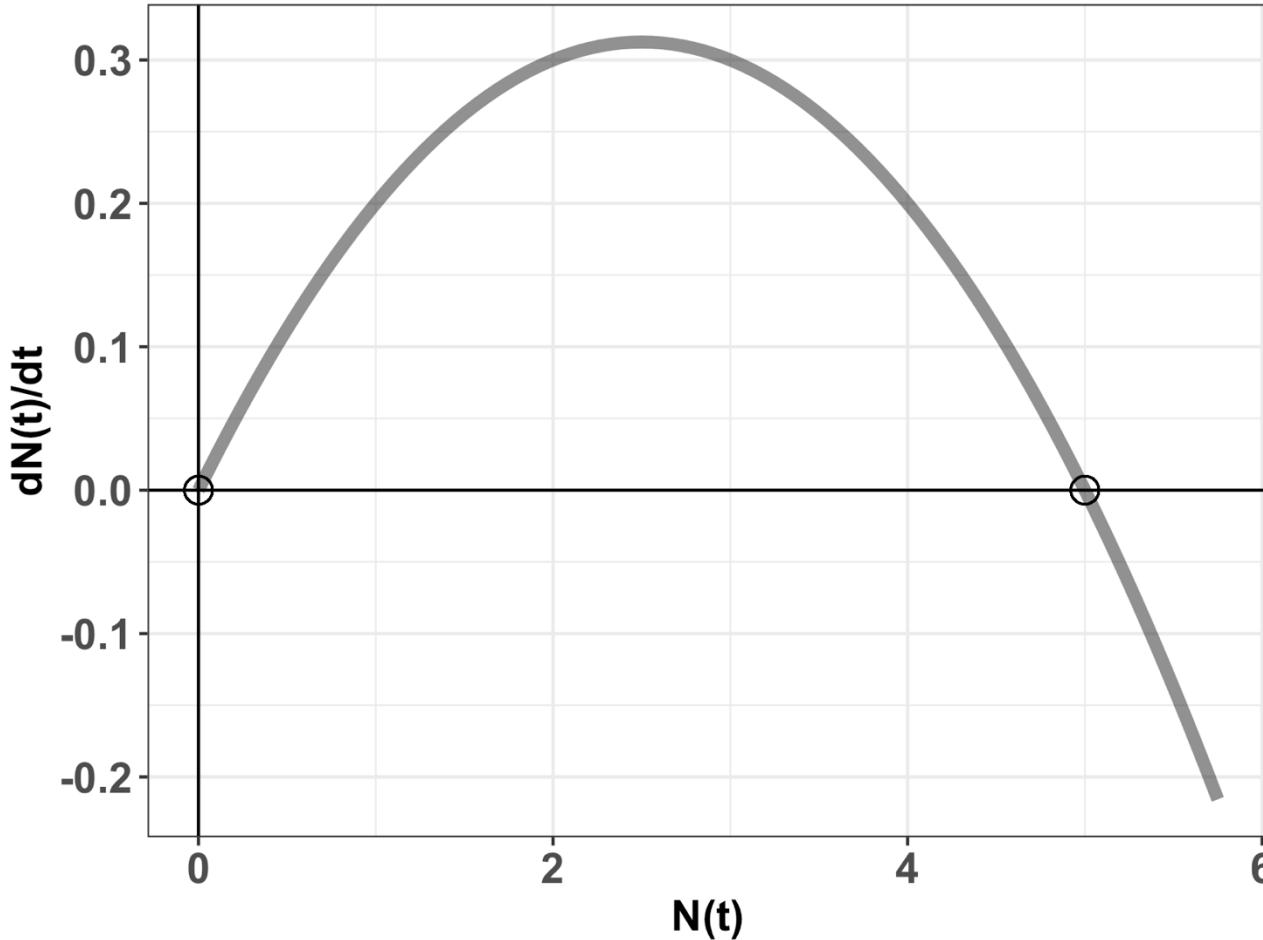
$$\frac{dN}{dt} = 0$$

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

$$N = K$$

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

Logistic growth and equilibrium



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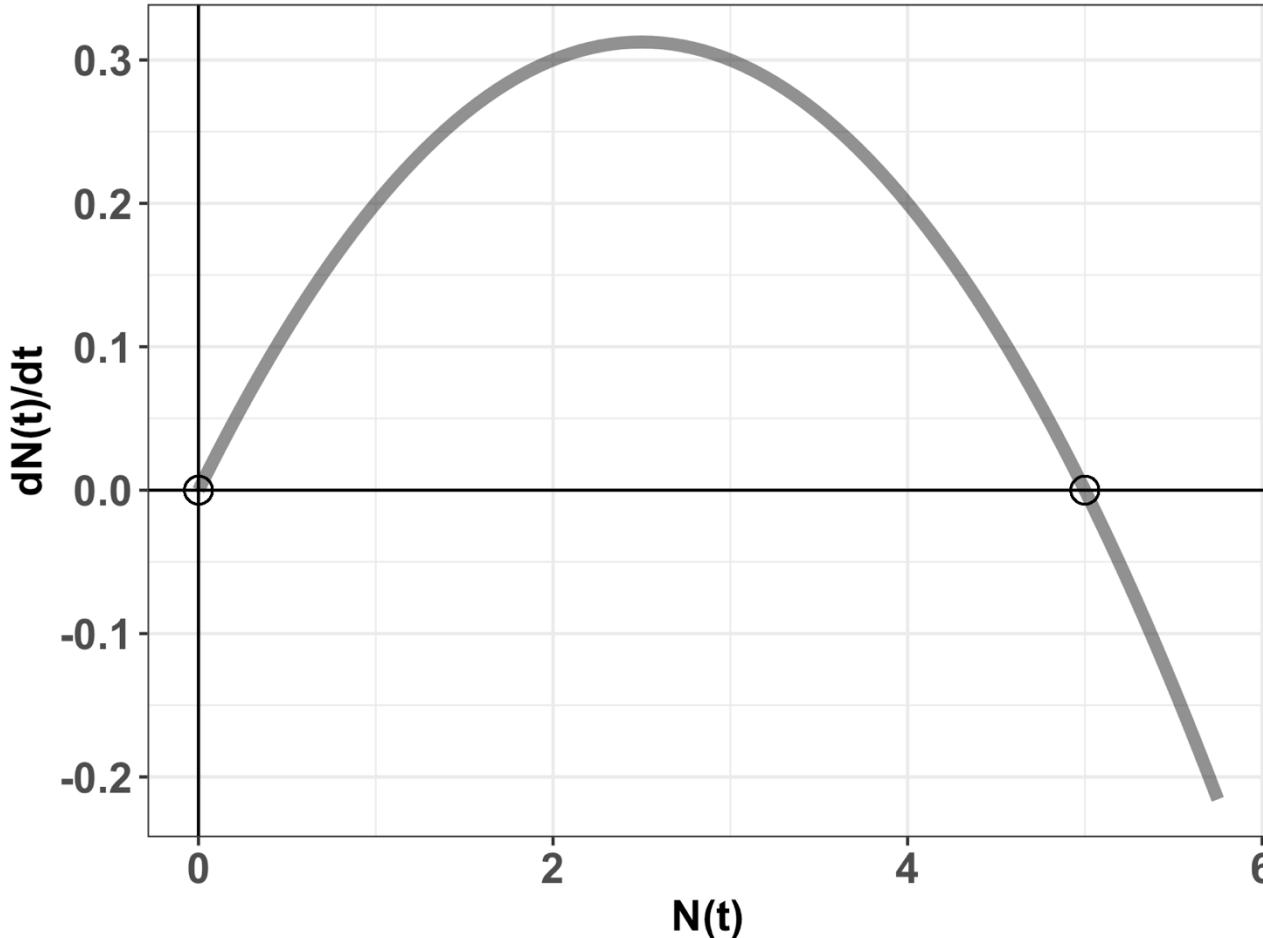
$$\frac{dN}{dt} = 0$$

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

$N = K$ or
 $N = 0$

logistic
growth
equilibria

Logistic growth and equilibrium



What is **K**?

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

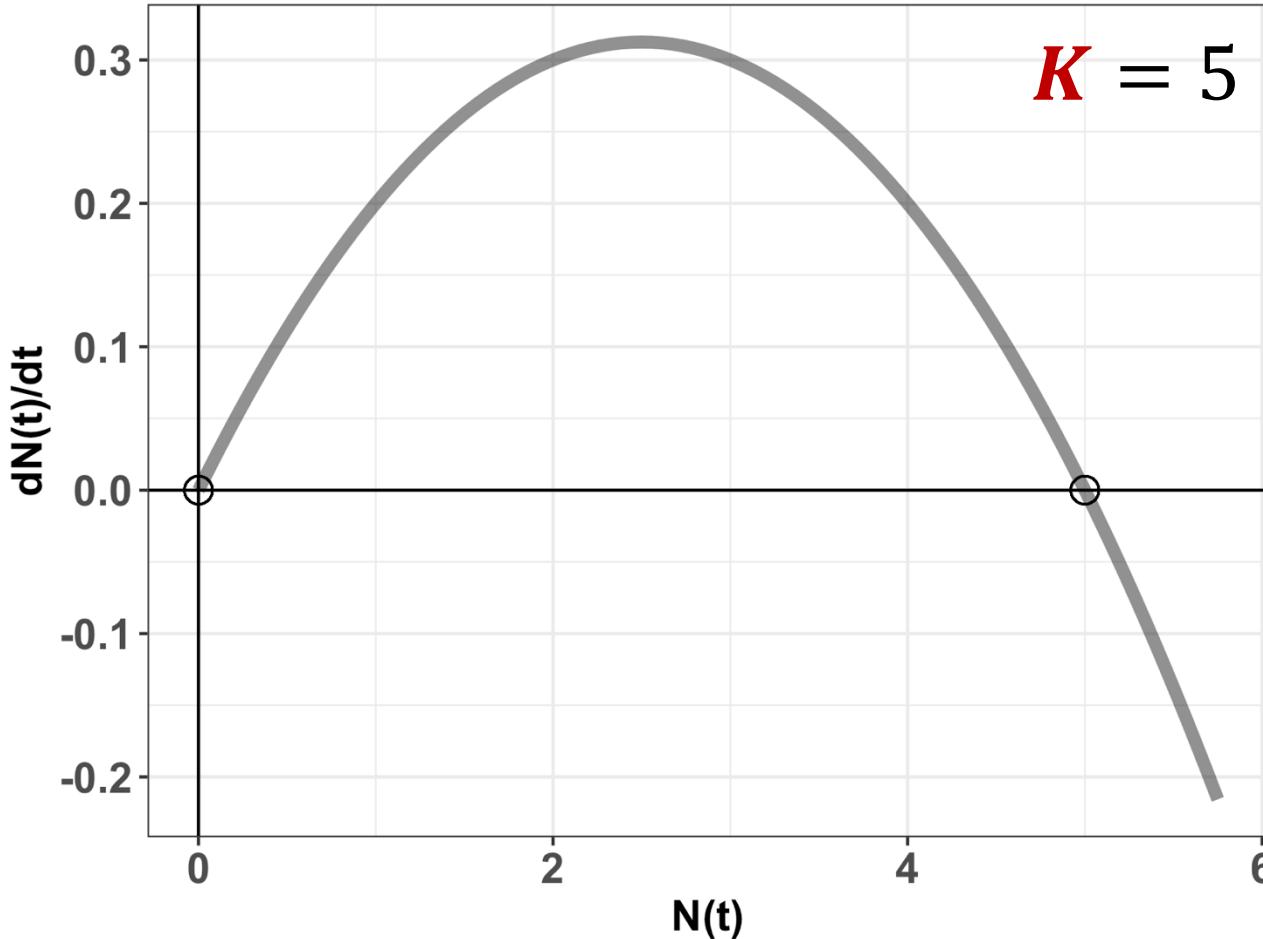
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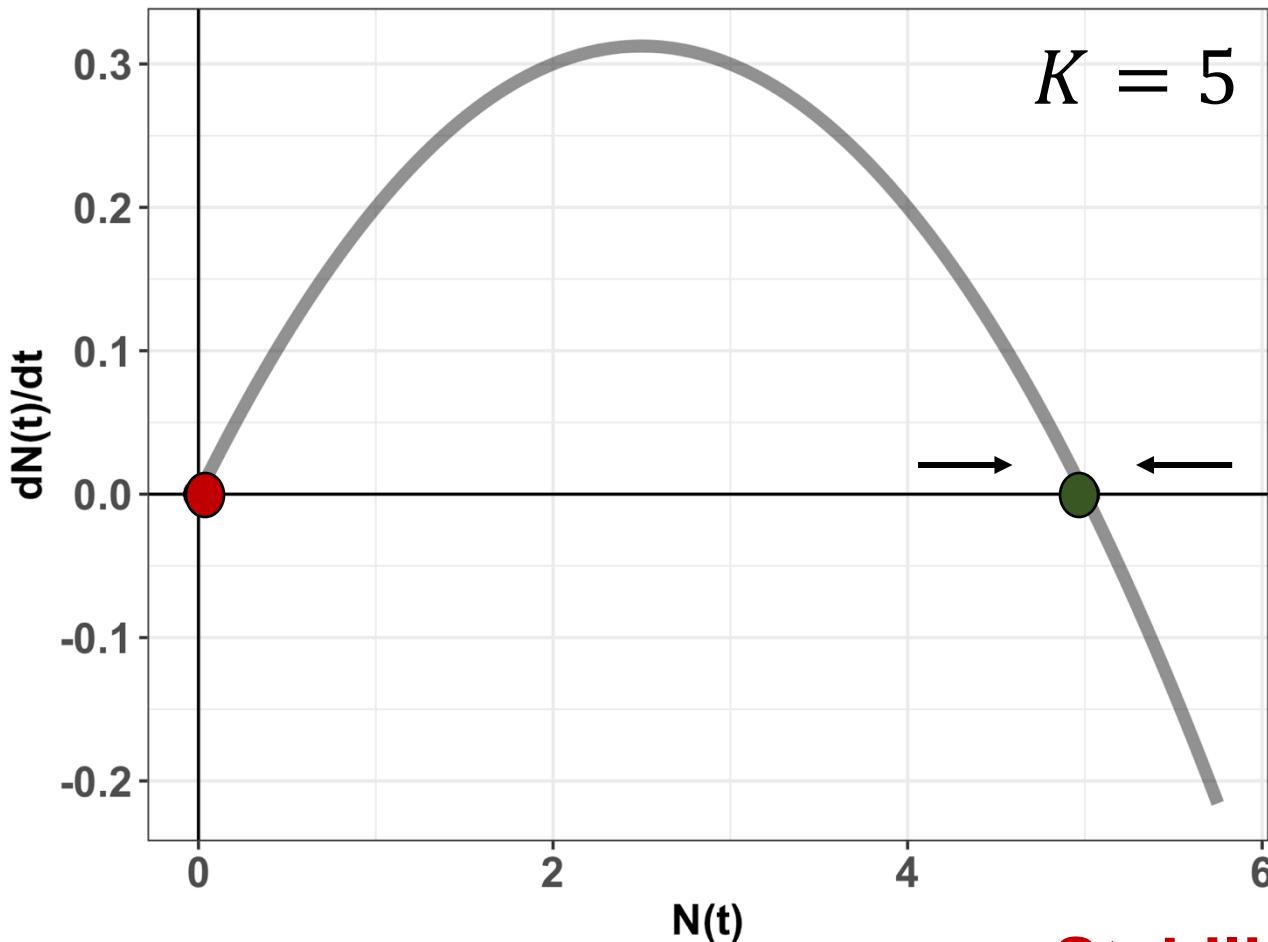
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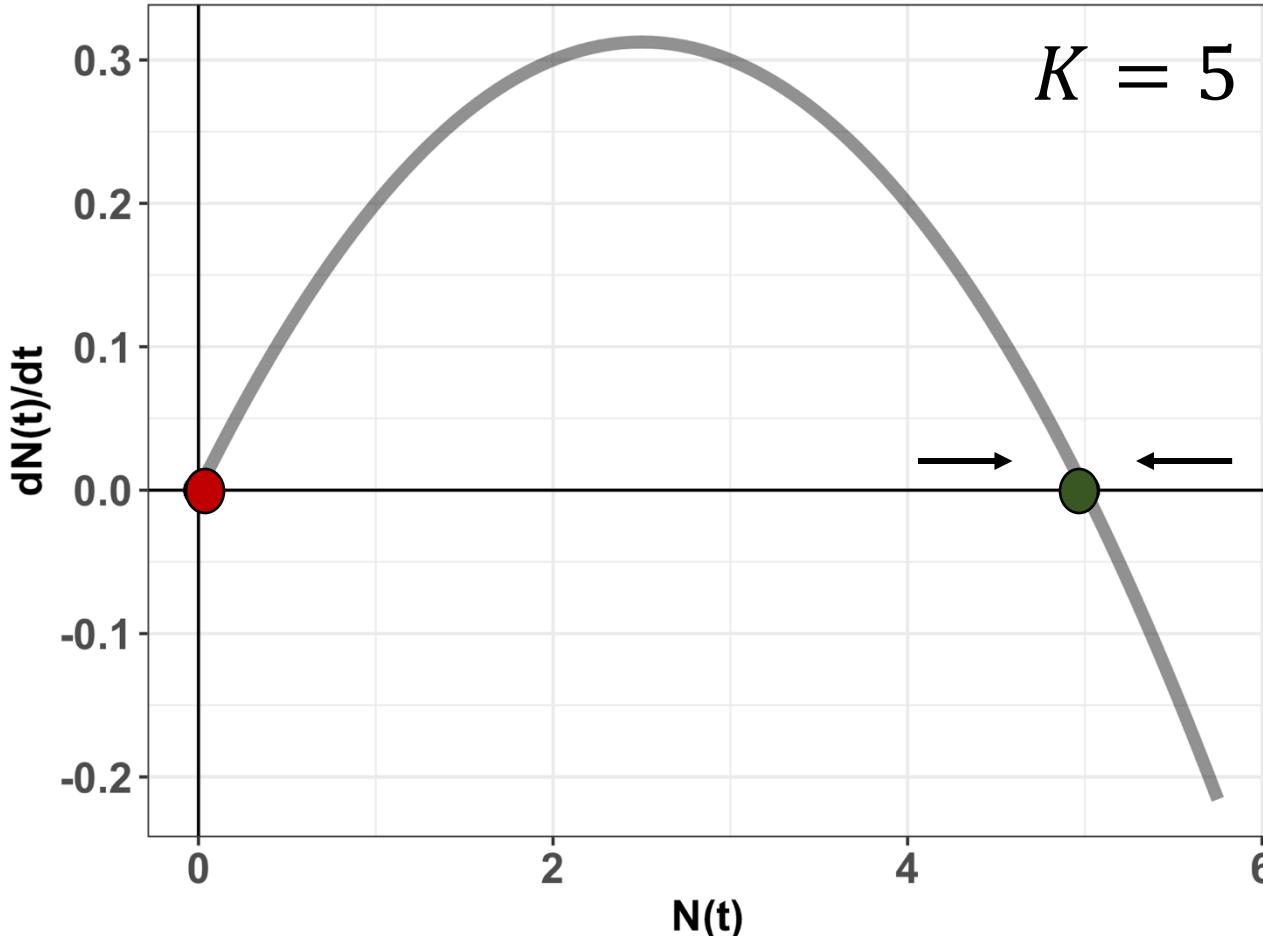
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Stability: If the population is perturbed, will it return to equilibrium?

Logistic growth and equilibrium



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

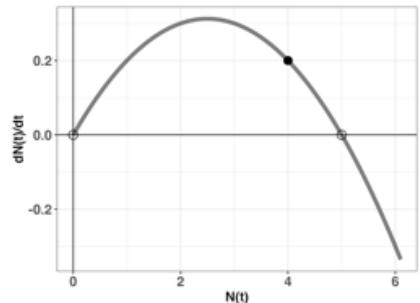
$$\frac{dN}{dt} = 0$$

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

Mathematically, the carrying capacity (K) can be shown to be a **stable equilibrium**, meaning that if the system is perturbed, growth will accelerate or decelerate to return the population to K .



A population of 4 lemmings grows logistically with carrying capacity (K) of 5 and an intrinsic growth rate (r) of 0.25 individuals/month. How many lemmings will we have 1 month from now?

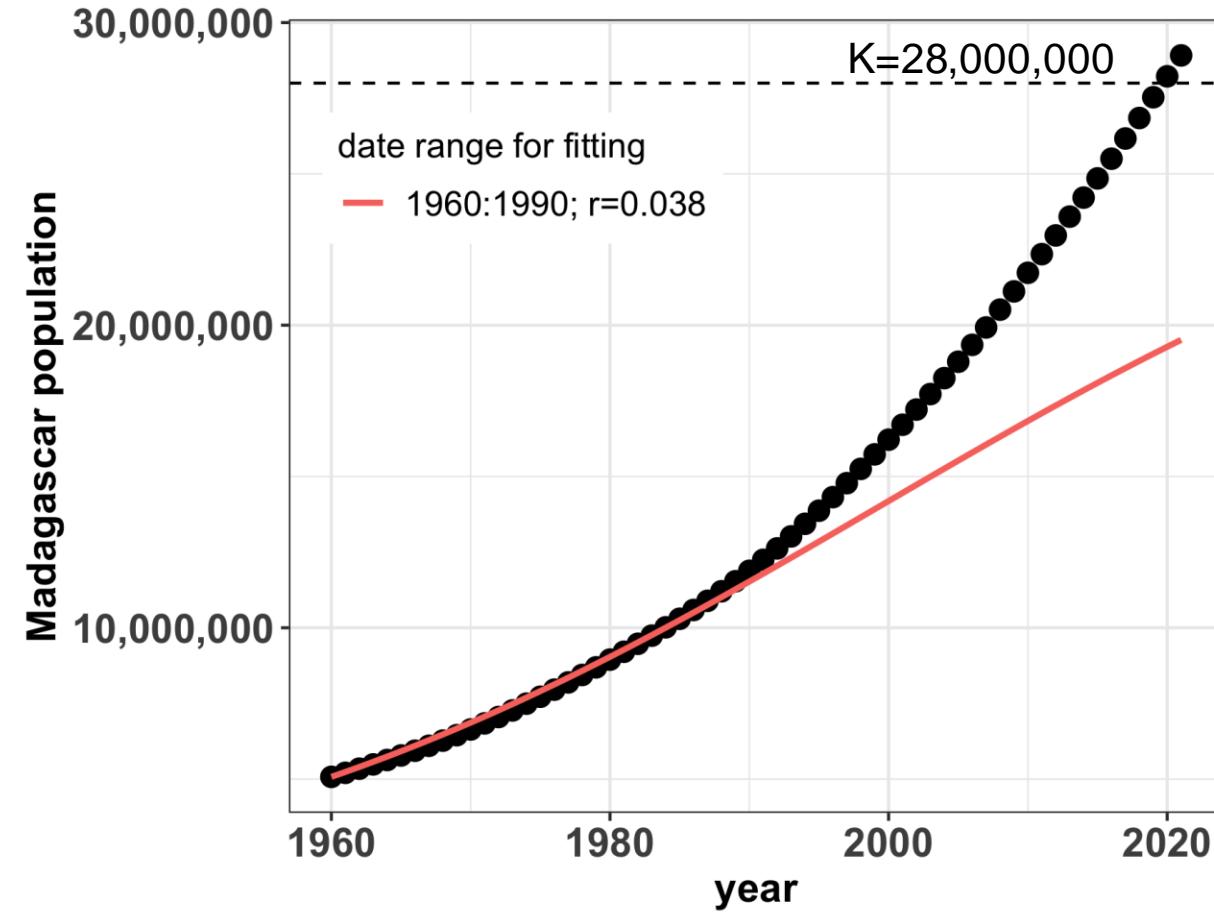
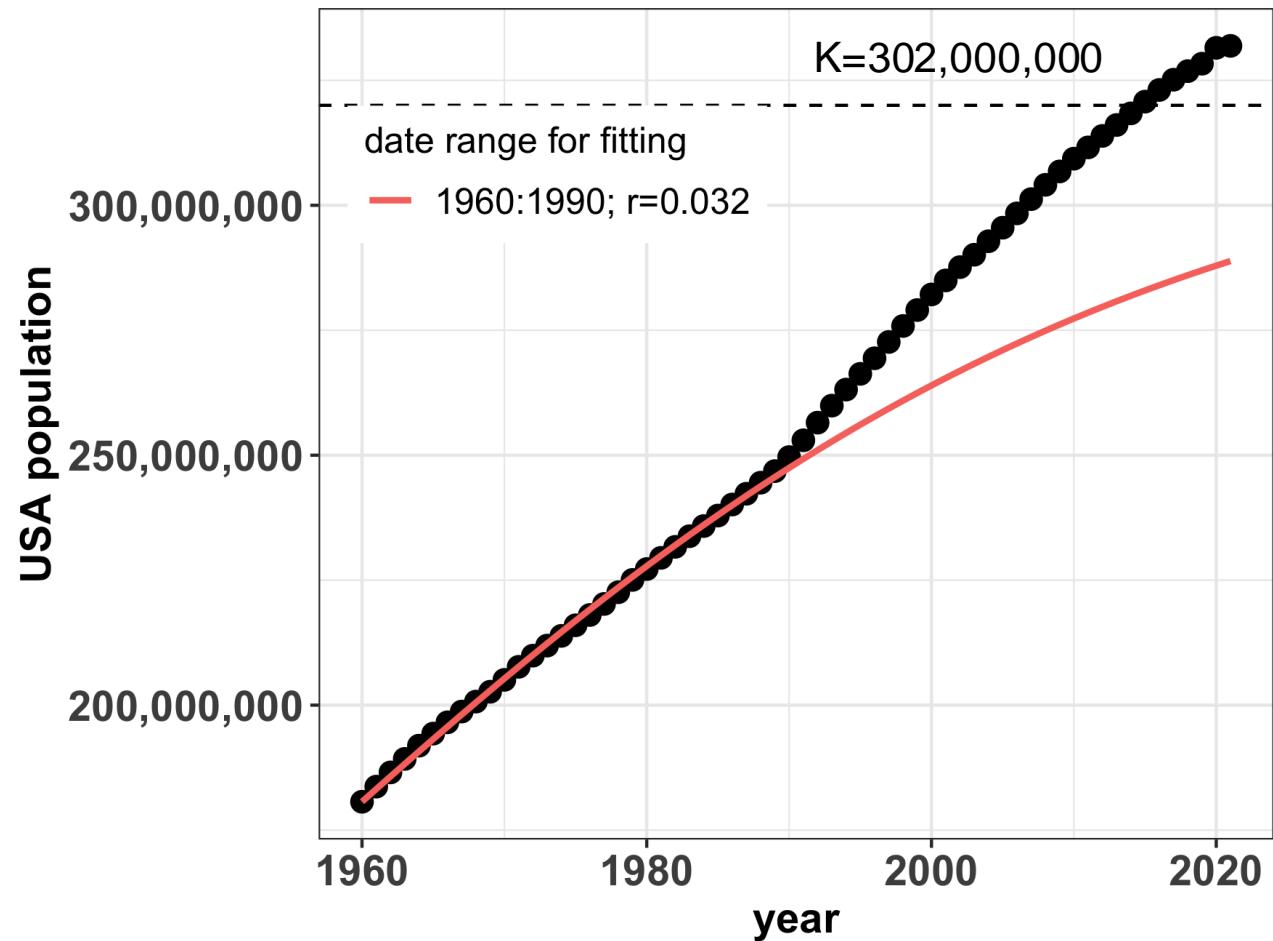


A. 3 lemmings

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Despite Malthus' predictions, logistic growth still does not describe human populations well.



Logistic growth and harvesting

Humans have attempted to leverage density-dependent growth rates for **sustainable harvesting**, which refers to the offtake of individuals within a population's capacity for replenishment. Frequently, this refers to the harvesting of animals for human consumption.

Logistic growth and harvesting

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The science of sustainable harvest is used extensively in fisheries management.

Logistic growth and harvesting

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change in population size with time $\rightarrow \frac{dN}{dt} = rN \left(1 - \frac{N}{K}\right) - H$

intrinsic growth rate density-dependence carrying capacity harvesting rate

population size

Logistic growth and harvesting

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

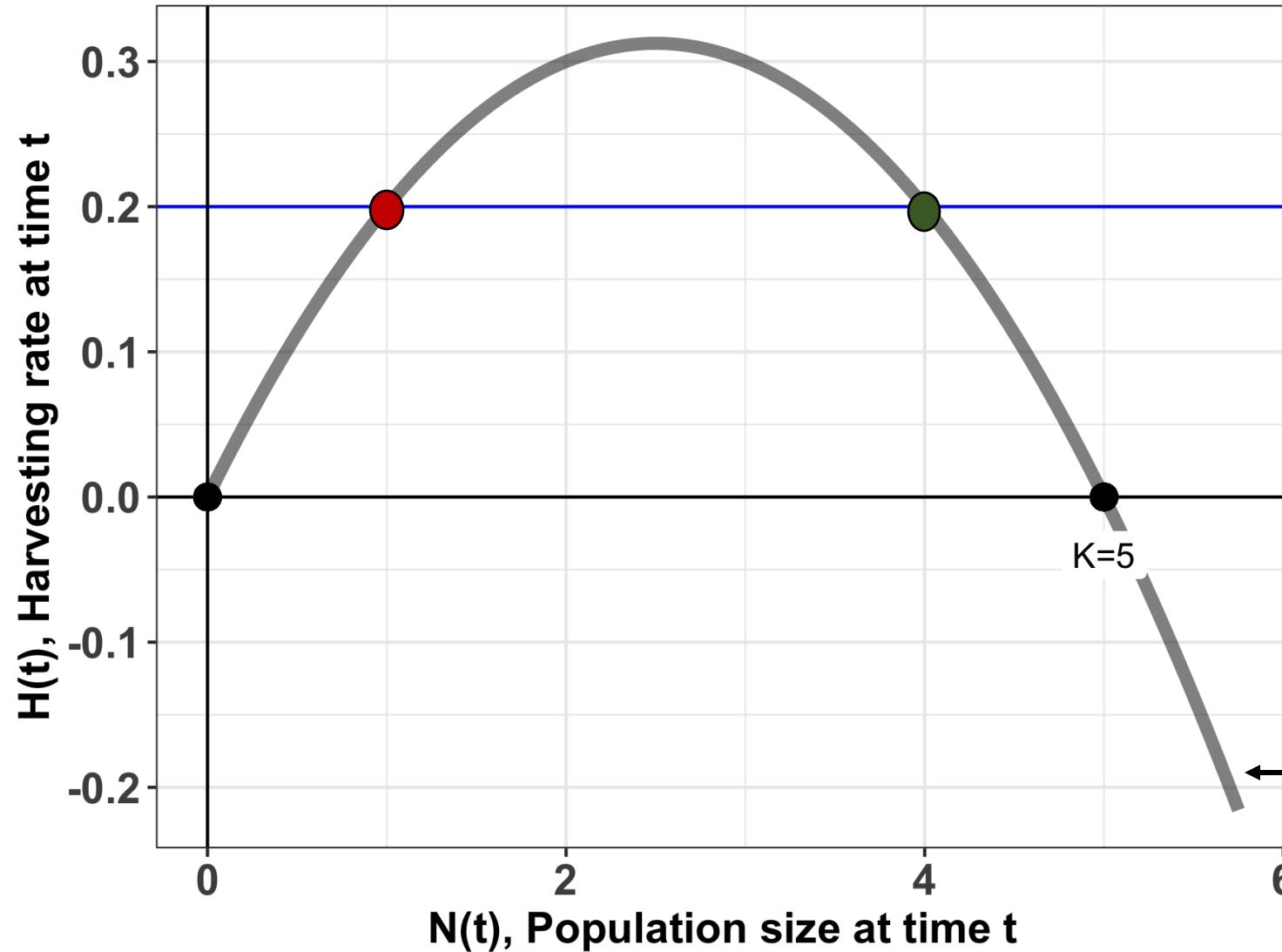
$$0 = rN \left(1 - \frac{N}{K}\right) - H$$

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

For a harvested population,
theoretically, the population
size is at equilibrium if the
**harvest rate equals the
population change.**

The stability of harvesting depends on population size.

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



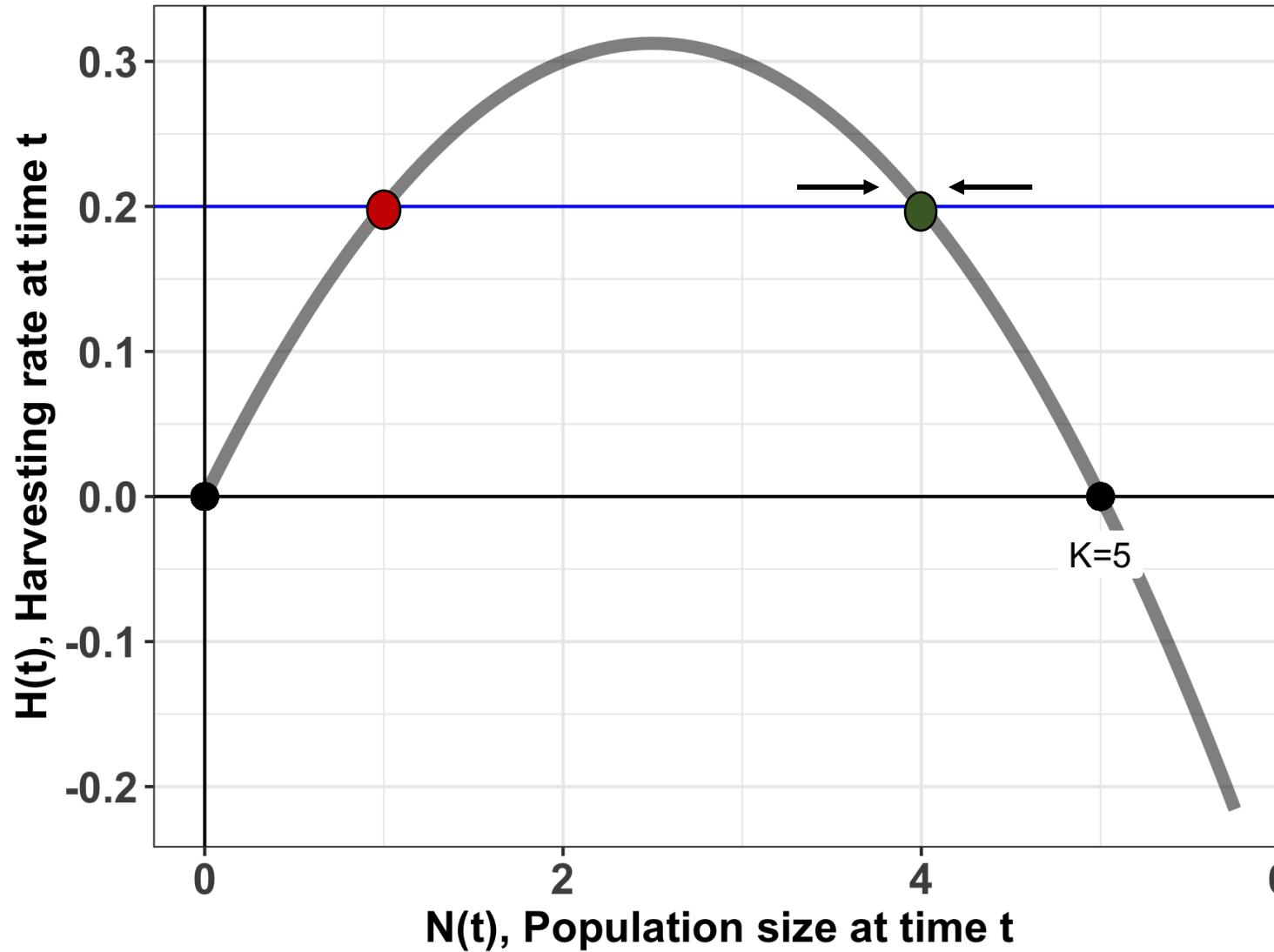
← harvesting rate

← carrying capacity

Curve shows equilibrium solutions to harvesting equation, with $r = 0.25$ & $K = 5$. Some equilibria are **stable**, and some are **unstable**.

The stability of harvesting depends on population size.

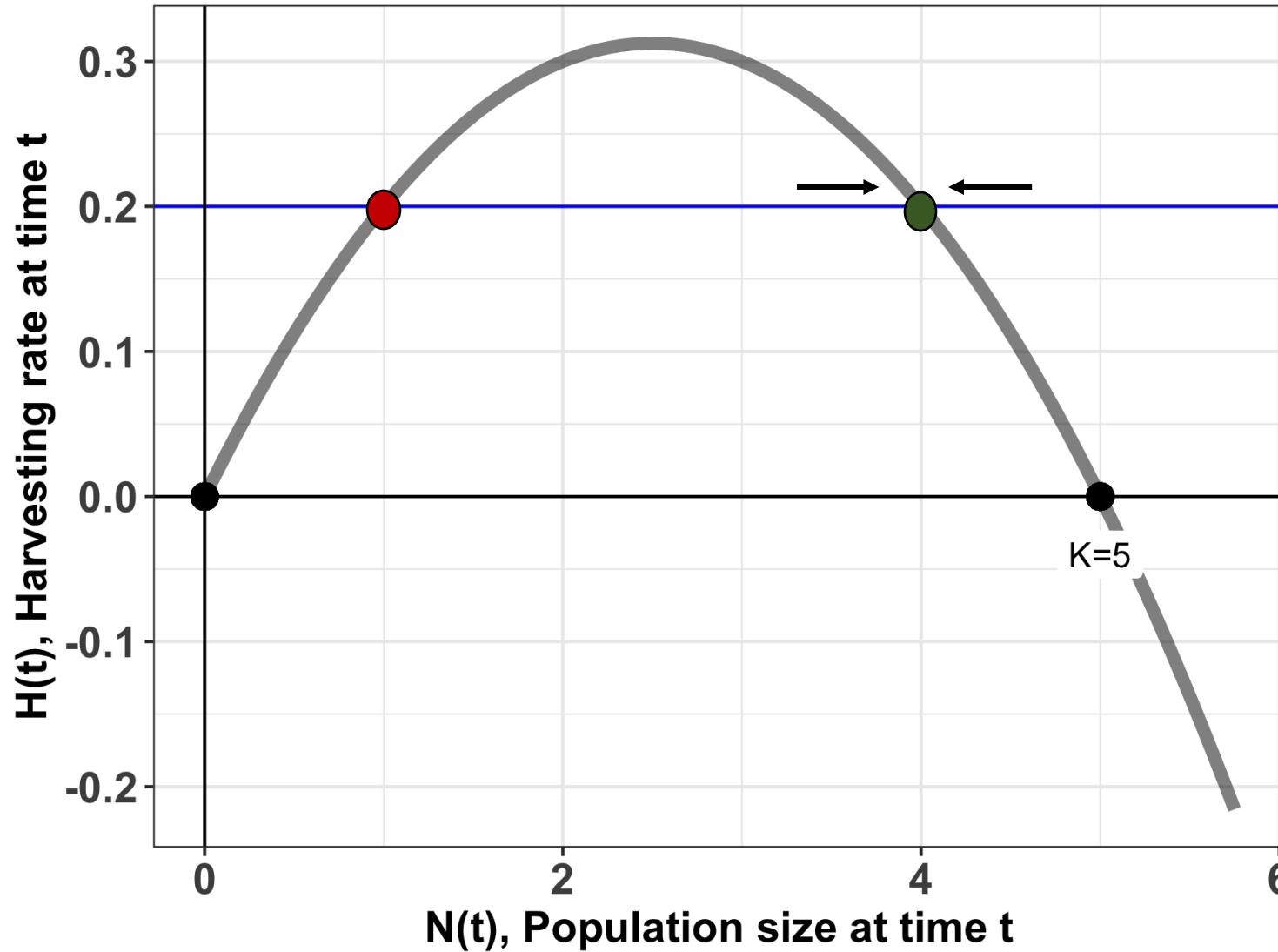
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← **stable equilibrium**
For a population of $N=4$,
a harvest rate of 0.2
(animals/timestep)
results in a stable
equilibrium (**sustainable
harvest**).

The stability of harvesting depends on population size.

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

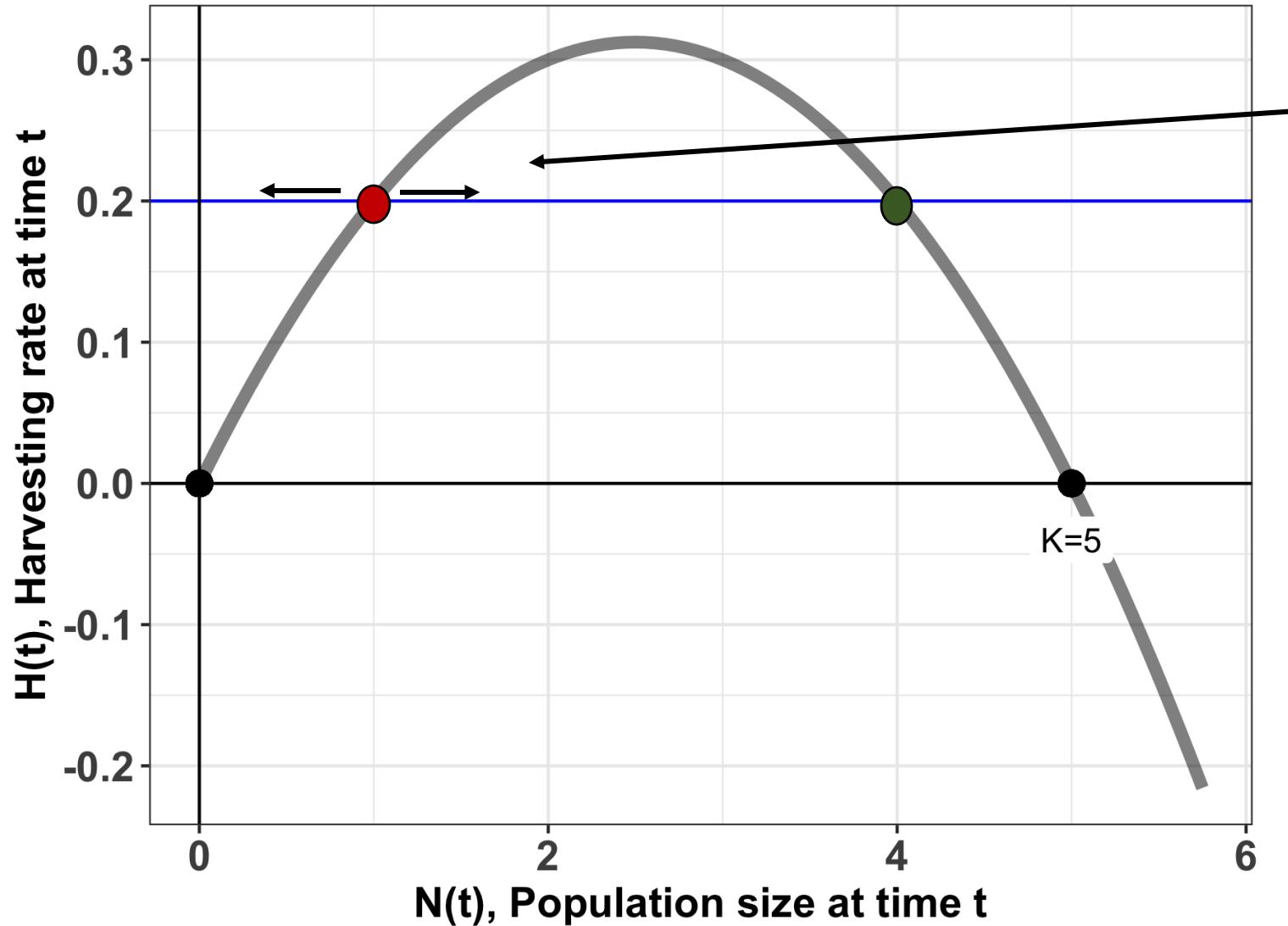


← **stable equilibrium**
For a population of $N=4$,
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Increases or decreases
in population size will be
compensated to return
the system to $N=4$.

The stability of harvesting depends on population size.

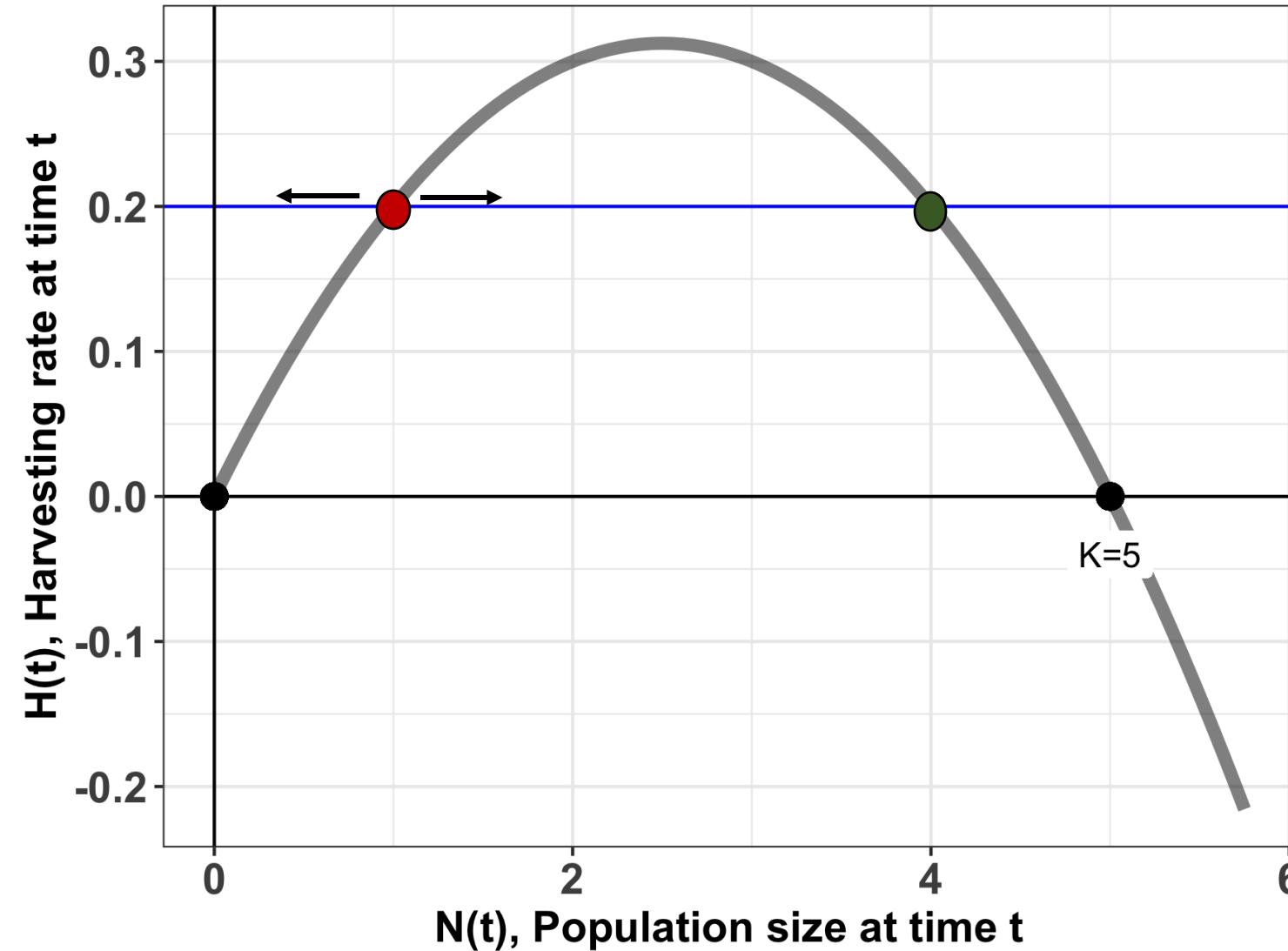
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unstable equilibrium

For a population of $N=1$, a harvest rate of 0.2 (animals/timestep) results in an unsustainable equilibrium.

The stability of harvesting depends on population size.



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

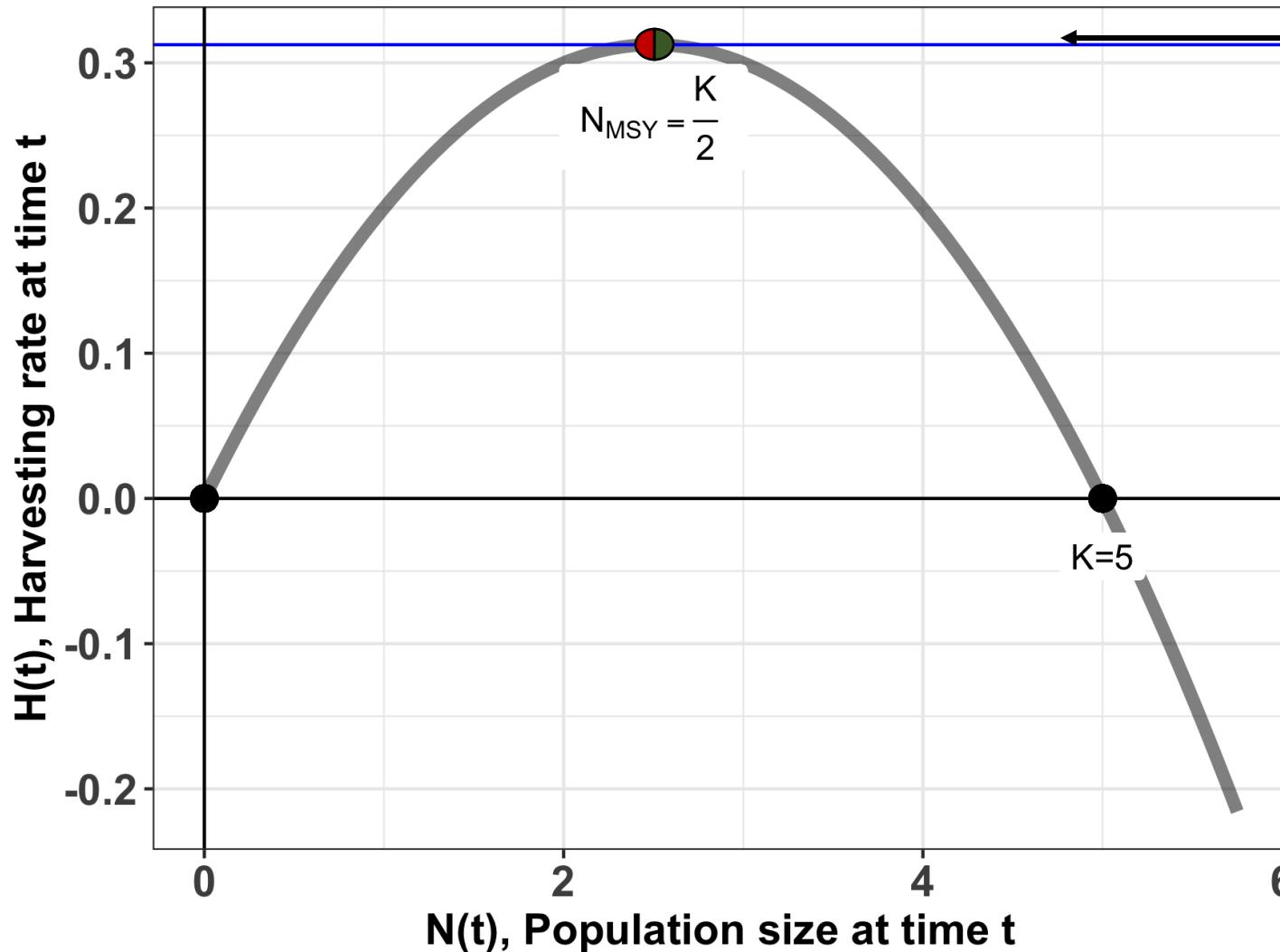
unstable equilibrium

For a population of $N=1$, a harvest rate of 0.2 (animals/timestep) results in an unsustainable equilibrium.

Random increases or decreases in population size will result in the population moving away from $N=1$ to, respectively, $N=4$ or $N=0$ (the latter is a **population collapse**).

Maximum sustainable yield (MSY)

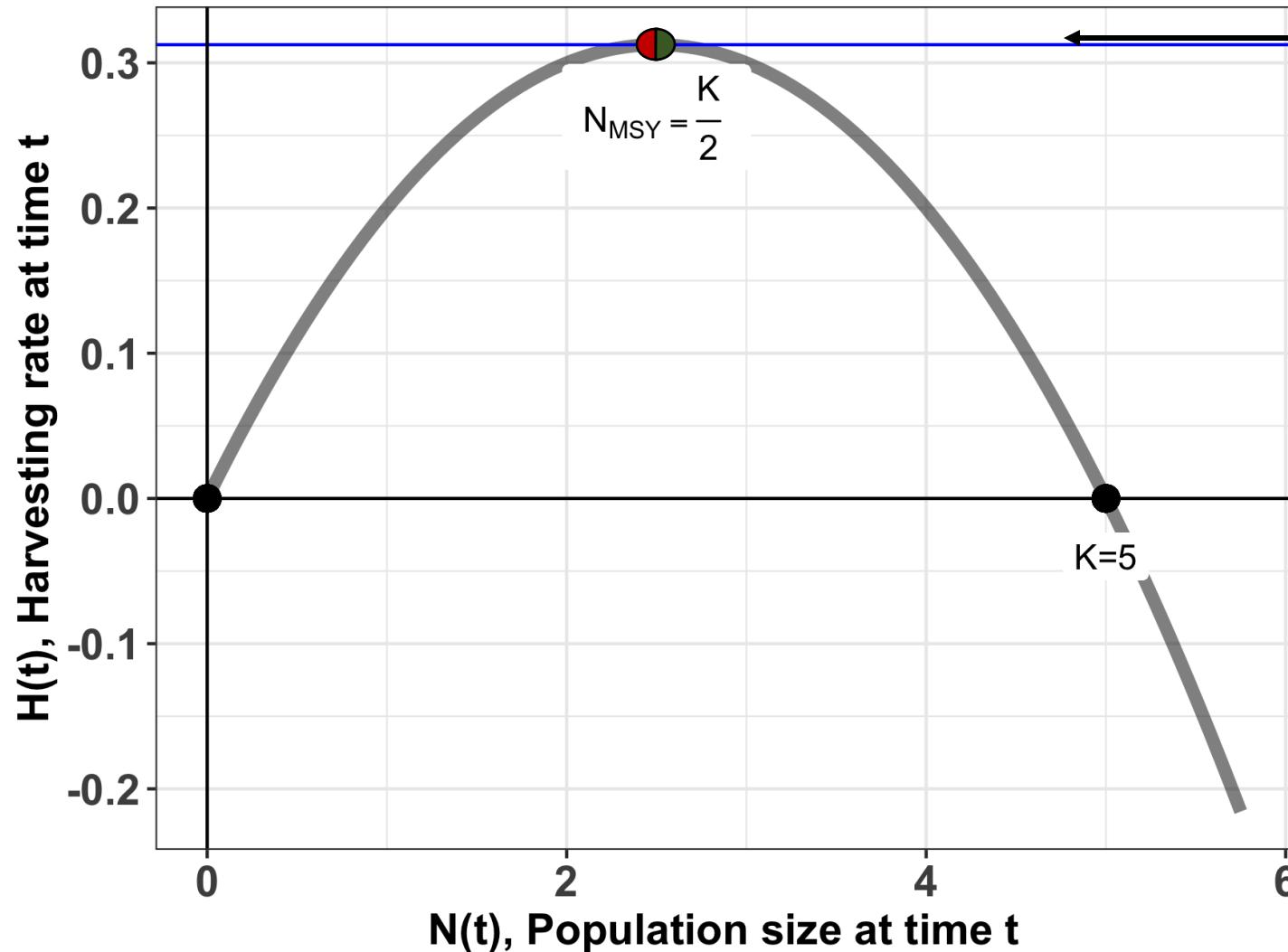
$$H = rN \left(1 - \frac{N}{K}\right)$$



In the logistic growth equation, population growth (dN/dt) is maximized at half the carrying capacity $N = \frac{K}{2}$

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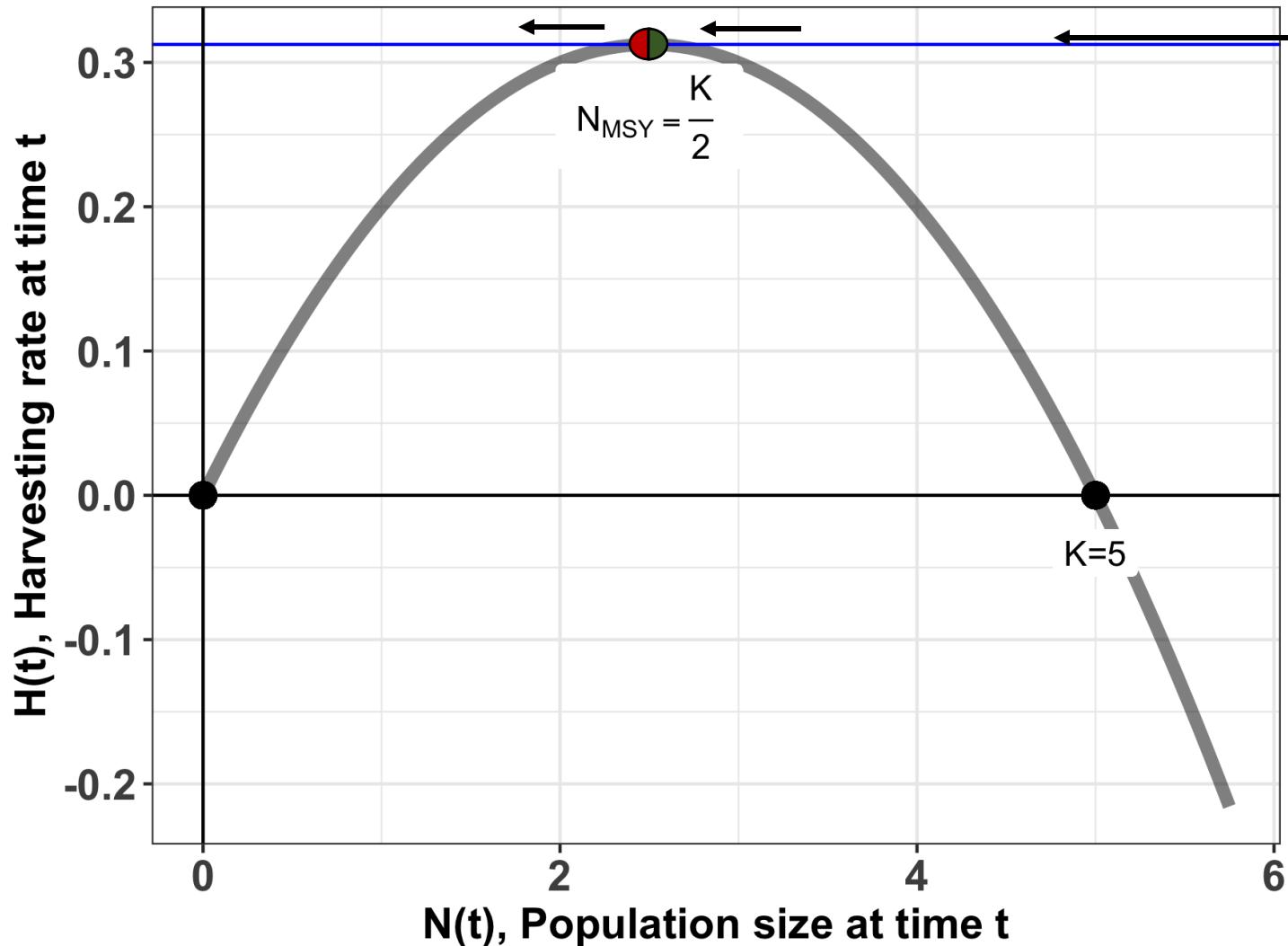
Theoretically, harvest could be maximized here as well:

$$\text{MSY: } H_{max} = \frac{rK}{4}$$

take the derivative with respect to N

Maximum sustainable yield (MSY)

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



MSY: $H_{max} = \frac{rK}{4}$

The MSY is a **semi-stable equilibrium**, meaning that small gains in population size (N) will be compensated to return the system to N_{MSY} , while small losses will result in the system collapsing to $N=0$.



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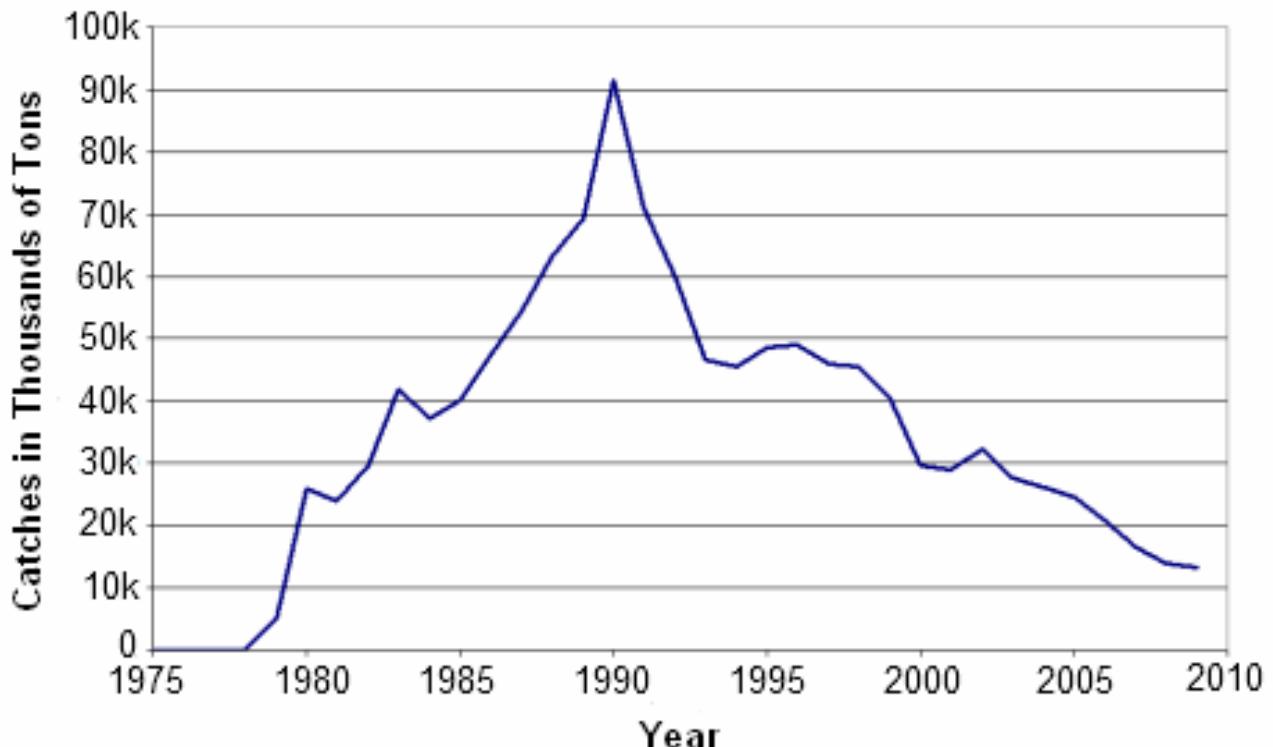


A population of rabbits of size $N=300$ with a growth rate of $r = 0.25$ individuals per year and a carrying capacity of 500 rabbits is harvested at a rate of 30 rabbits per year. If 5 rabbits die

Case Study: Orange Roughy



Worldwide Catches of Orange Roughy 1975 - 2009



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

Many populations will fluctuate above or below carrying capacity.

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

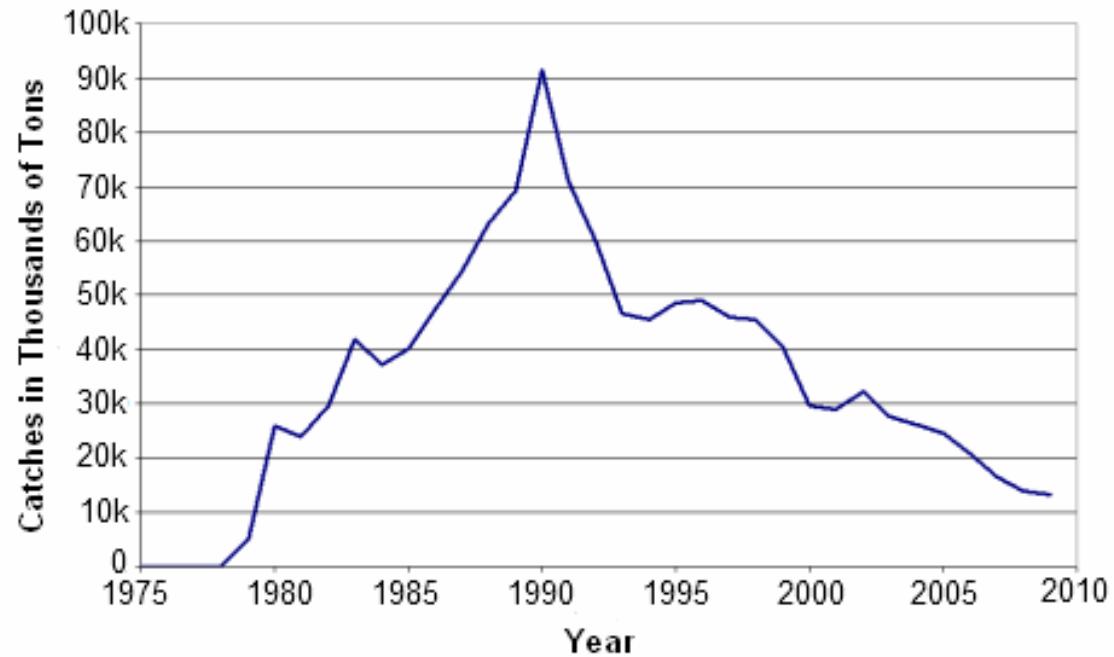
In some cases, it is not possible to recover.

Case Study: Orange Roughy



- Found in deep waters of eastern Pacific (Chile), western Pacific (Australia/NZ), and southeastern Atlantic (Namibia to South Africa)

Worldwide Catches of Orange Roughy 1975 - 2009

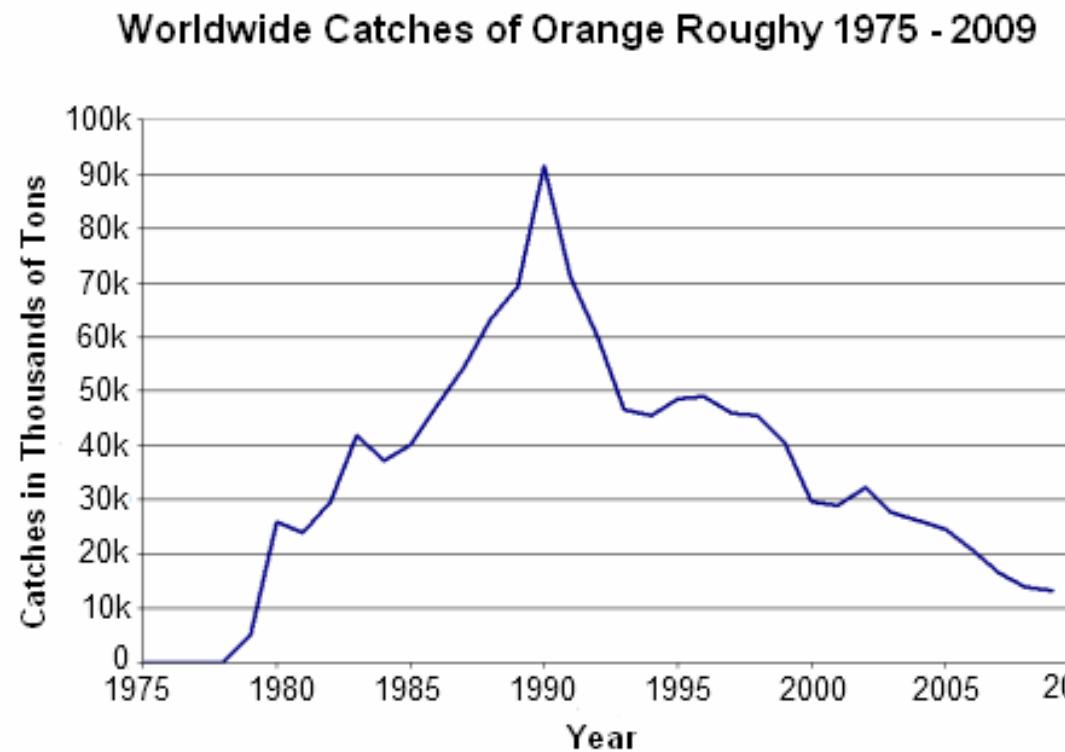


Source: FAO (Fisheries and Agriculture Organisation of the United Nations) Fisheries and Aquaculture Information and Statistics Service. © L. Baumont

Case Study: Orange Roughy



- Found in deep waters of eastern Pacific (Chile), western Pacific (Australia/NZ), and southeastern Atlantic (Namibia to South Africa)
- Can live up to 200 years! Matures at 20-30 yrs

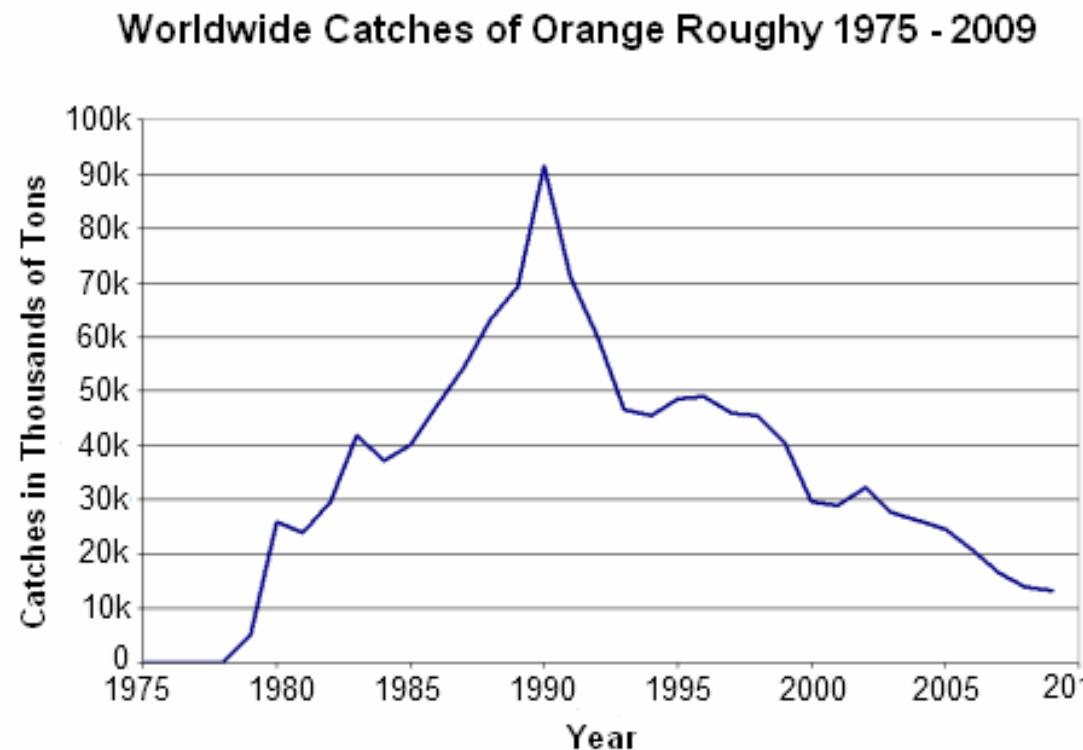


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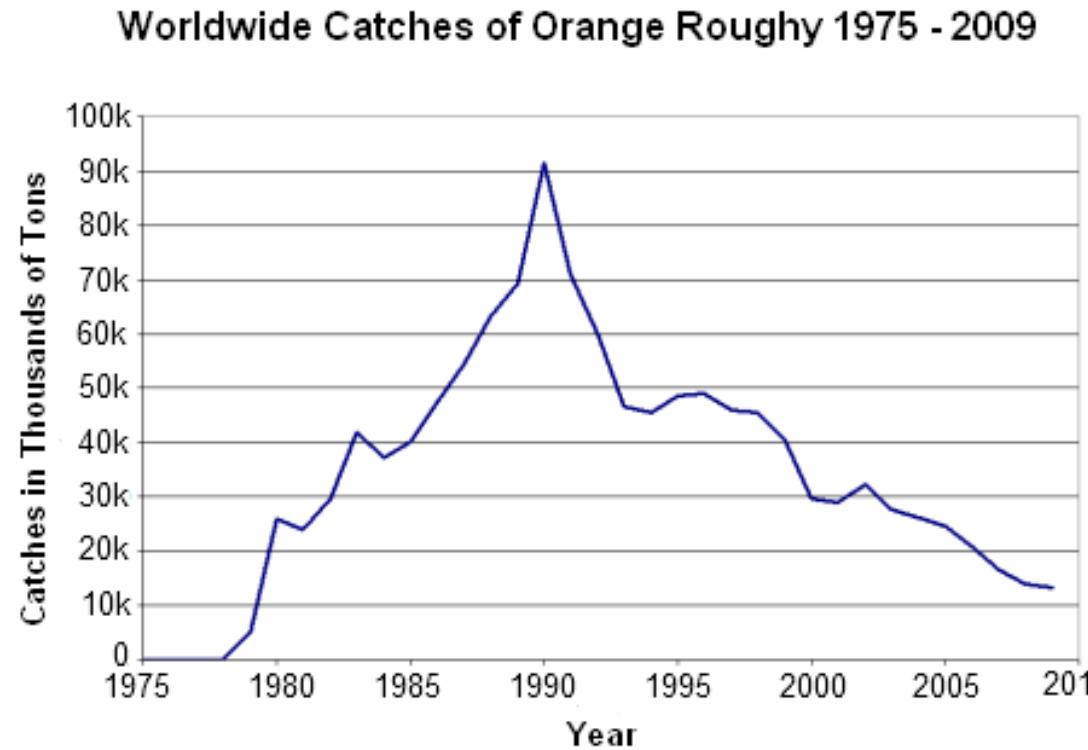


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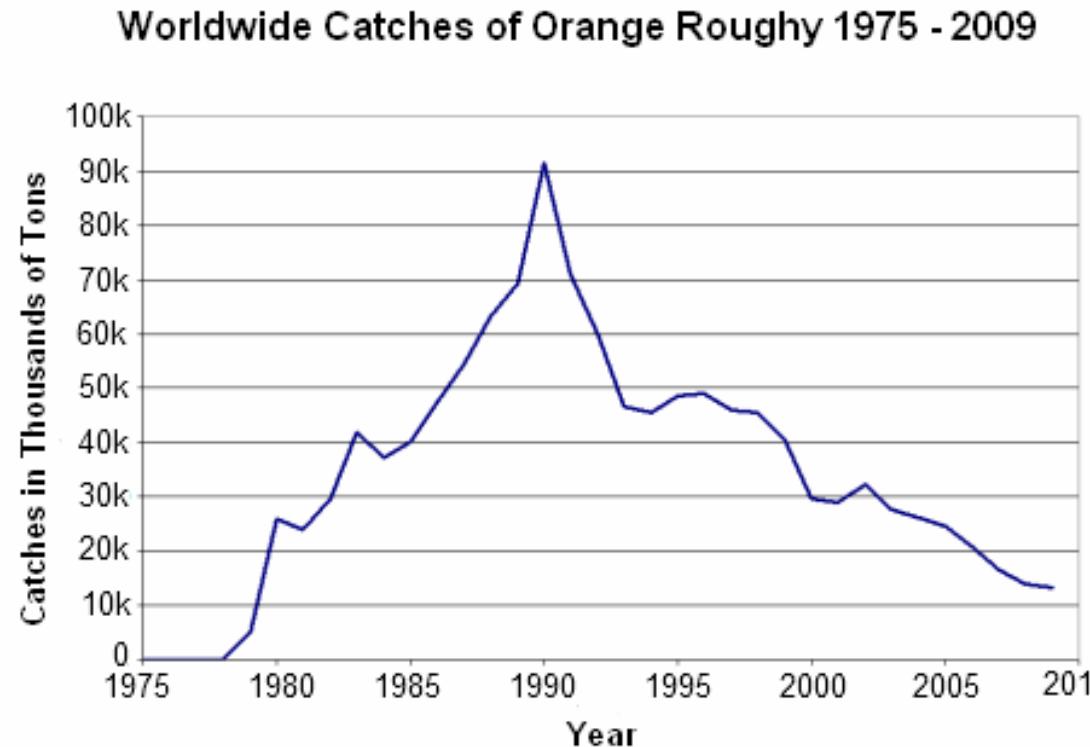


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- Fished via trawling, originally thought to have only a 30-year lifespan
- Annual global catches began in 1979 and increased to over 90,000 tons in the late 1980s.
- High catch levels quickly decreased as stocks were fished down. By the late 1990s, three of the eight NZ orange roughy fisheries had collapsed and were closed.



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

The case of the orange roughy highlights many of the **inherent problems with MSY**



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

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- r and K and N are difficult to measure.

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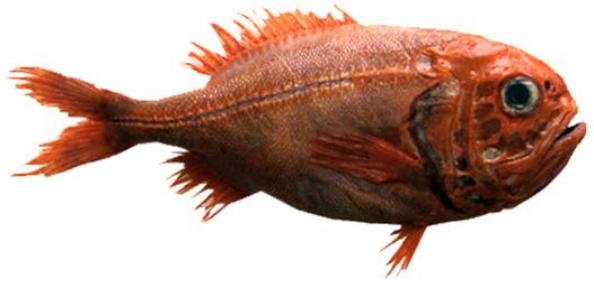
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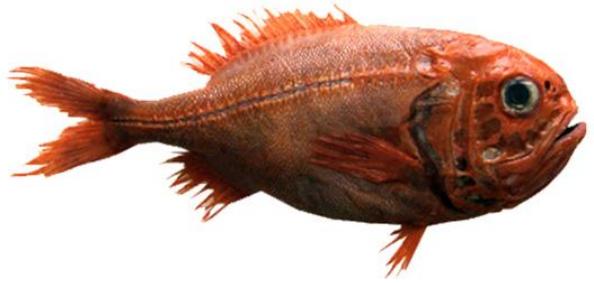
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The case of the orange roughy highlights many of the **inherent problems with MSY**



- r and K and N are difficult to measure.
- Many harvesting models neglect population structure or model only a single species in isolation.
- Simple harvesting models assume constant harvest.
- MSY fails to acknowledge the reality of **overfishing**.

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

Overfishing: A Tragedy of the Commons



Overfishing: A Tragedy of the Commons

- *Tragedy of the Commons:*
 - Individuals incentivized to use as much of a **shared, open access resource** as possible to maximize their own benefit.
 - The **cost of depleting the resource** (e.g., overgrazing the pasture, overfishing, polluting the air) **is borne by the entire group**, not just by the individual who is using it heavily.



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- Each individual's actions can negatively impact everyone.
- Tragedy results: Too many fish are removed, the pasture is overgrazed



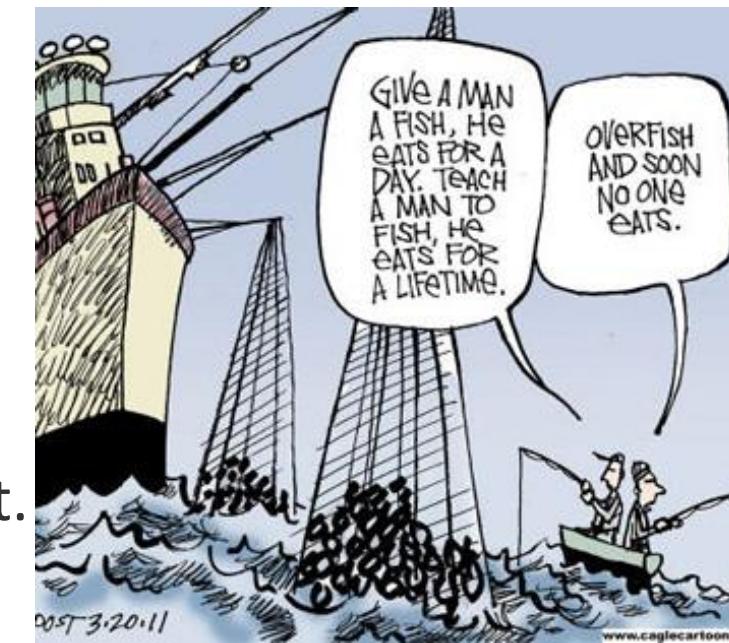
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- Fisheries provide a classic example of Tragedy of the Commons because property rights are incomplete and access is open. Many examples of fisheries collapse:
 - Sturgeon in Caspian sea in 2000s
 - Atlantic cod in Canada & elsewhere in 1990s
 - Orange roughy in NZ in 1990s



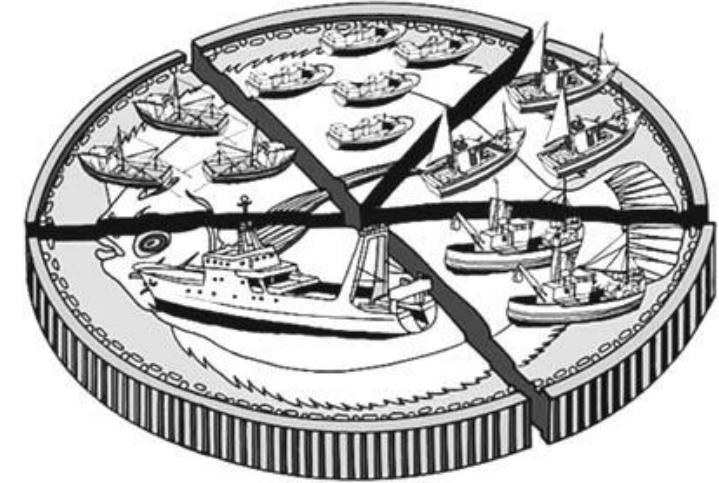
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- ***Tragedy of the Commons:***
 - Individuals incentivized to use as much of a **shared, open access resource** as possible to maximize their own benefit.
 - The **cost of depleting the resource** (e.g., overgrazing the pasture, overfishing, polluting the air) **is borne by the entire group**, not just by the individual who is using it heavily.
 - Each individual's actions can negatively impact everyone.
 - Tragedy results: Too many fish are removed, the pasture is overgrazed
- Idea was popularized by ecologist Garret Hardin in 1968, a Malthus-like reference to the overpopulation of the Earth
- Fisheries provide a classic example of Tragedy of the Commons because property rights are incomplete and access is open. Many examples of fisheries collapse:
 - Sturgeon in Caspian sea in 2000s
 - Atlantic cod in Canada & elsewhere in 1990s
 - Orange roughy in NZ in 1990s
- Despite its dangers, MSY is still highlighted as a policy in many **international treaties**.



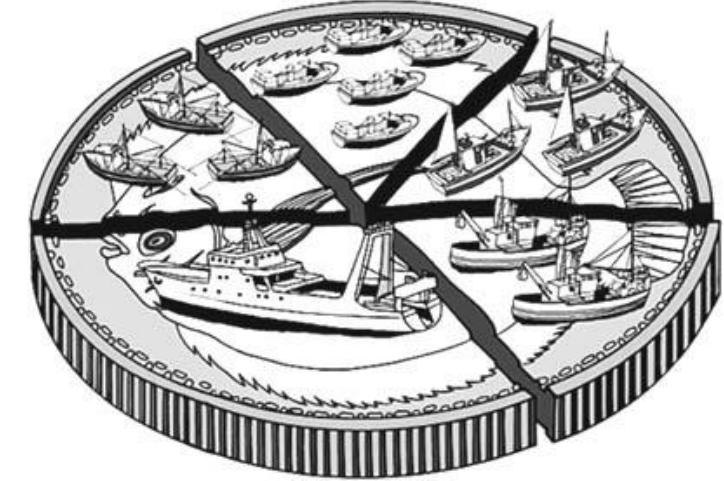
Managing the Commons - Internationally

- **Total Allowable Catch (TAC)** = total number of fish allowed to be caught in each fishery each year
 - Government coordination attempt to set international management goals
 - Can lead to intense pressure to fish all at once at the season's opening, sometimes overshooting the TAC.



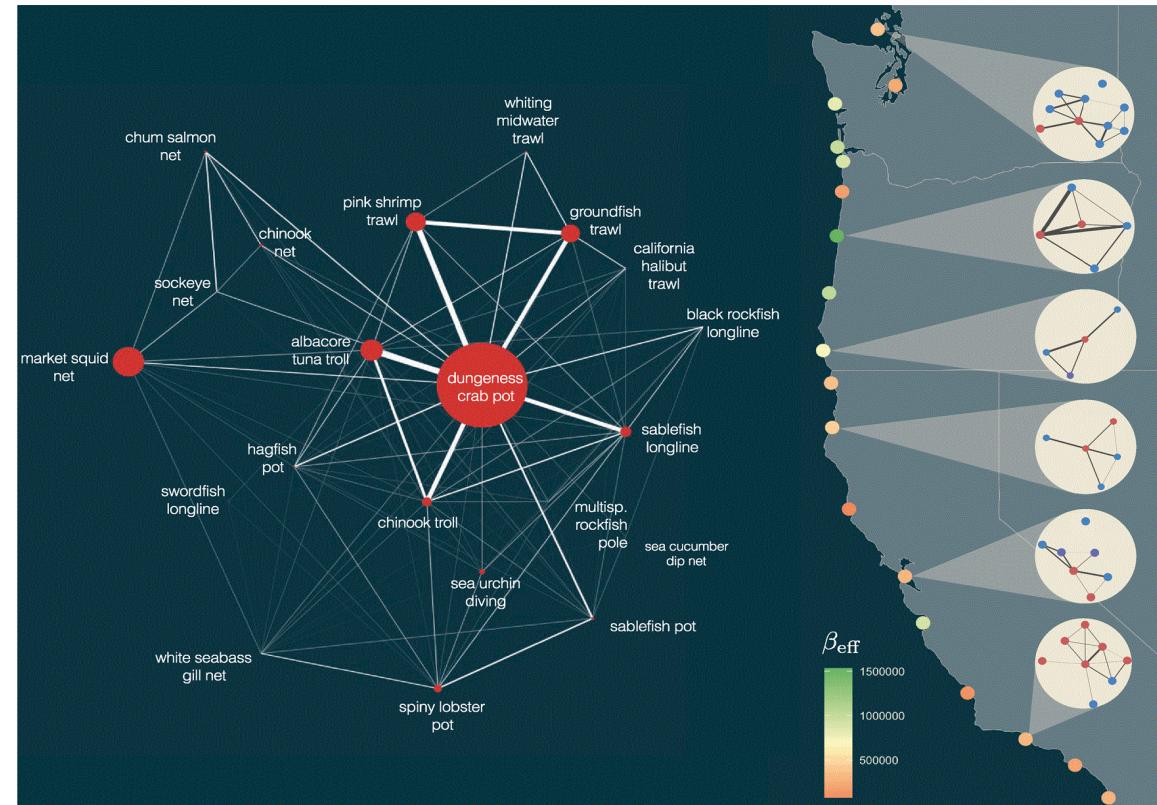
Managing the Commons - Internationally

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 - Can lead to intense pressure to fish all at once at the season's opening, sometimes overshooting the TAC.
- **Individual Fishing Quotas (IFQs)** = allocation by country or individual fisher
 - Can mitigate TAC challenges
 - **Individual Transferrable Quotas (ITQs)** = can be traded or transferred
 - allocation is still a challenge



Managing the Commons - Locally

- The work of Elinor Ostrom showed that **some of these challenges can be overcome** when:
 - resource limits are clearly defined
 - the group of stakeholders is small
 - communication is high



Dr. Emma Fuller,
Fractal Agriculture

The case of the orange roughy highlights many of the **inherent problems with MSY**



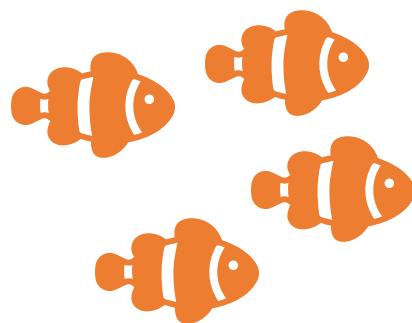
- r and K and N are difficult to measure.
- Many harvesting models neglect population structure or model only a single species in isolation.
- Simple harvesting models assume constant harvest.
- MSY fails to acknowledge the reality of **overfishing**.
- Because of the **semi-stable equilibrium** at MSY, small (natural) decreases in N can be devastating
 - environmental **stochasticity**
 - demographic **stochasticity**

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

Deterministic vs. Stochastic

Deterministic vs. Stochastic

starting population

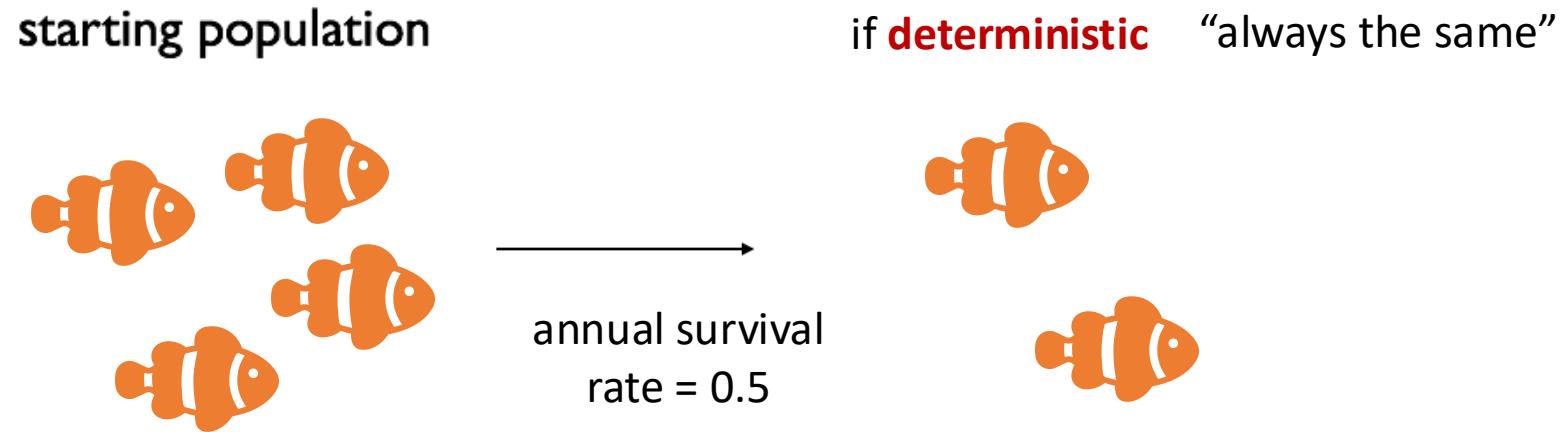


if **deterministic** “always the same”

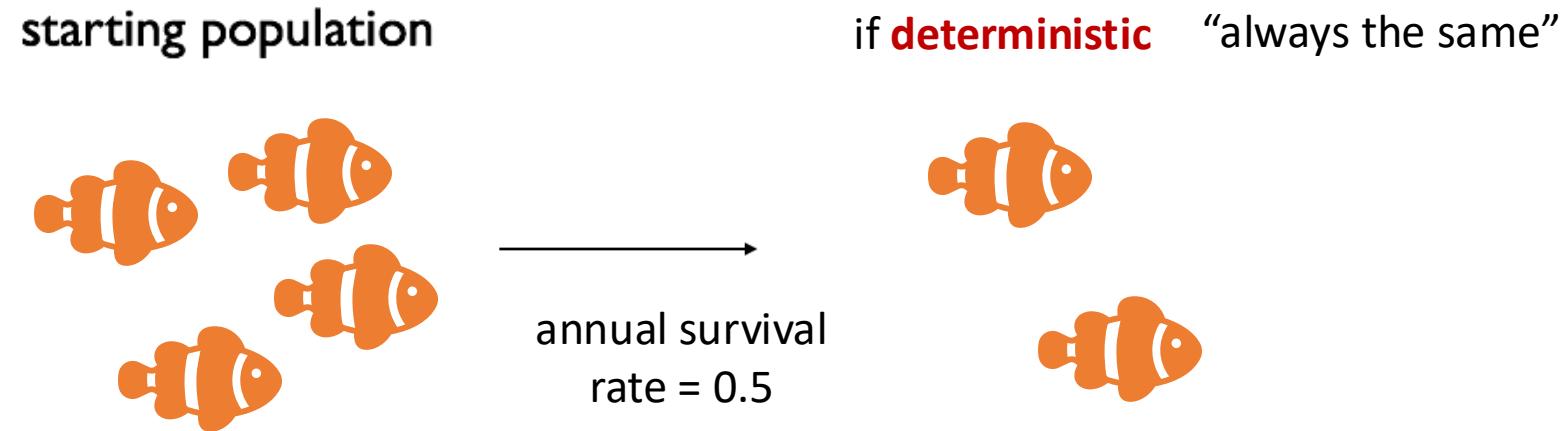


annual survival
rate = 0.5

Deterministic vs. Stochastic

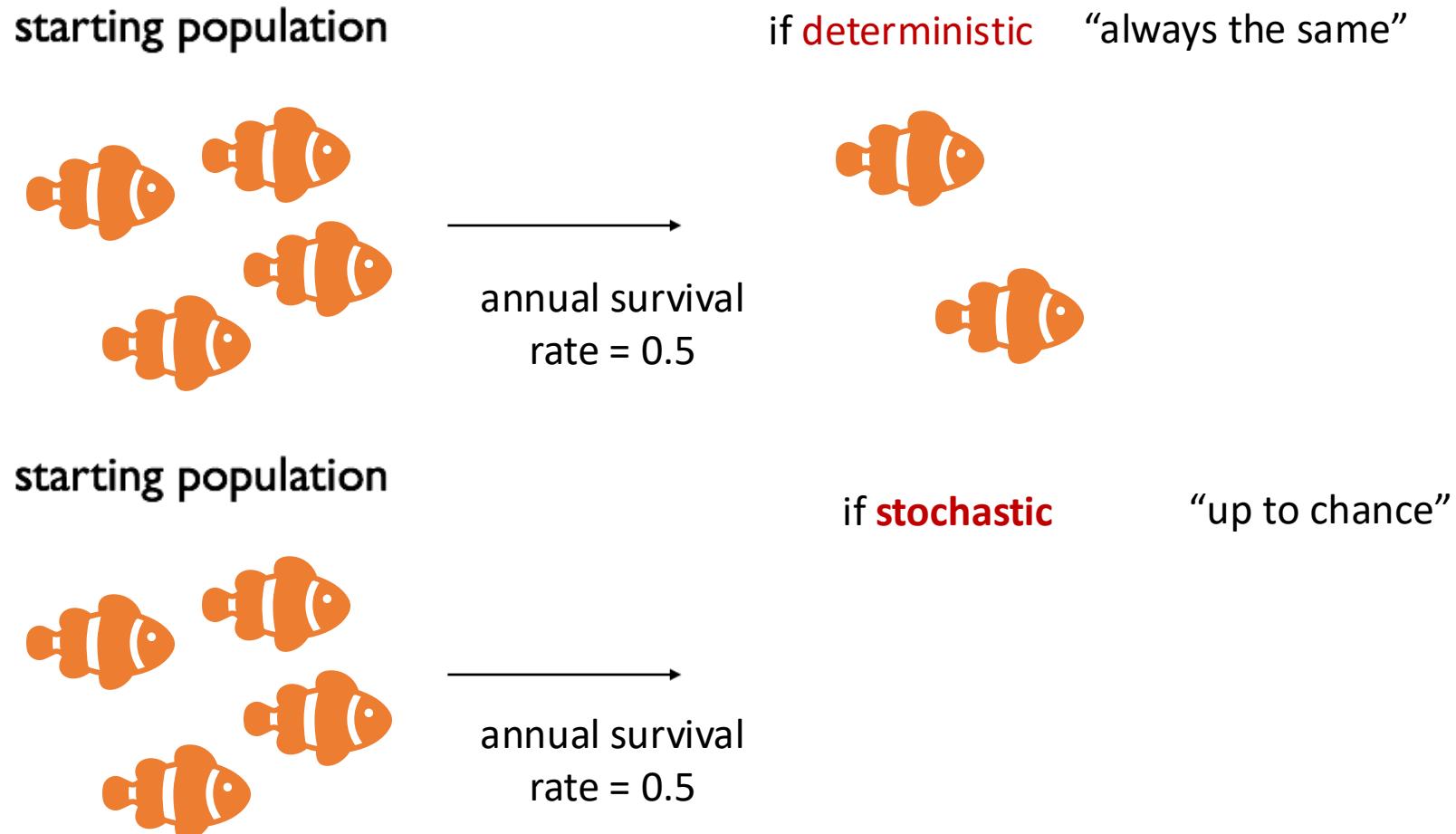


Deterministic vs. Stochastic

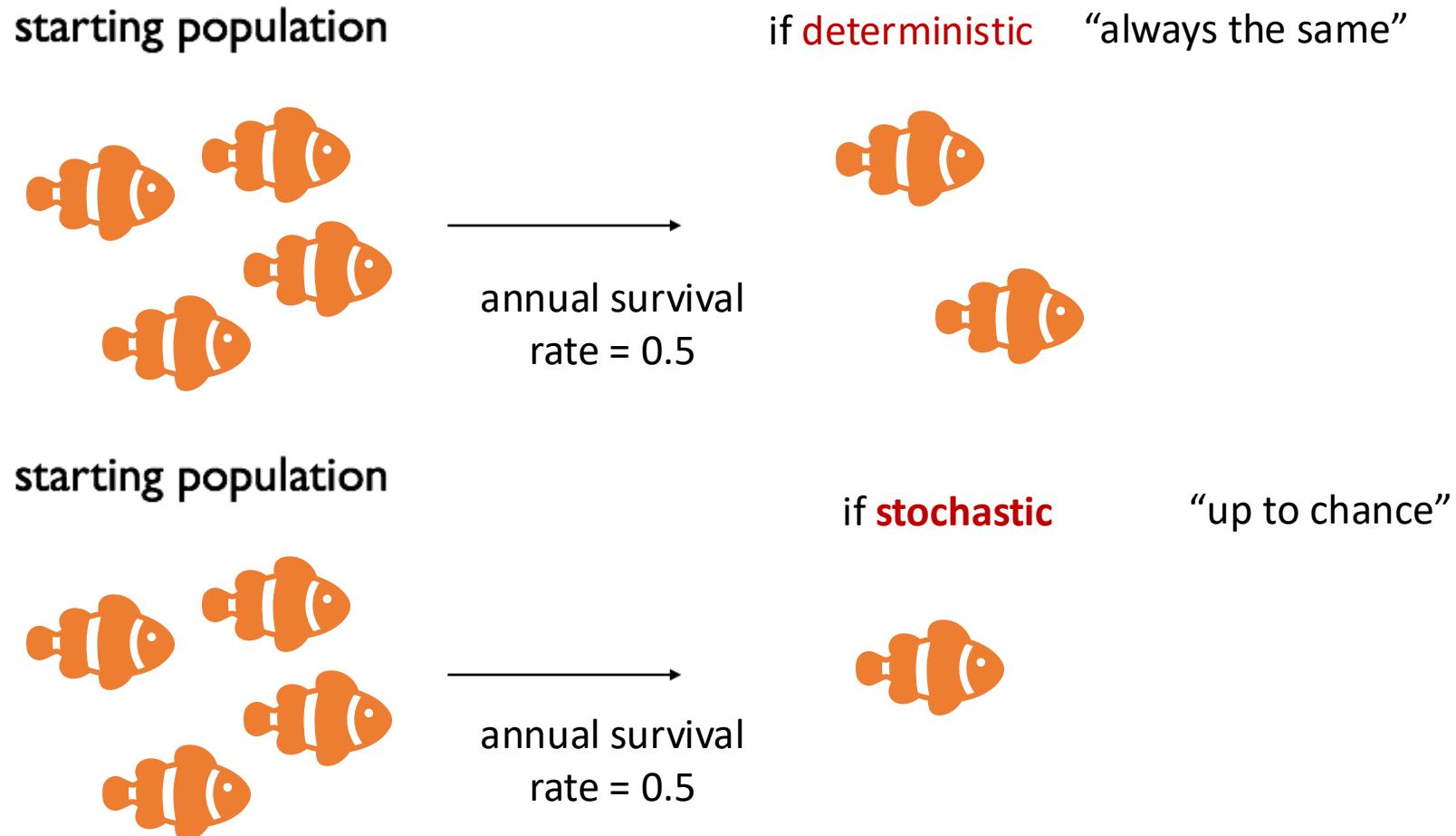


All the models we have looked at so far have been deterministic!

Deterministic vs. Stochastic

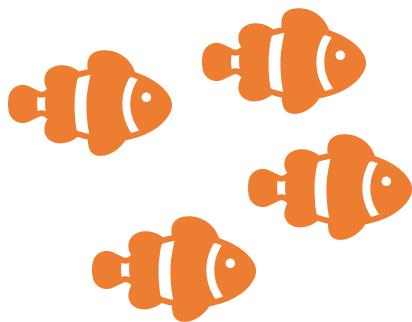


Deterministic vs. Stochastic



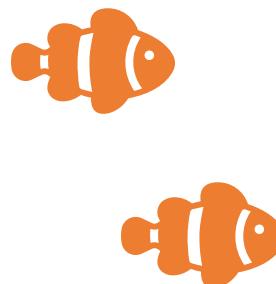
Deterministic vs. Stochastic

starting population

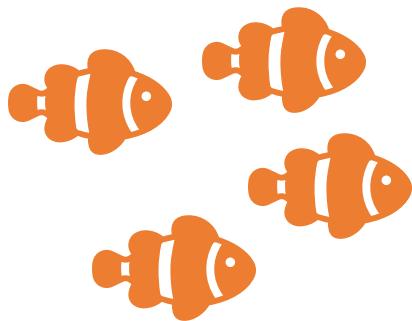


if **deterministic**

“always the same”

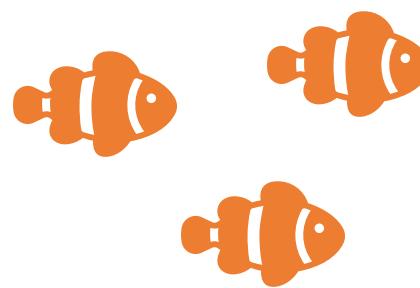


starting population



if **stochastic**

“up to chance”



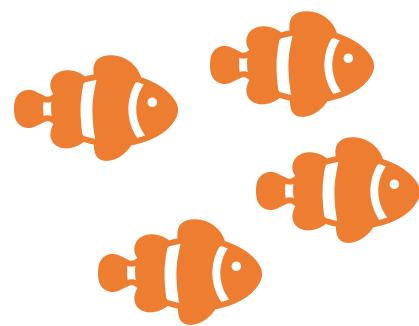
annual survival
rate = 0.5

annual survival
rate = 0.5

The case of the orange roughy highlights many of the **inherent problems with MSY**



starting population



if **stochastic**

“up to chance”



cyclone year!

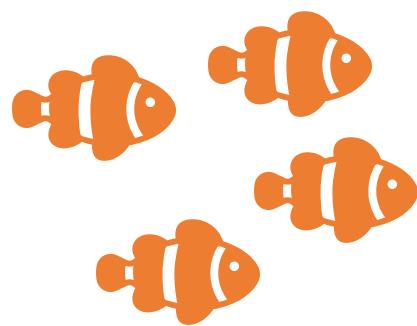
annual survival
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- r and K and N = difficult to measure.
- Neglect population structure.
- Single species models.
- Assumes constant harvest.
- Ignores reality of overfishing.
- Because of the **semi-stable equilibrium** at MSY, small (natural) decreases in N can be devastating
 - **environmental stochasticity**
 - temporal changes in mortality or reproductive rate (e.g. due to climate)

The case of the orange roughy highlights many of the **inherent problems with MSY**

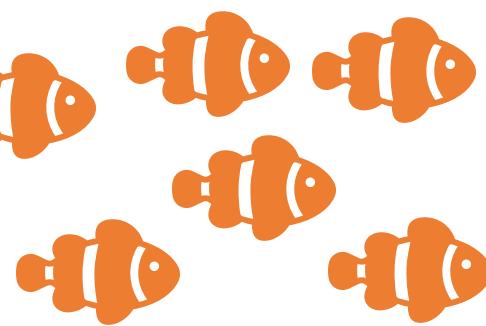


starting population



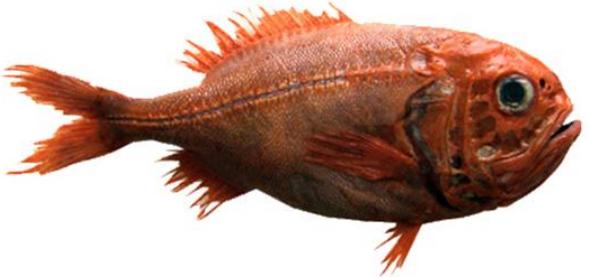
if **deterministic** “always the same”

annual fecundity
= 0.5

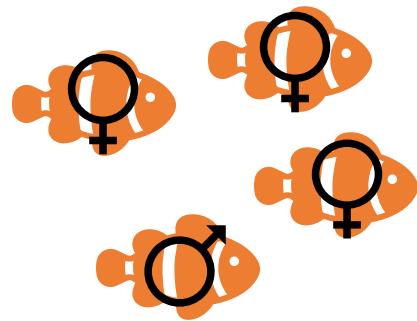


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 - temporal changes in mortality or reproductive rate (due to climate)
 - **demographic stochasticity**
 - individual-level differences in mortality and reproduction, esp. at small pop size

The case of the orange roughy highlights many of the **inherent problems with MSY**



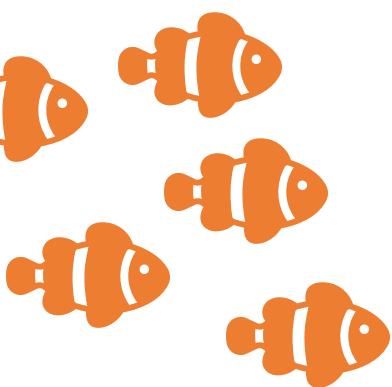
starting population



if stochastic

annual fecundity
= 0.5

“up to chance”



Only one male encounters only one female, so only 1 new fish is born!

- r and K and N = difficult to measure.
- Neglect population structure.
- Single species models.
- Assumes constant harvest.
- Ignores reality of overfishing.
- Because of the **semi-stable equilibrium** at MSY, small (natural) decreases in N can be devastating
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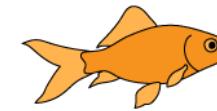
To harvest the most fish over the long term, assuming the population is subject to logistic growth, one should

- A. never harvest more than about 20% of the carrying capacity

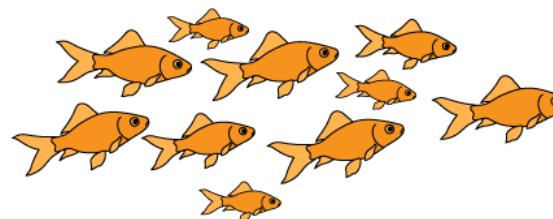
0%

SEE MORE ▾

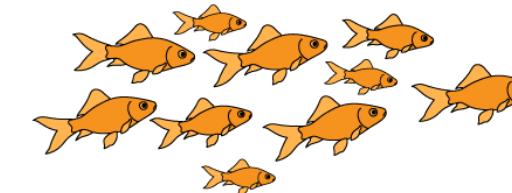
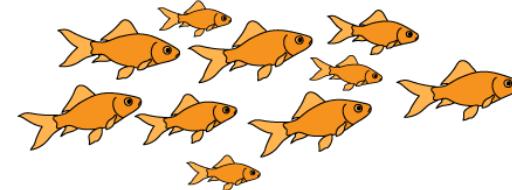
Ecology is the study of
the **interactions** of
organisms with each
other and their
environment.



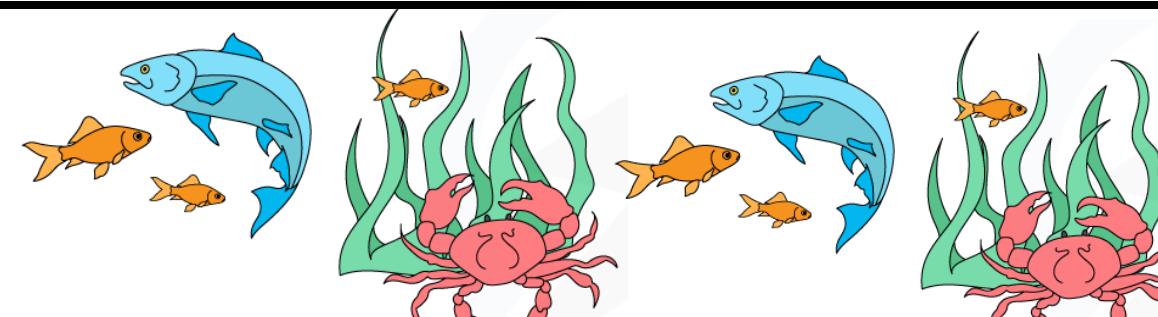
individual



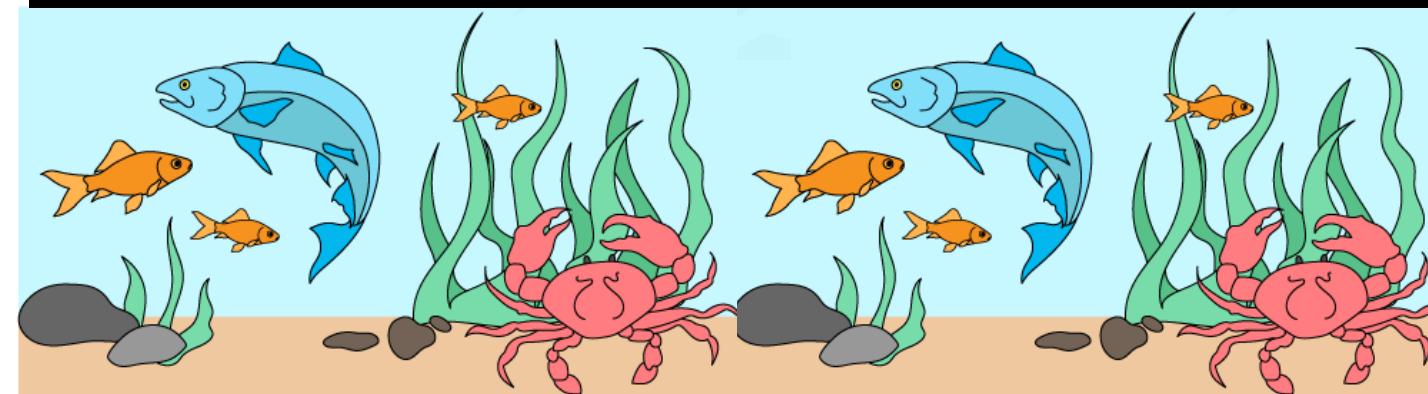
population



metapopulation

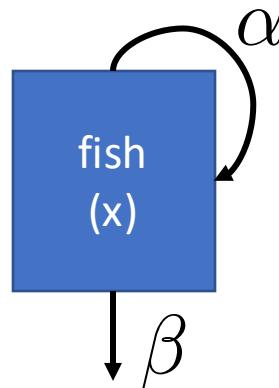


community

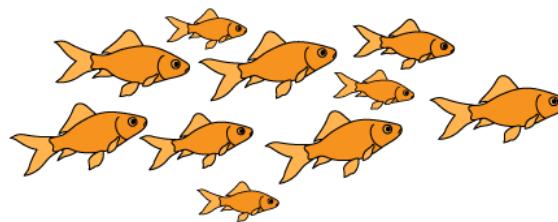


ecosystem

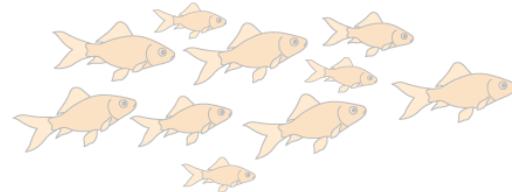
Population = multiple individuals of the same species (**conspecifics**) in the same habitat



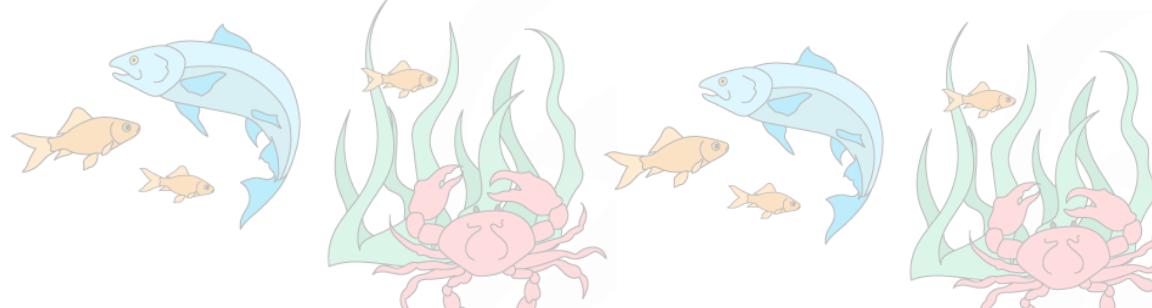
individual



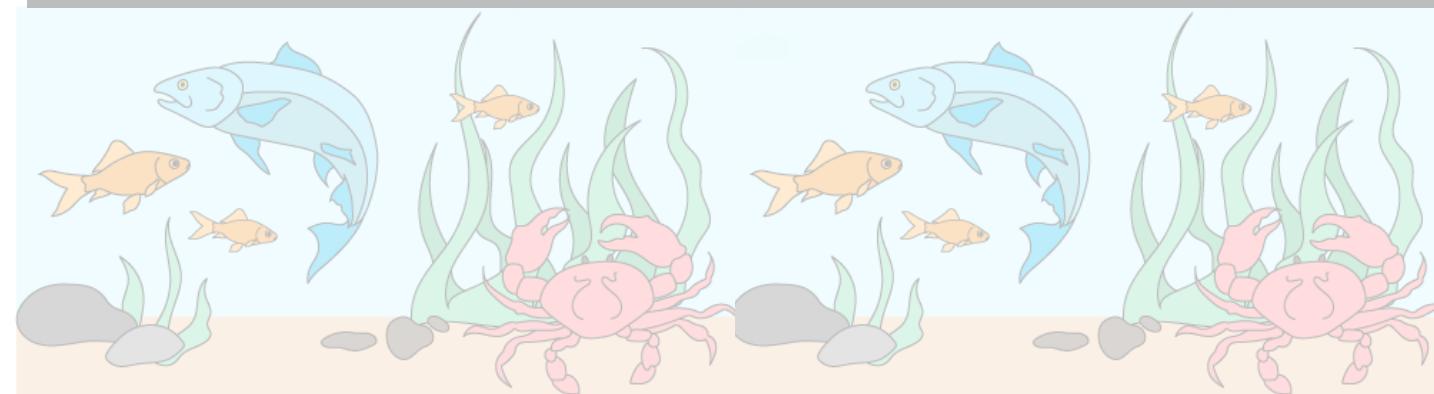
population



metapopulation



community



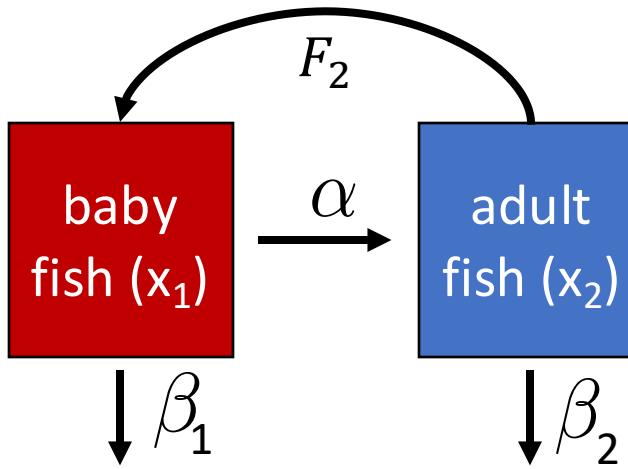
ecosystem

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

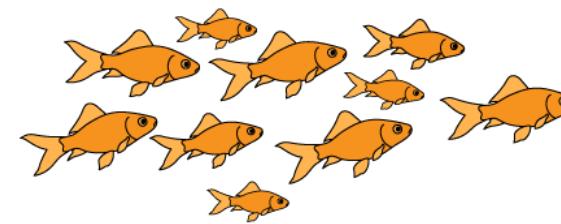
individual



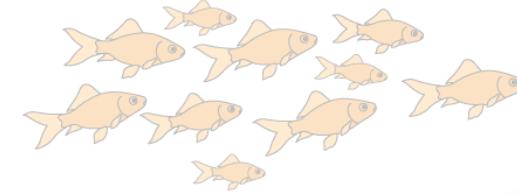
Structured Population =
multiple individuals of the
same species
(conspecifics) in the same
habitat but in different
life history stages



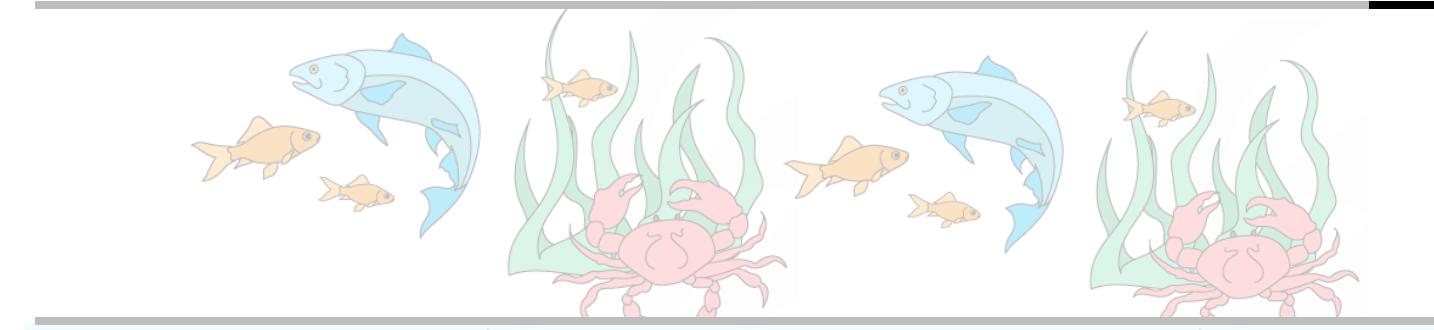
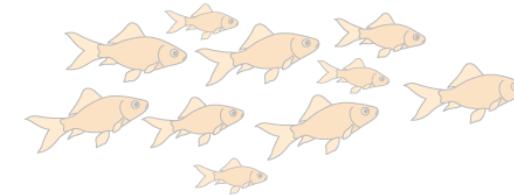
population



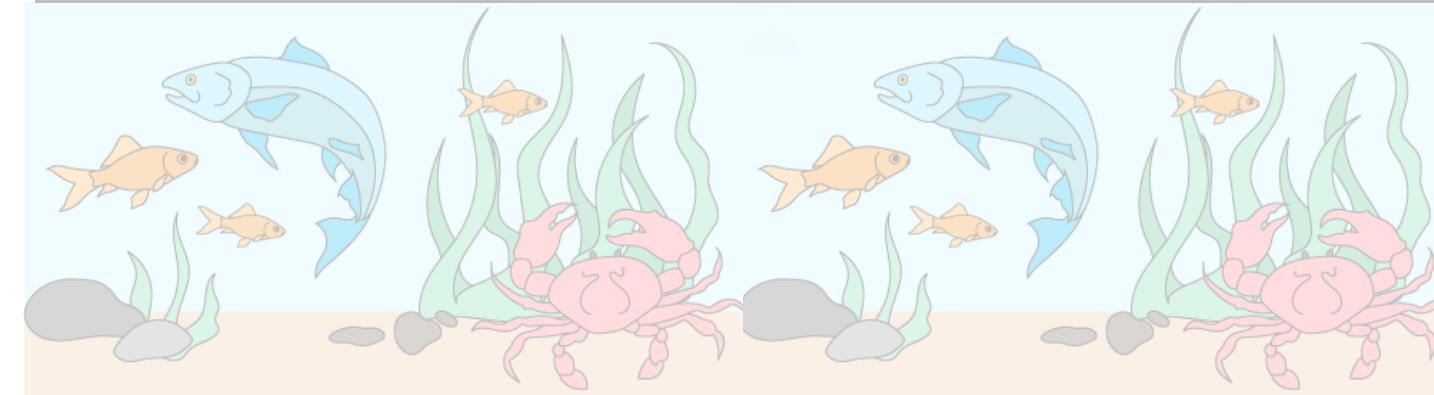
metapopulation



community



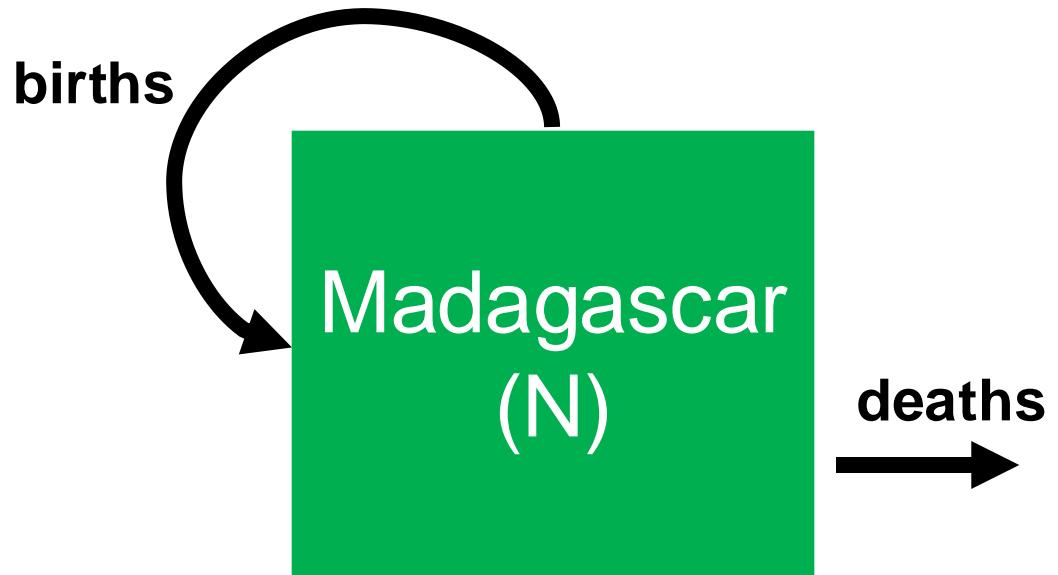
ecosystem



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

Modeling demographic complexity

Modeling demographic complexity

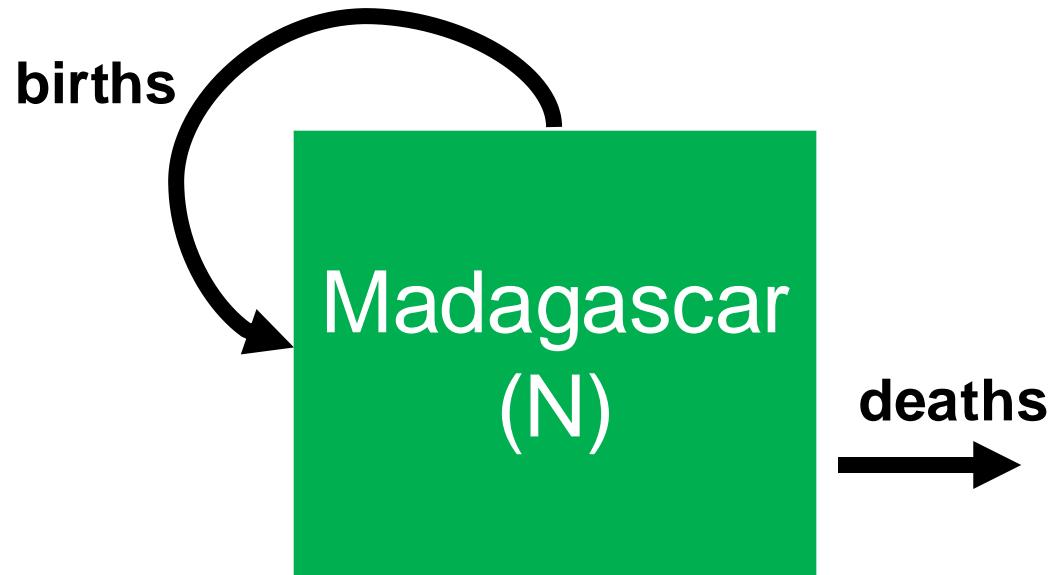


1. Populations are divided into compartments
2. Individuals within a compartment are homogeneously mixed
3. Compartments and transition rates are determined by biological systems
4. Rates of transferring between compartments are expressed mathematically



The simplest population model

Modeling demographic complexity

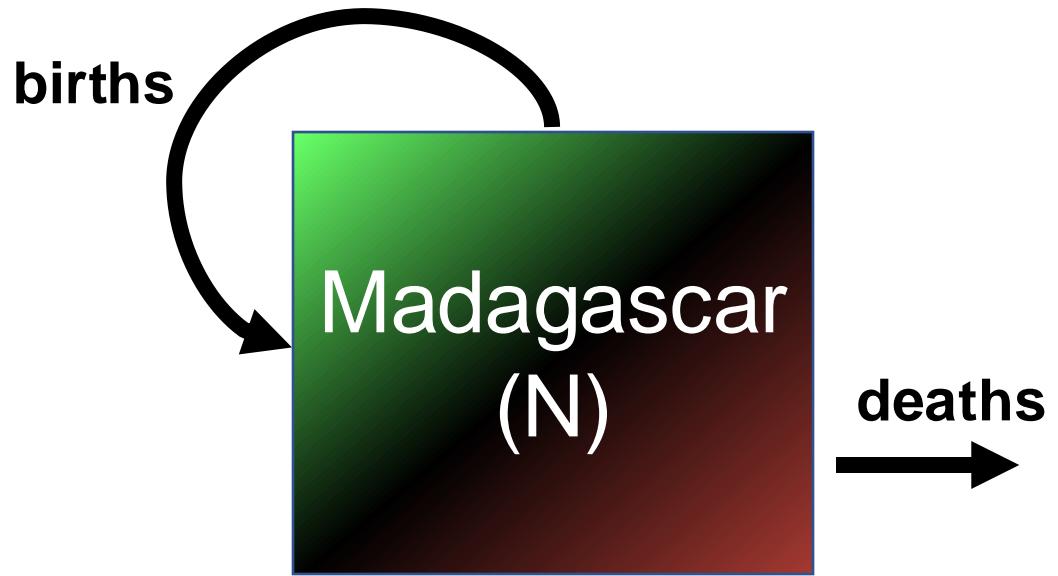


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What is wrong about this model?

Modeling demographic complexity



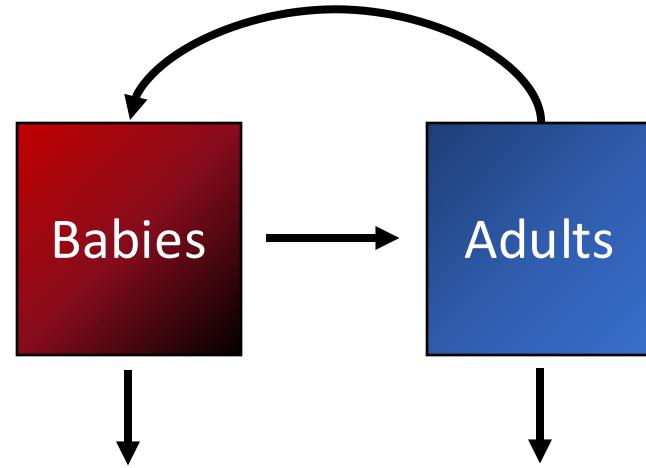
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Modeling demographic complexity

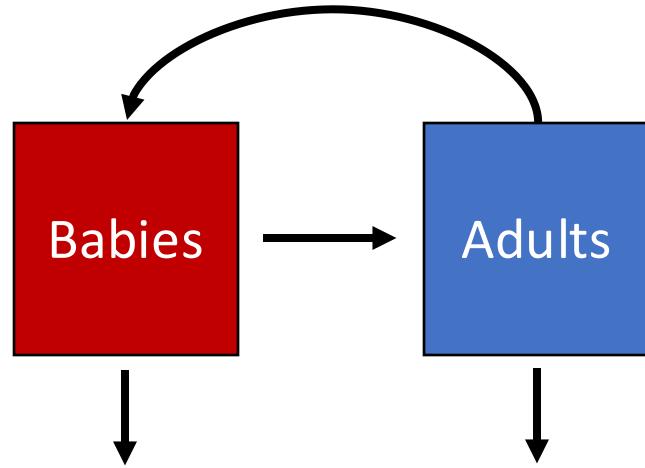
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The structured population model

Modeling demographic complexity

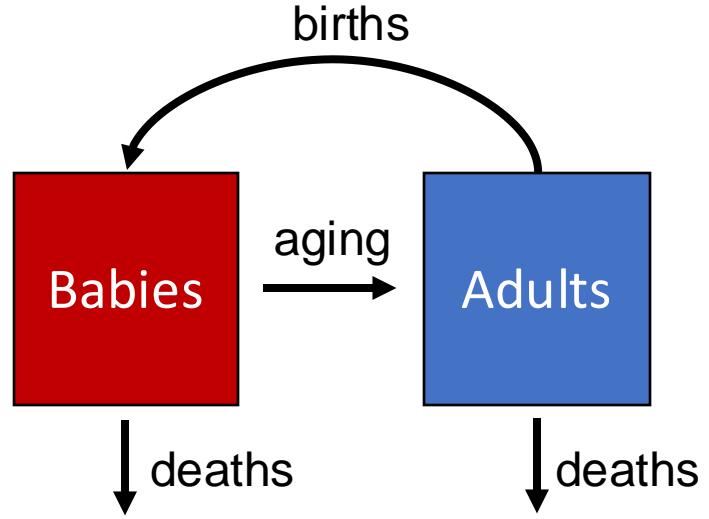
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The structured population model

Modeling demographic complexity

1. Populations are divided into compartments
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- 3. Compartments and transition rates are determined by biological systems**
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The structured population model

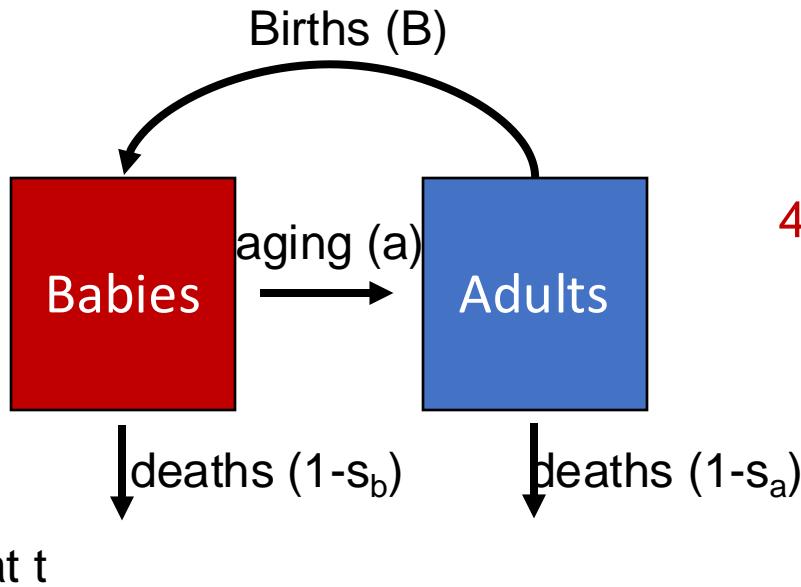
The structured population model

Population rate of increase

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

pop size at t + 1

pop size at t



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

$$N_{t+1} = A^* N_t$$

matrix of survival
and fecundity rates

$s_b(1-a)$	B
$s_b a$	s_a

vector of
population sizes

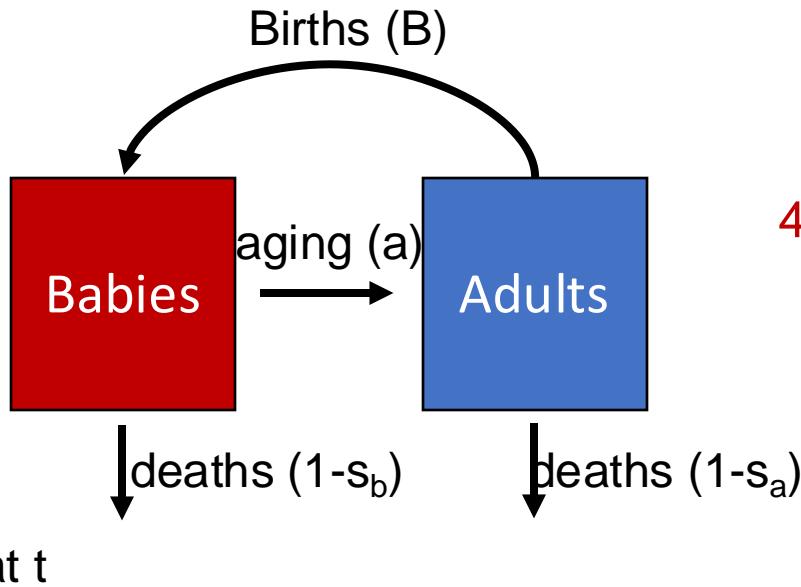
The structured population model

Population rate of increase

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

pop size at t + 1

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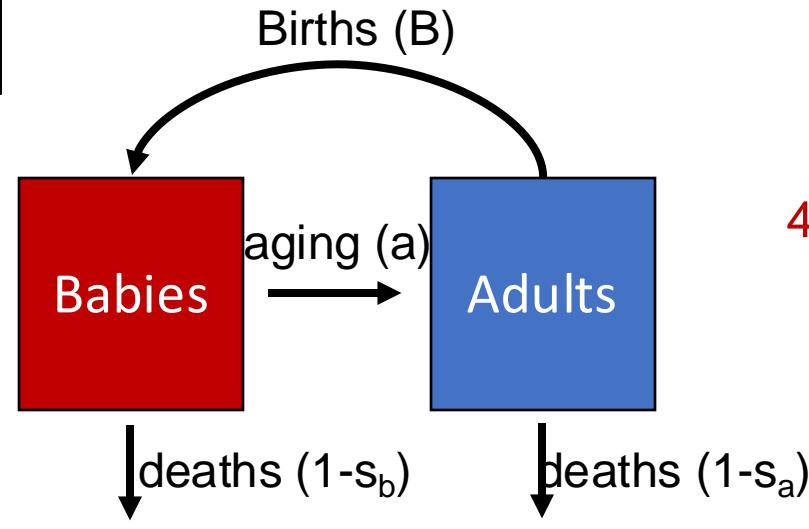
matrix of survival
and fecundity rates

$s_b(1-a)$	B
$s_b a$	s_a

vector of
population sizes

*Discrete time

The structured population model

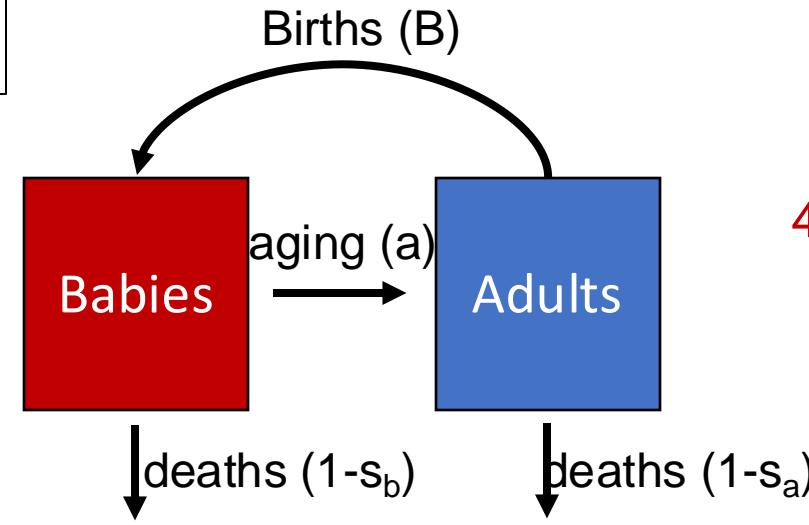


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$$N_{t+1} = A^* N_t$$

$$\begin{array}{c} \mathbf{A} \\ \begin{matrix} s_b(1-a) & B \\ \hline s_b a & s_a \end{matrix} \end{array} \times \begin{array}{c} \mathbf{N}_t \\ \begin{matrix} N_b \\ \hline N_a \end{matrix} \end{array} = \begin{array}{c} \mathbf{N}_{t+1} \\ \begin{matrix} s_b(1-a) N_b + B N_a \\ \hline s_b a N_b + s_a N_a \end{matrix} \end{array}$$

The structured population model



1. Populations are divided into compartments
2. Individuals within a compartment are homogeneously mixed
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4. Rates of transferring between compartments are expressed mathematically

$$N_{t+1} = A^* N_t$$

Population rate of increase – can be derived from the transition matrix!

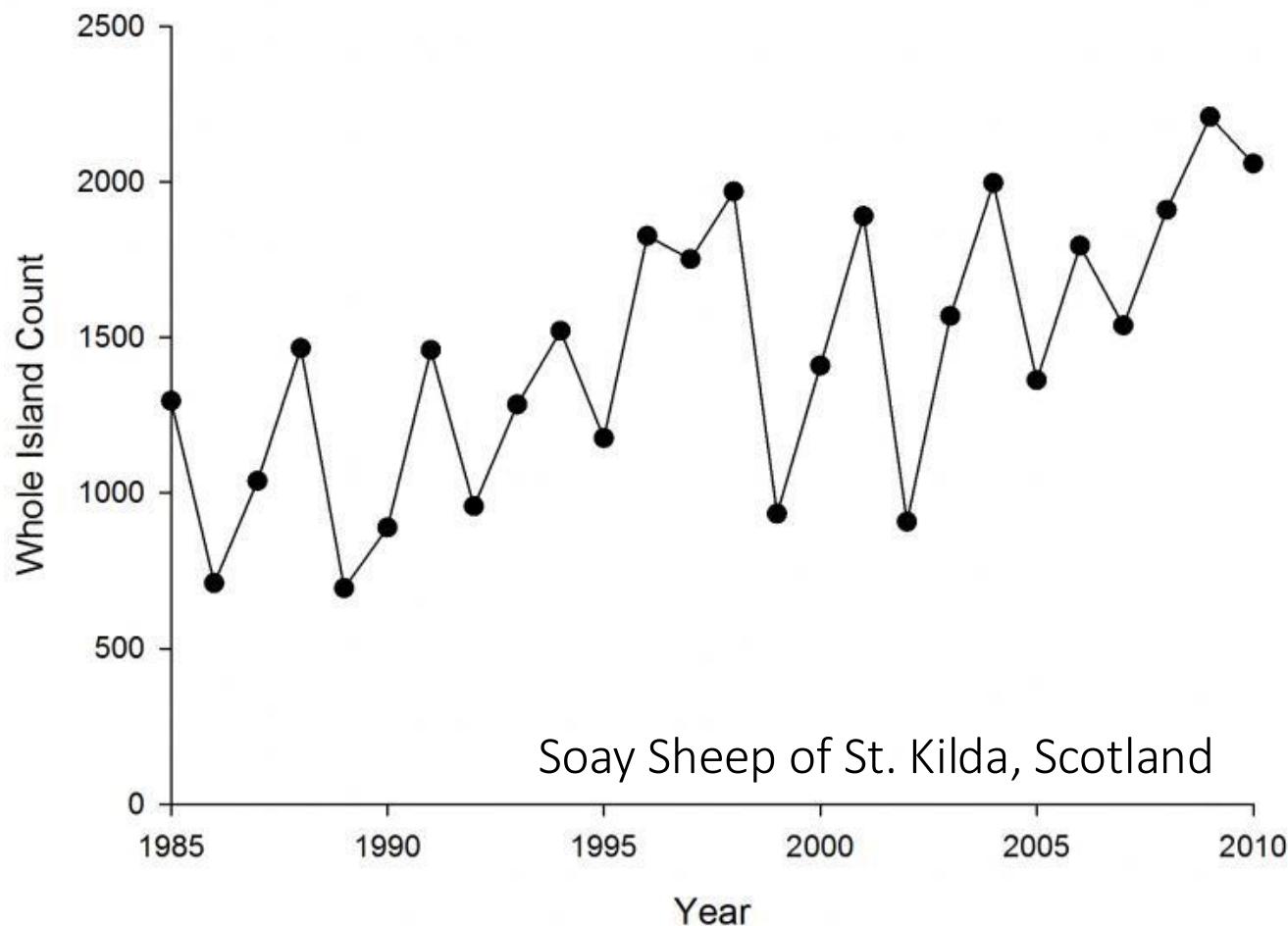
λ

$$\begin{array}{c} \mathbf{A} \\ \xrightarrow{\quad} \begin{matrix} s_b(1-a) & B \\ s_b a & s_a \end{matrix} \end{array} \times \begin{matrix} N_b \\ N_a \end{matrix} = \begin{matrix} s_b(1-a) N_b + B N_a \\ s_b a N_b + s_a N_a \end{matrix}$$

Population growth will depend on population structure!

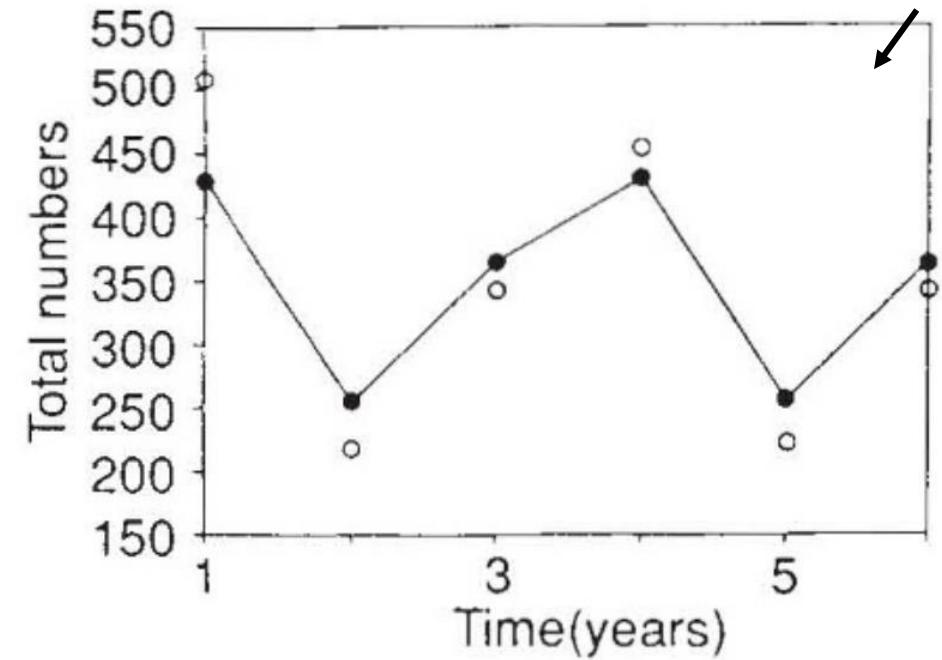
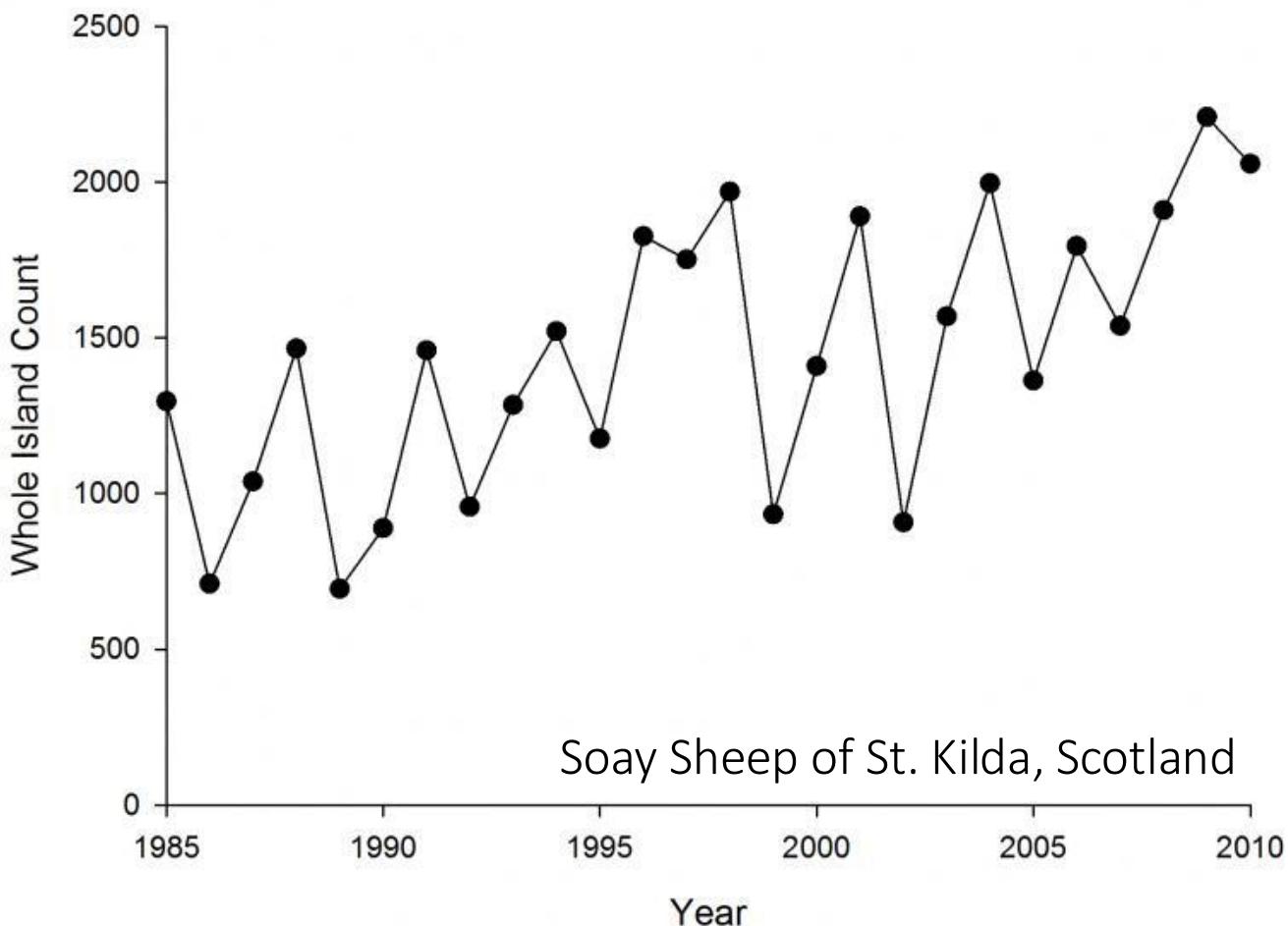
(pop grows @ $\lambda > 1$ & declines @ $\lambda < 1$)

Structured populations in practice



Structured populations in practice

Model
compared
against
data



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](#)

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Model
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against
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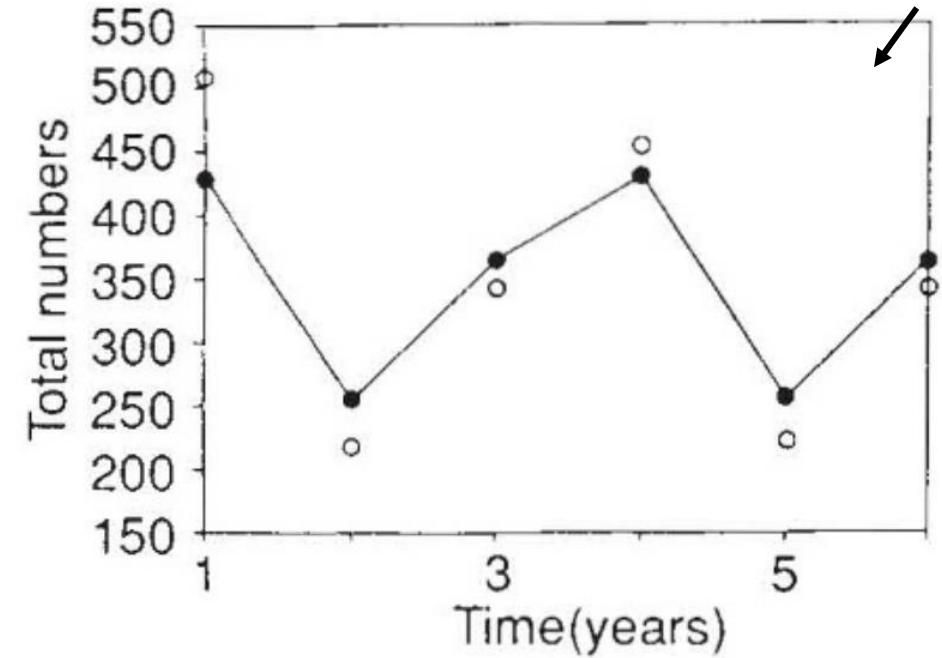
Structured populations in practice

These results used a simple **density-dependent** model only!

$$N_{t+1} = \lambda d N_t / (1 + (aN_t)^b)$$

↑ ↑ growth rate }
population at t+1 average fecundity population at t

a and *b* control the strength of density dependence.



Overcompensation and population cycles in an ungulate

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

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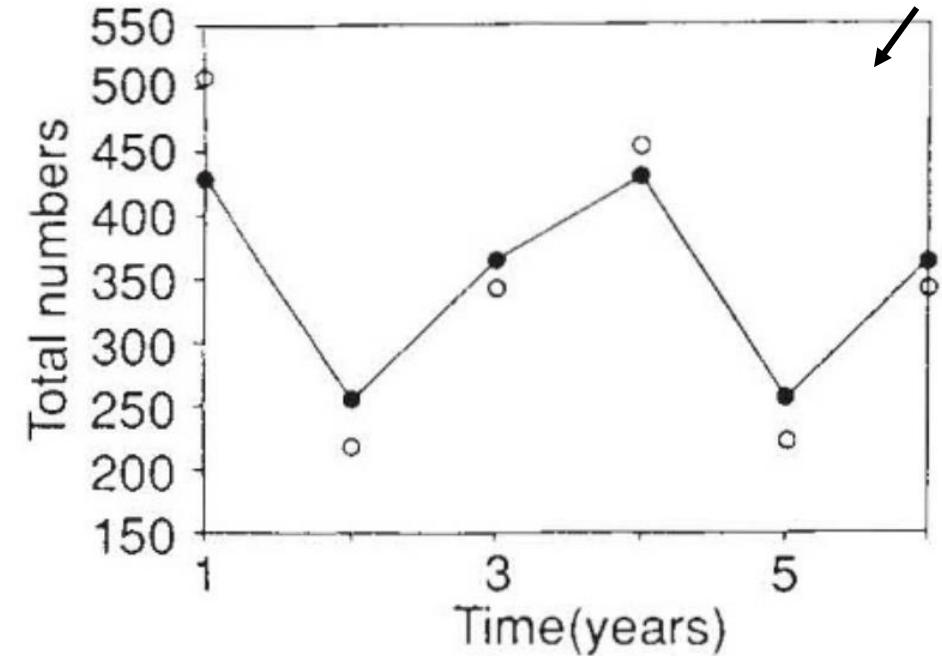
$$N_{t+1} = \lambda d N_t / (1 + (aN_t)^b)$$

↑ ↑ growth rate }
population at t+1 average fecundity population at t

a and *b* control the strength of density dependence.

Similar to the simple logistic growth equation!

$$N_{t+1} = N_t \left(1 - \frac{N_t}{K}\right)$$



Overcompensation and population cycles in an ungulate

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

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Structured populations in practice

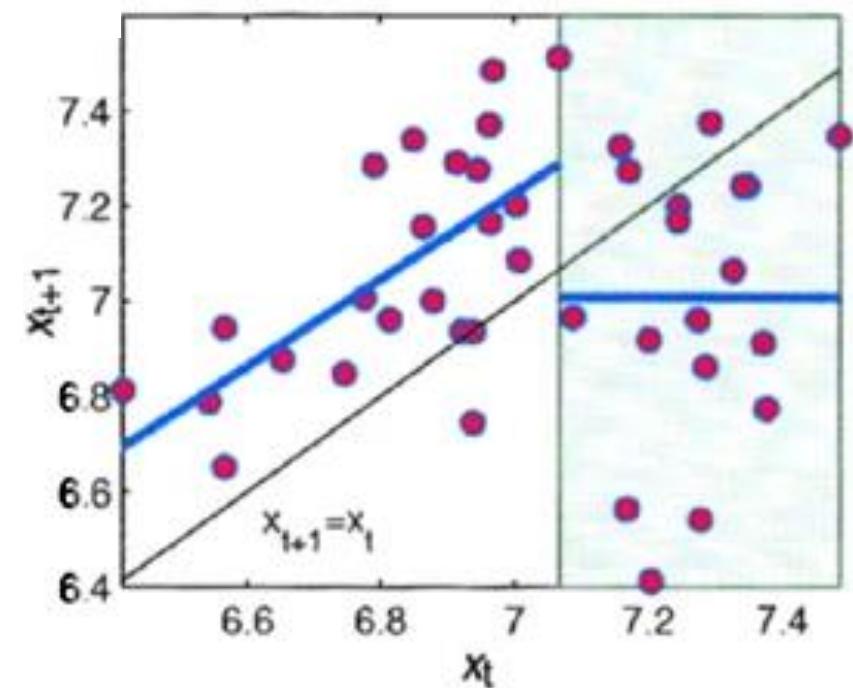
In later work, the authors added **environmental stochasticity** (bad weather) to **better represent** the data.....

Noise and determinism in synchronized sheep dynamics

[B. T. Grenfell](#) , [K. Wilson](#), [B. F. Finkenstädt](#), [T. N. Coulson](#), [S. Murray](#), [S. D. Albon](#), [J. M. Pemberton](#), [T. H. Clutton-Brock](#) & [M. J. Crawley](#)

[Nature](#) **394**, 674–677 (1998) | [Cite this article](#)

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Structured populations in practice

In later work, the authors added **environmental stochasticity** (bad weather) to **better represent** the data.....

At high population sizes, population crashes can occur due to density dependence – but these happen preferentially in bad weather!

Noise and determinism in synchronized sheep dynamics

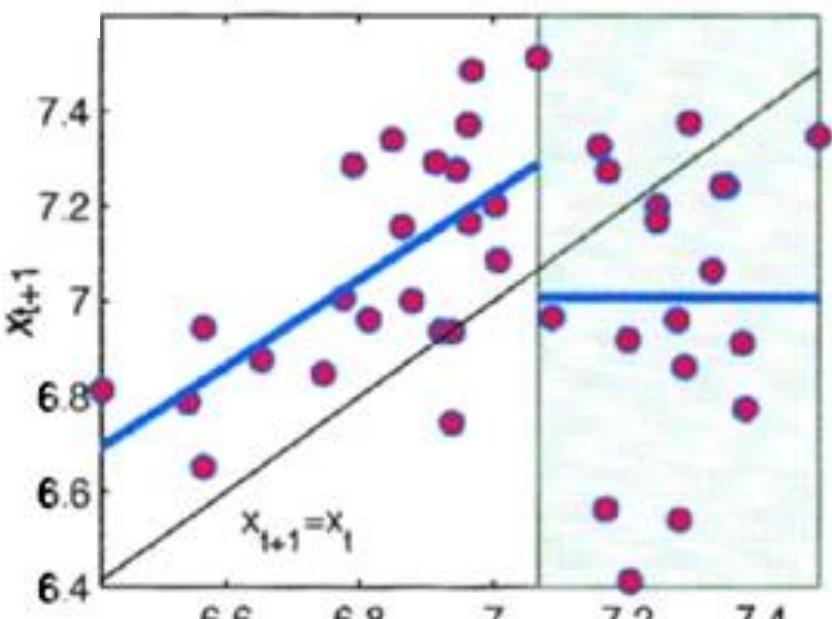
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sheep
population at
time $t+1$

sheep population at time t → x_t



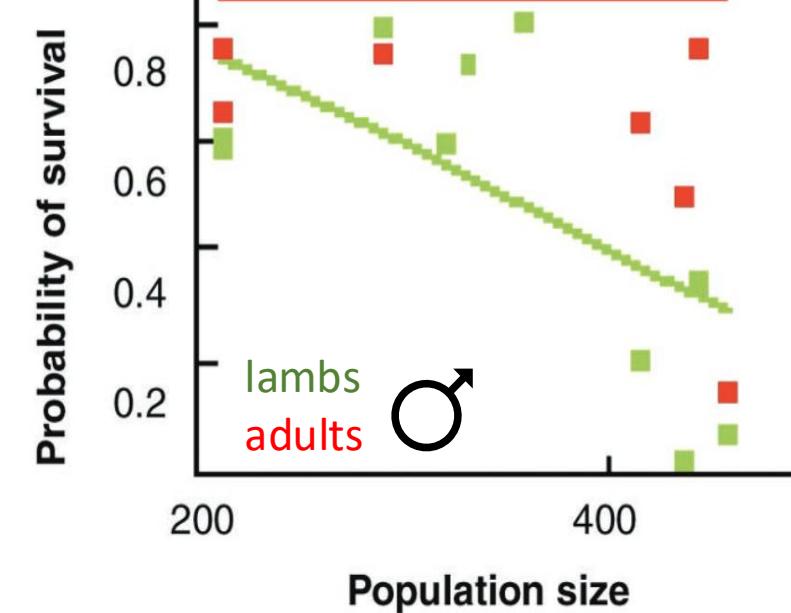
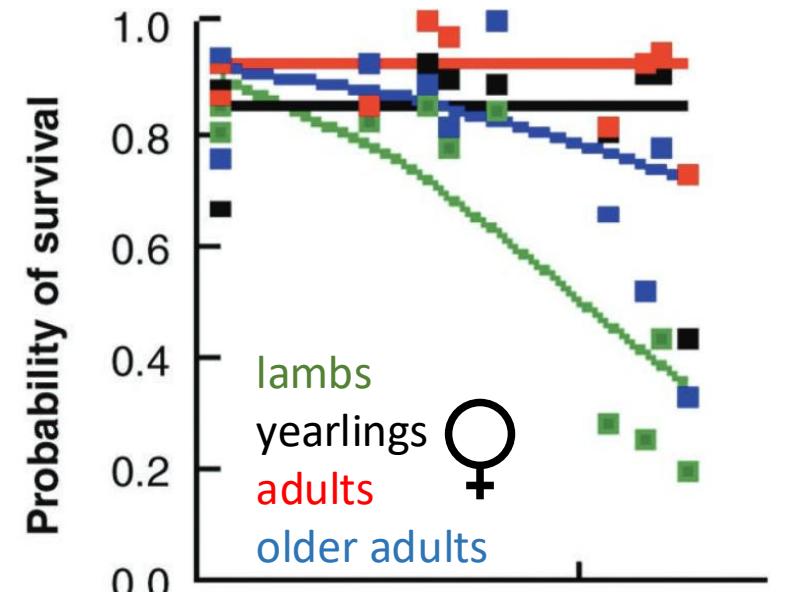
Structured populations in practice

And, finally, they added in **population structure** as well!

Age, Sex, Density, Winter Weather, and Population Crashes in Soay Sheep

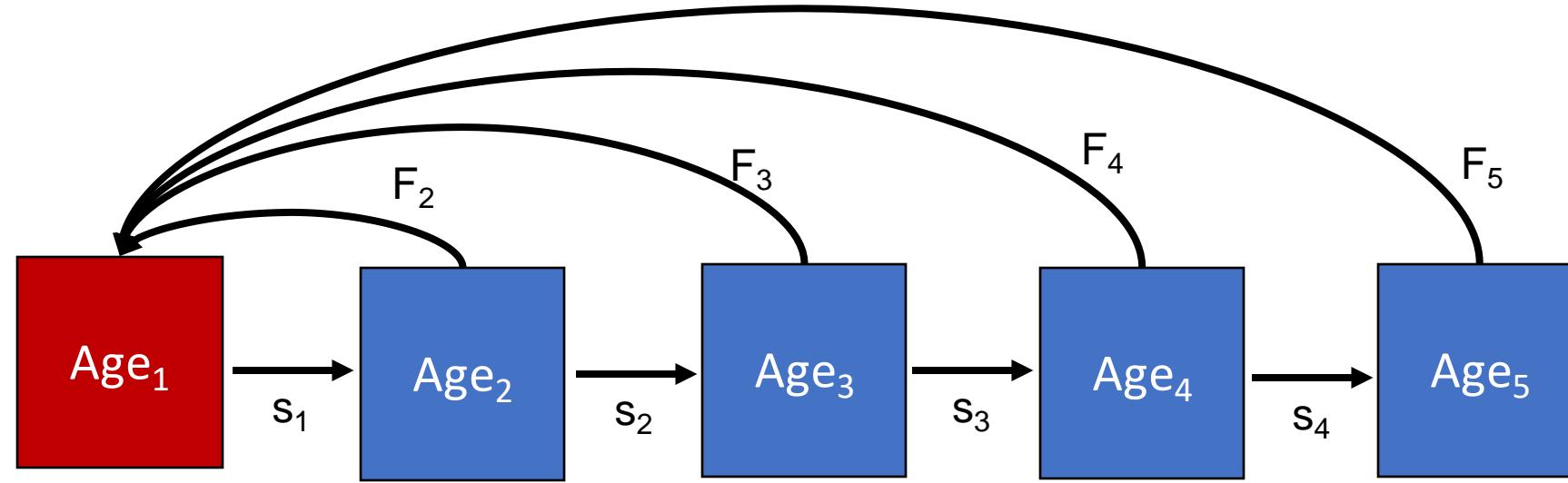
T. Coulson,^{1*}† E. A. Catchpole,² S. D. Albon,³ B. J. T. Morgan,⁴
J. M. Pemberton,⁵ T. H. Clutton-Brock,⁶ M. J. Crawley,⁶
B. T. Grenfell⁷

25 MAY 2001 VOL 292 SCIENCE www.sciencemag.org



The structured population model

If data are available, we can model much more detailed population structures using the same approach.

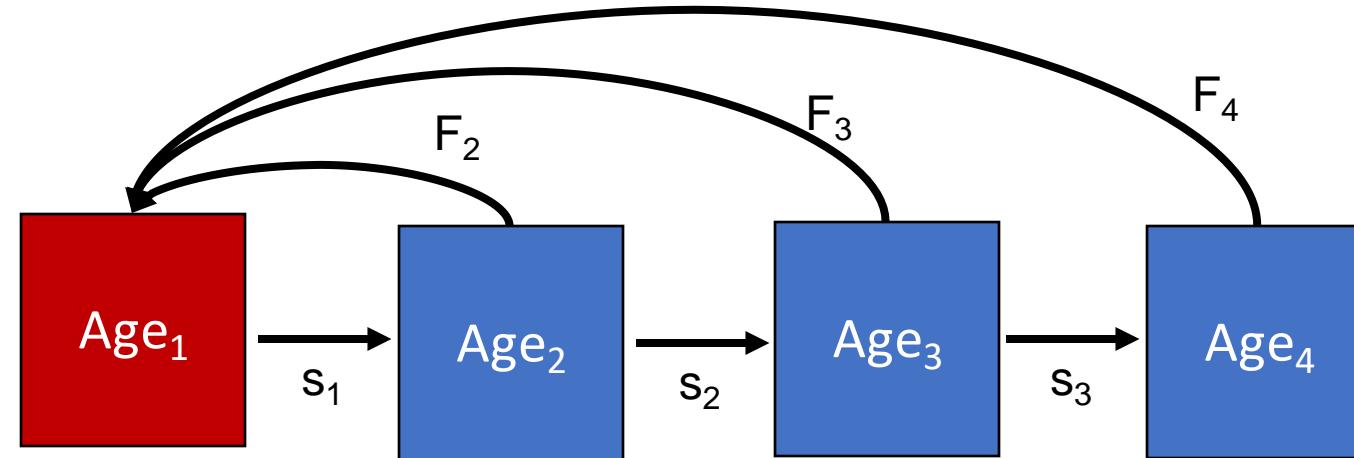


The **Leslie matrix** model divides classes based on age.

The **Lefkovitch matrix** model divides classes based on life stage.

The structured population model

If data are available, we can model much more detailed population structures using the same approach.



λ =can be
derived from
transition matrix

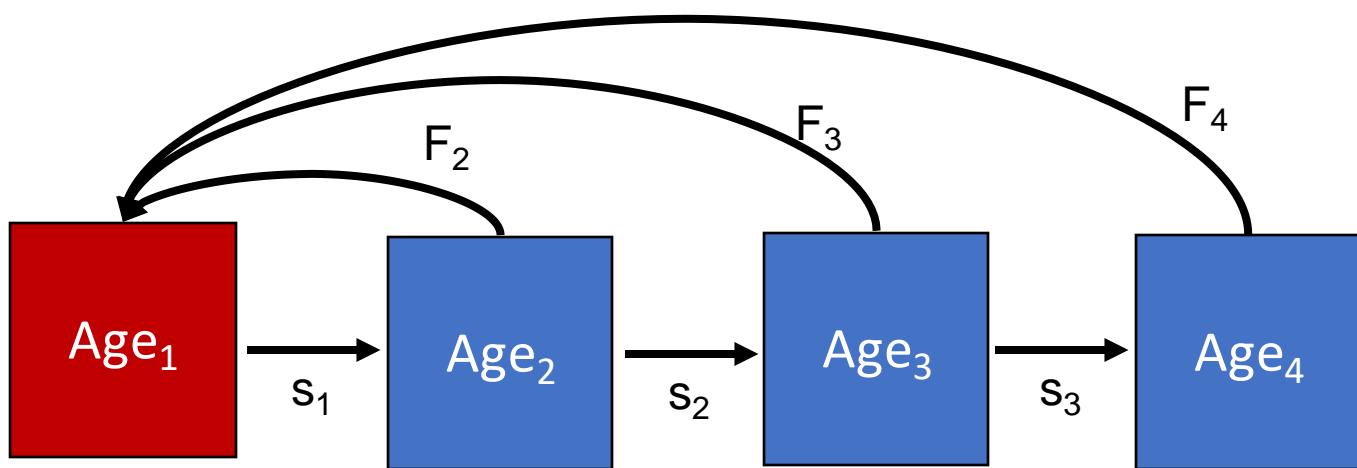
$$\rightarrow \begin{matrix} & \mathbf{A} & \\ \begin{bmatrix} 0 & F_2 & F_3 & F_4 \\ s_1 & 0 & 0 & 0 \\ 0 & s_2 & 0 & 0 \\ 0 & 0 & s_3 & 0 \end{bmatrix} & \times & \begin{bmatrix} N_t \\ N_1 \\ N_2 \\ N_3 \\ N_4 \end{bmatrix} = \begin{bmatrix} N_{t+1} \\ N_{1,t+1} \\ N_{2,t+1} \\ N_{3,t+1} \\ N_{4,t+1} \end{bmatrix} \end{matrix}$$

$$N_{t+1} = A^* N_t$$

Leslie 1945 *Biometrika*. Leslie 1948 *Biometrika*.
Lefkovitch 1965 *Biometrics*.

The structured population model

Demographers collect these rates in life tables



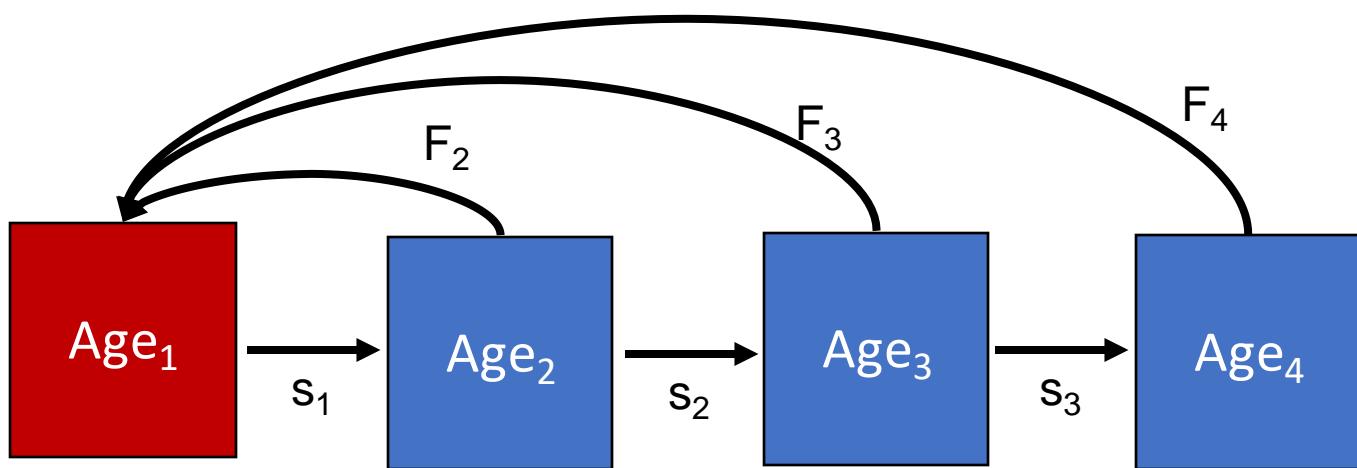
x (age)	N _x (number in cohort)	I _x (survivorship to age x)	m _x (fecundity)	I _x m _x
0	100	1	0	0
1	60	.6	2	1.2
2	30	.3	3	0.9
3	10	.1	1	0.1
4	1	.01	1	0.01



Gross reproductive rate (GRR): $\sum m_x = 7$

The structured population model

Demographers collect these rates in life tables



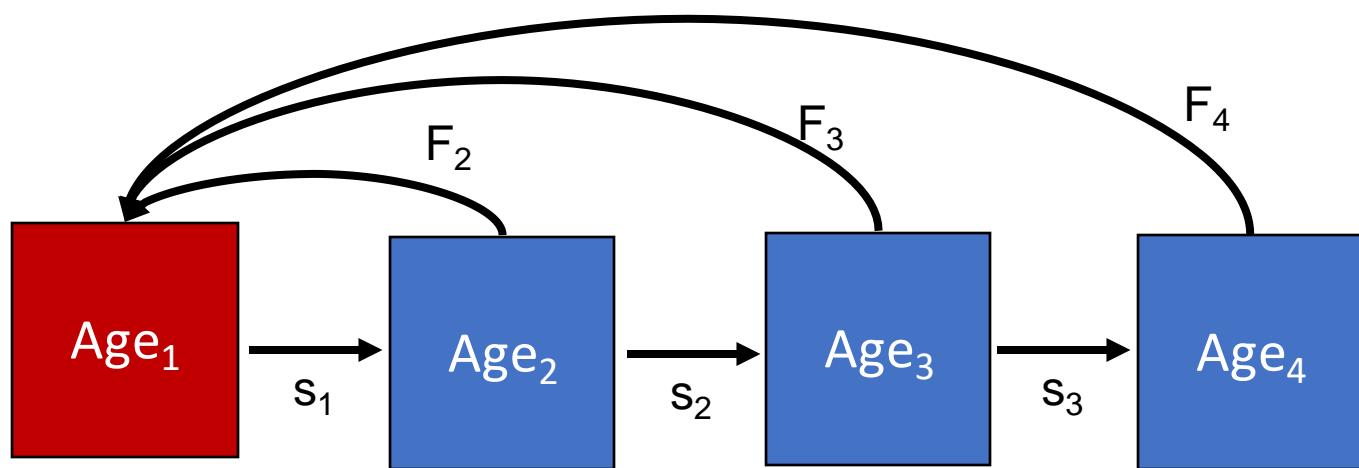
x (age)	N _x (number in cohort)	I _x (survivorship to age x)	m _x (fecundity)	I _x m _x
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4	1	.01	1	0.01



Net reproductive rate (R_0): $\sum l_x m_x = 2.21$

The structured population model

Demographers collect these rates in life tables



x (age)	N _x (number in cohort)	l _x (survivorship to age x)	m _x (fecundity)	l _x m _x
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1	60	.6	2	1.2
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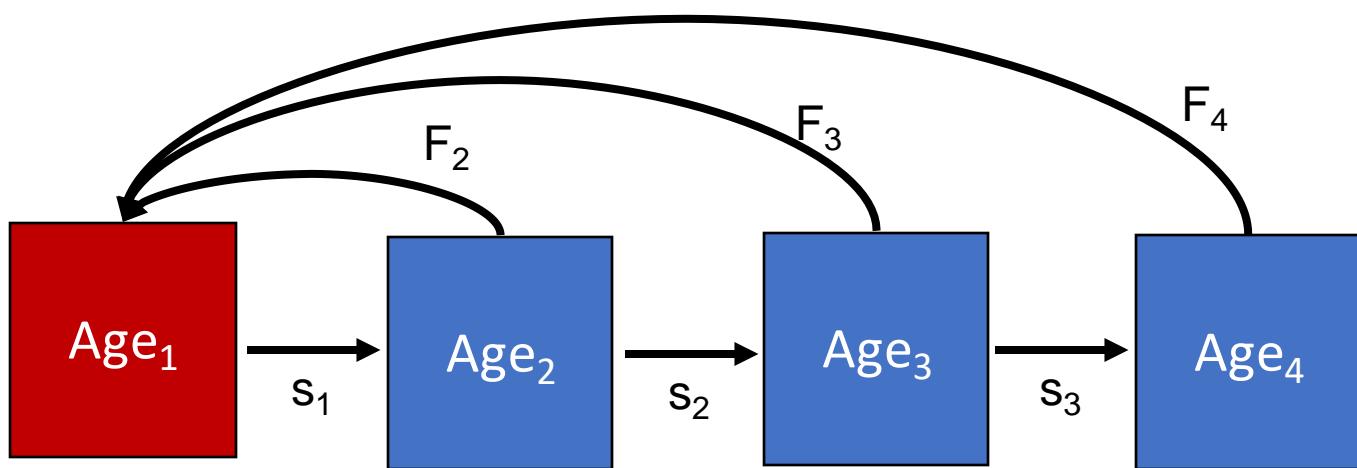


Net reproductive rate (R_0): $\sum l_x m_x = 2.21$

(pop grows at $R_0 > 1$ and declines at $R_0 < 1$)

The structured population model

Demographers collect these rates in life tables



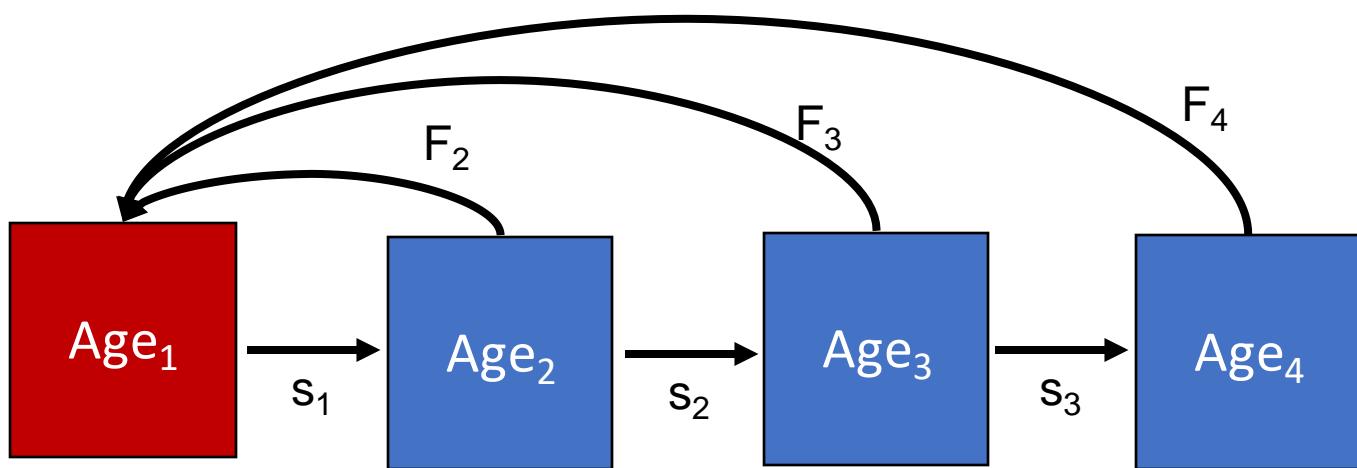
x (age)	N _x (number in cohort)	l _x (survivorship to age x)	m _x (fecundity)	l _x m _x
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4	1	.01	1	0.01



Net reproductive rate (R_0): $\sum l_x m_x = 2.21$

$\lambda = R_0^{1/G}$ where G = length of a generation (often 1 year)

The structured population model



x (age)	N _x (number in cohort)	I _x (survivorship to age x)	m _x (fecundity)	I _x m _x
0	100	1	0	0
1	60	.6	2	1.2
2	30	.3	3	0.9
3	10	.1	1	0.1
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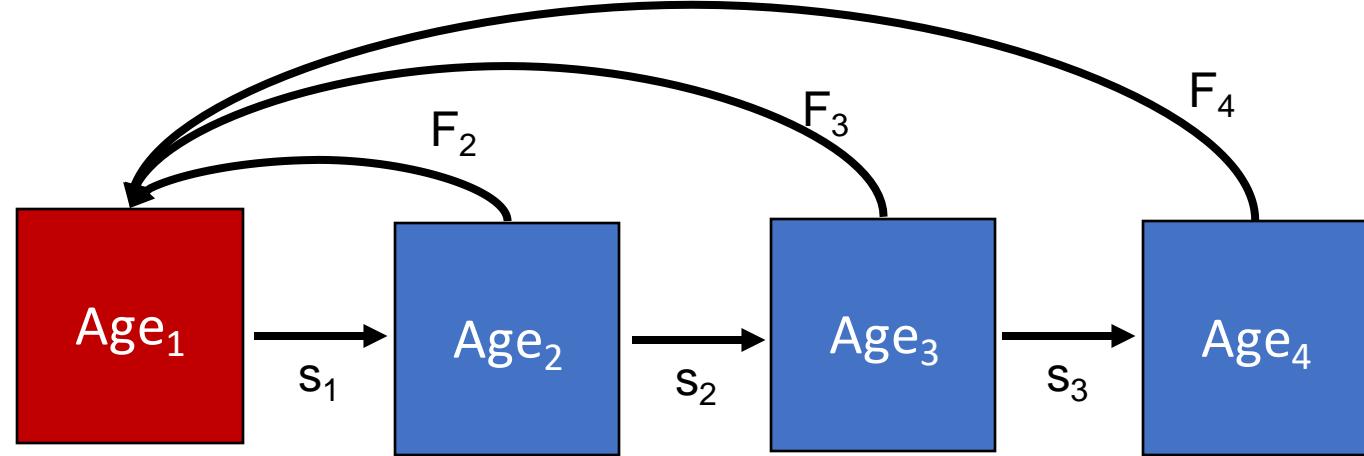
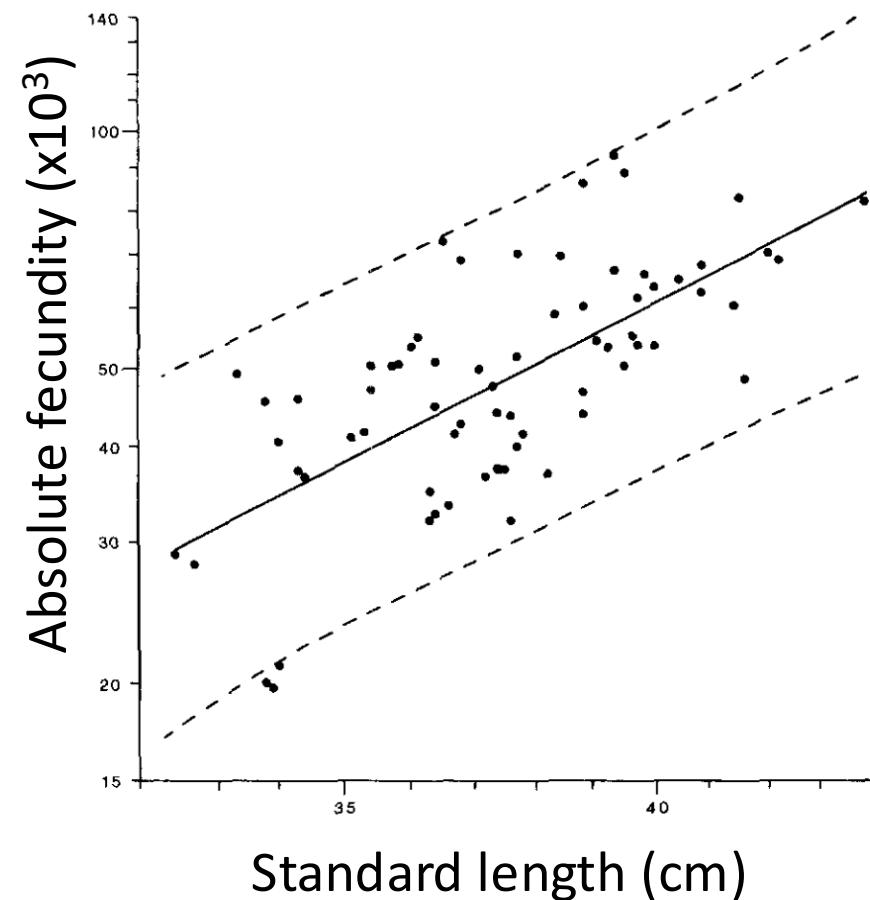


⋮

Orange roughy can live up to 200 years!

Net reproductive rate (R_0): $\sum l_x m_x = \dots$

The structured population model



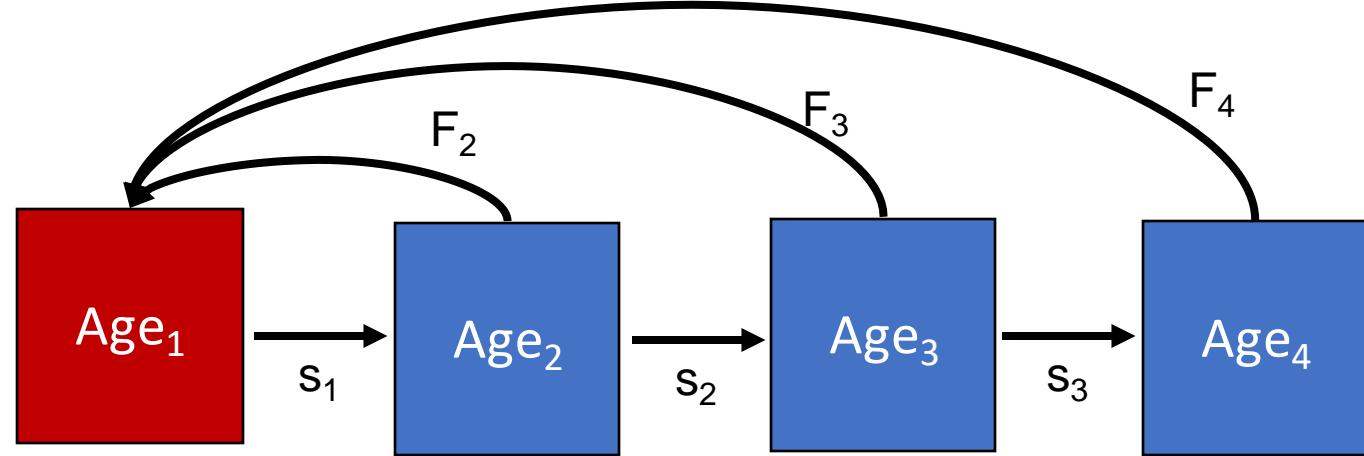
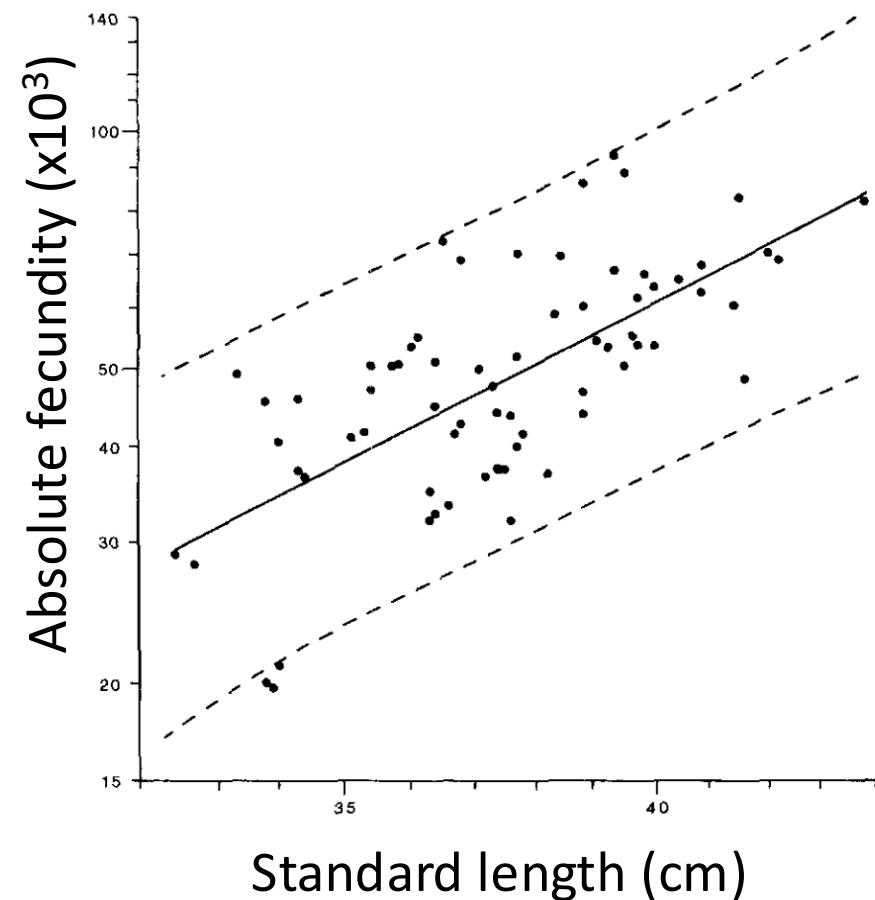
A brace on the left side of the text block groups the fecundity arrows. The text states:

Fecundity (eggs)
increases in older,
bigger fish!

Pankhurst & Conroy 1987

NZ J of Marine & Freshwater Res

The structured population model



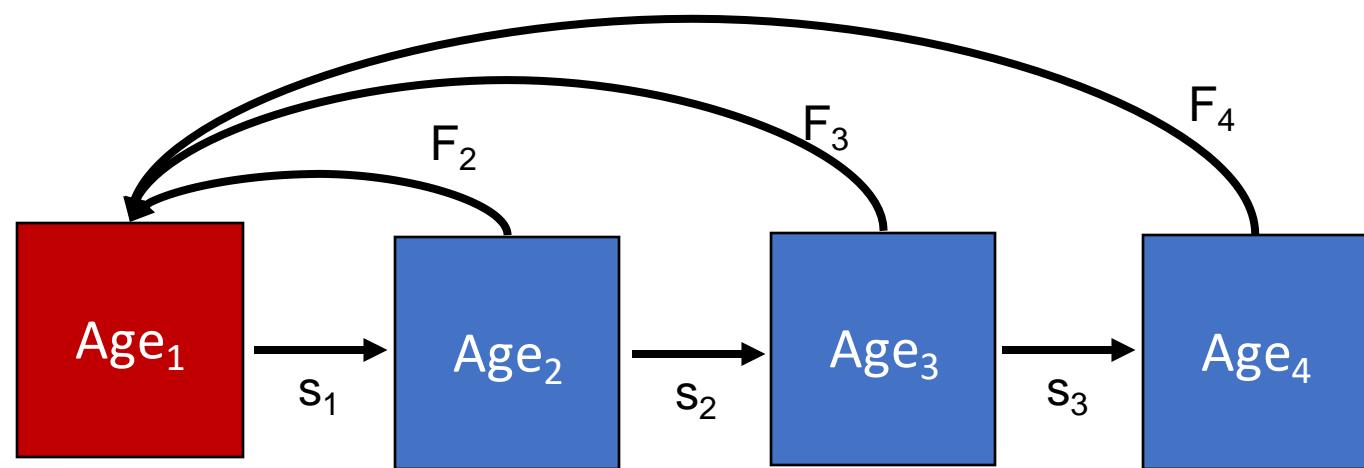
Fecundity (eggs)
increases in older,
bigger fish!

These are precisely
the fish we like to
catch! One of the
problems with
MSY...

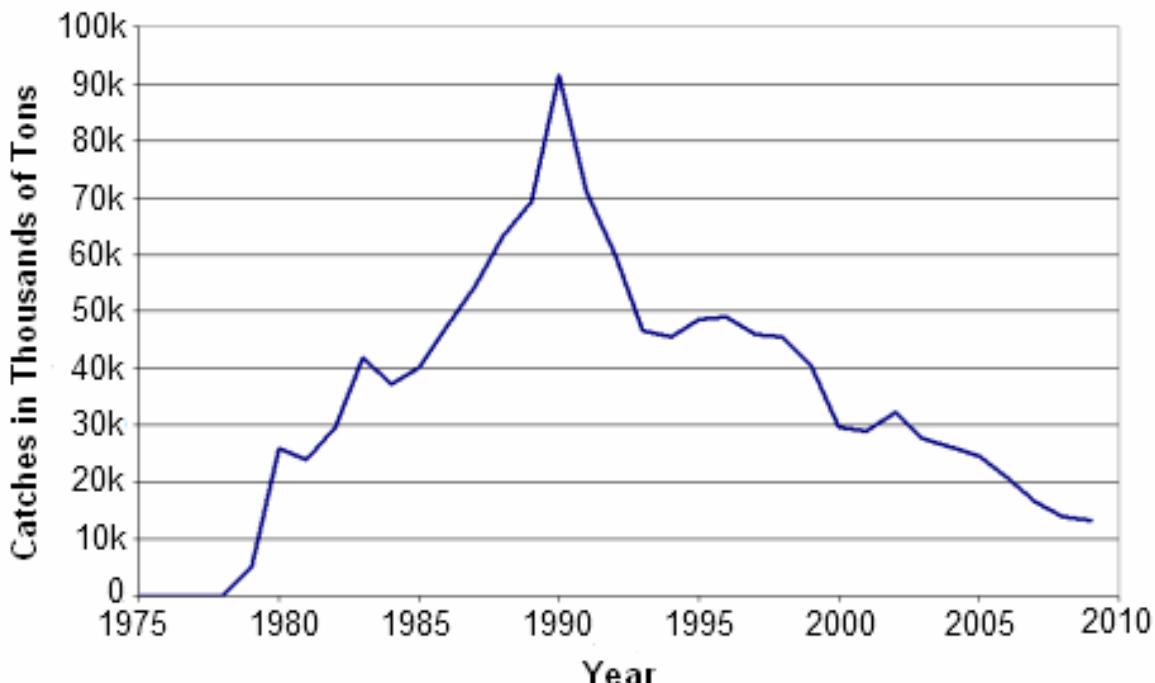


Norway 1910
(Norsk folkemuseum)

The structured population model



Worldwide Catches of Orange Roughy 1975 - 2009



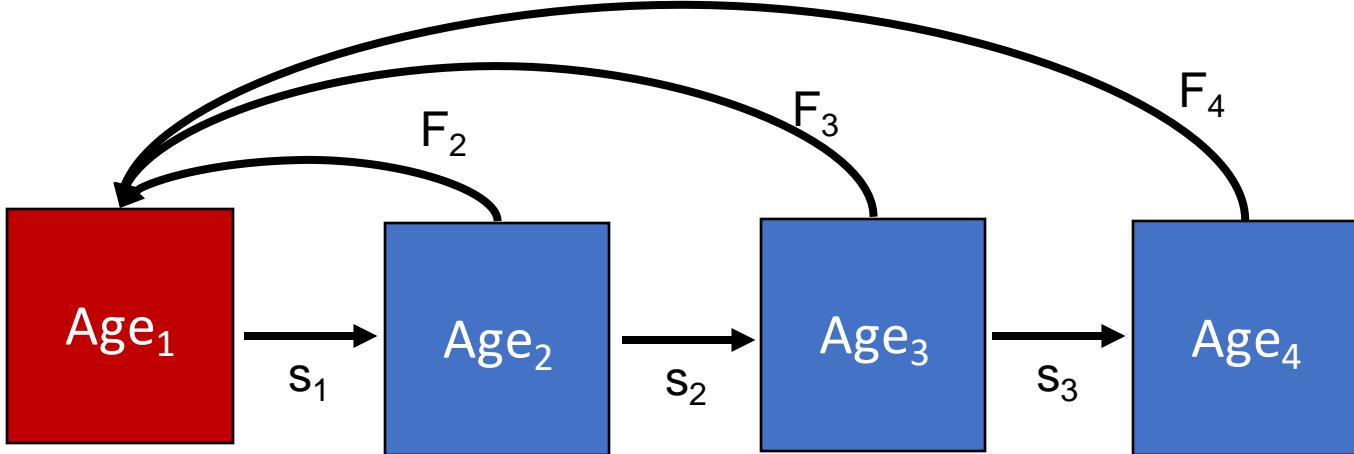
Poor modeling projections has led to severe overexploitation, a common problem in fisheries...

In 2008, the international TAC for orange roughy was reduced from 1470 tons to 914 tons... down from over 90,000 tons in the early 1990s...



The structured population model

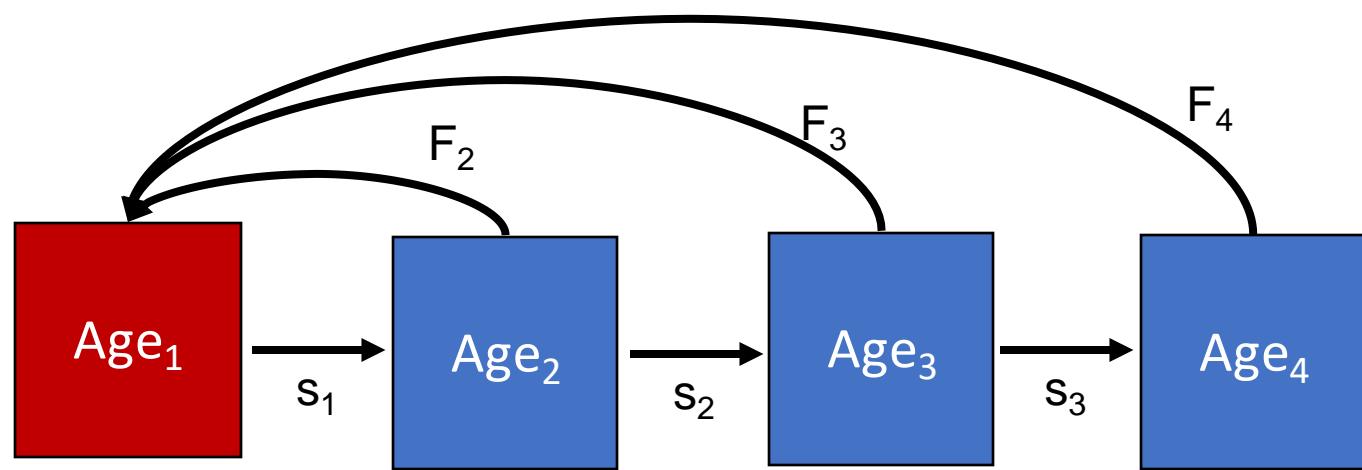
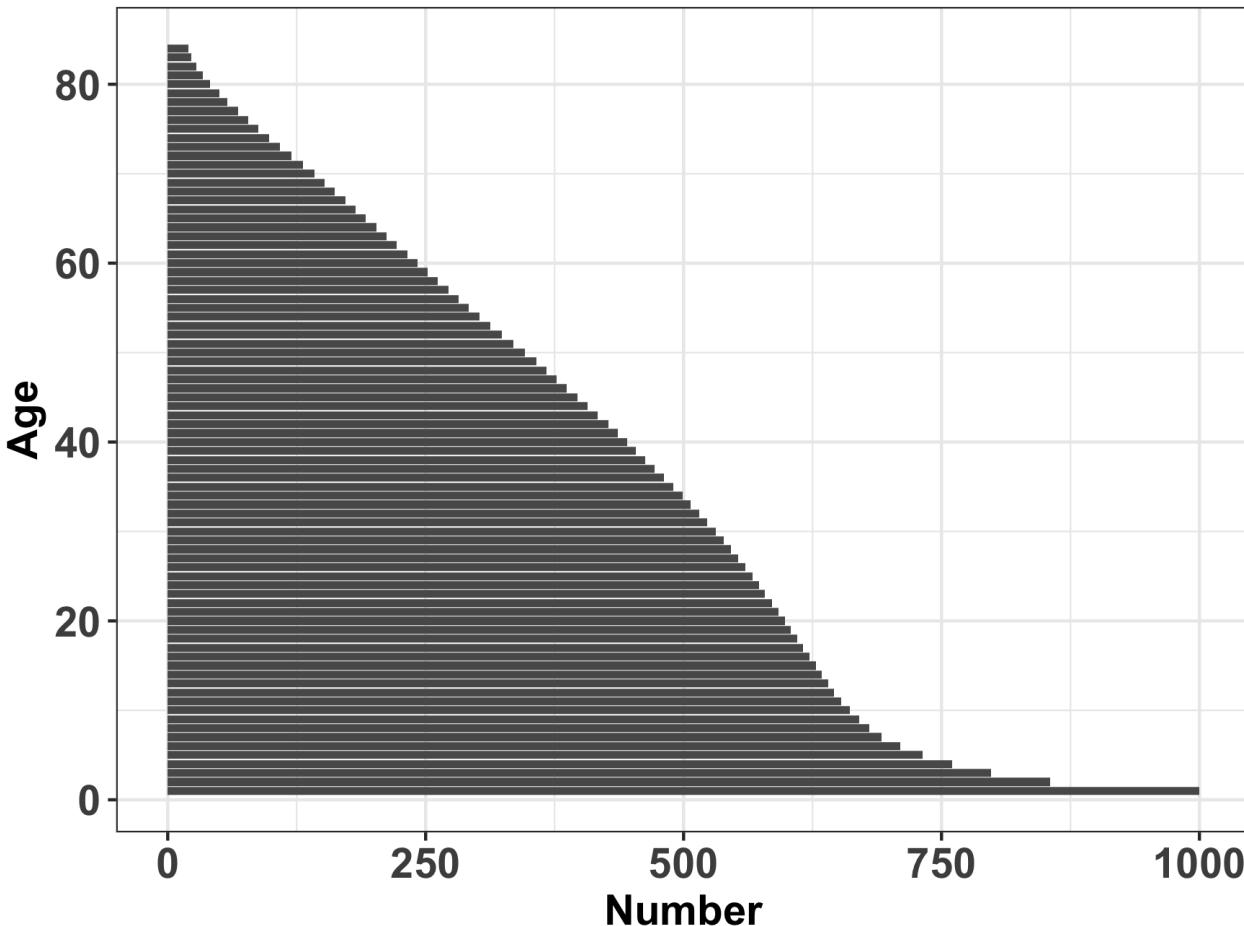
Life table analysis is also used extensively in **human demography**.



Edmond Halley, 1693
“An estimate of the degrees of the mortality of mankind, drawn from curious tables of the births and funerals at the city of Breslau, with an attempt to ascertain the price of annuities upon lives...”

The structured population model

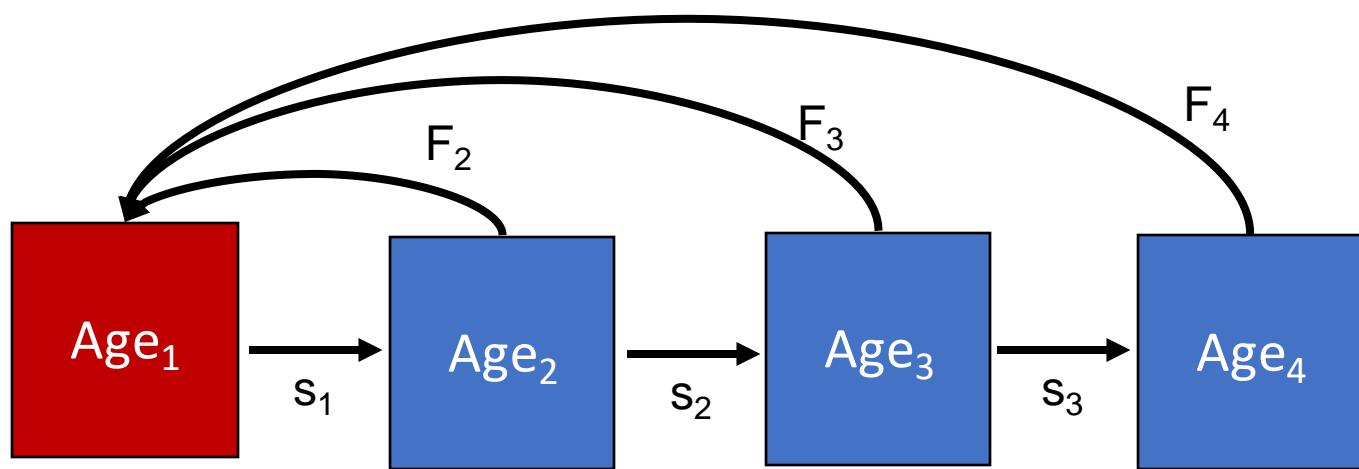
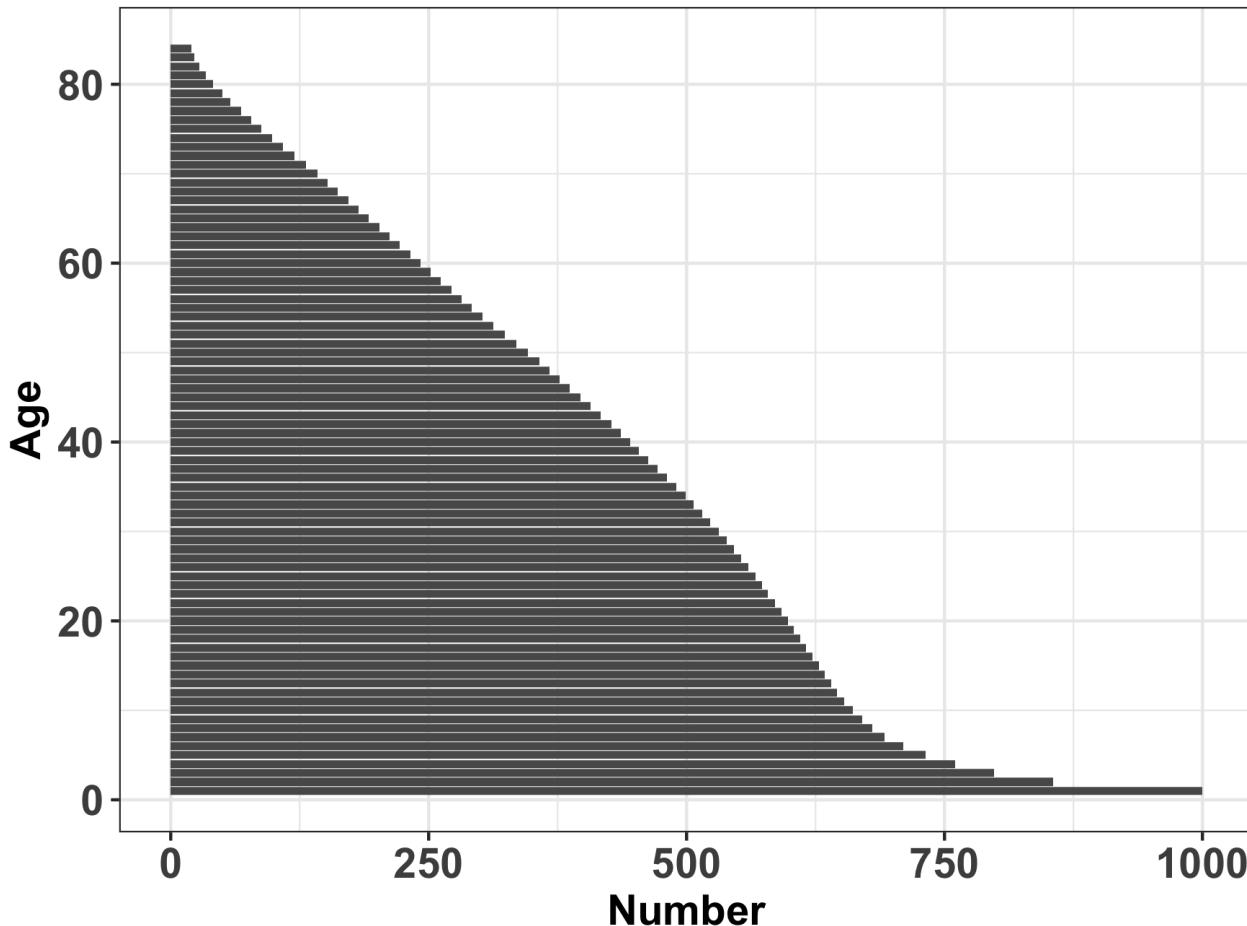
Population pyramid for Breslau



Edmond Halley, 1693
“An estimate of the degrees of the mortality of mankind, drawn from curious tables of the births and funerals at the city of Breslau, with an attempt to ascertain the price of annuities upon lives...”

The structured population model

Population pyramid for Breslau



Humans are not like fish!
Fecundity tends to decrease in older age
classes due to **reproductive senescence**.

**Younger human populations that start
giving birth earlier grow faster!**

$$\begin{bmatrix} A & N_t & N_{t+1} \\ \begin{bmatrix} 0 & F_2 & F_3 & F_4 \\ s_1 & 0 & 0 & 0 \\ 0 & s_2 & 0 & 0 \\ 0 & 0 & s_3 & 0 \end{bmatrix} & \begin{bmatrix} N_1 \\ N_2 \\ N_3 \\ N_4 \end{bmatrix} & = \begin{bmatrix} N_{1,t+1} \\ N_{2,t+1} \\ N_{3,t+1} \\ N_{4,t+1} \end{bmatrix} \end{bmatrix}$$



The number of individuals in age class 3 in the next year is given by:

$$\begin{bmatrix} 0 & F_2 & F_3 & F_4 \\ s_1 & 0 & 0 & 0 \\ 0 & s_2 & 0 & 0 \\ 0 & 0 & s_3 & 0 \end{bmatrix} \times \begin{bmatrix} N_1 \\ N_2 \\ N_3 \\ N_4 \end{bmatrix}$$

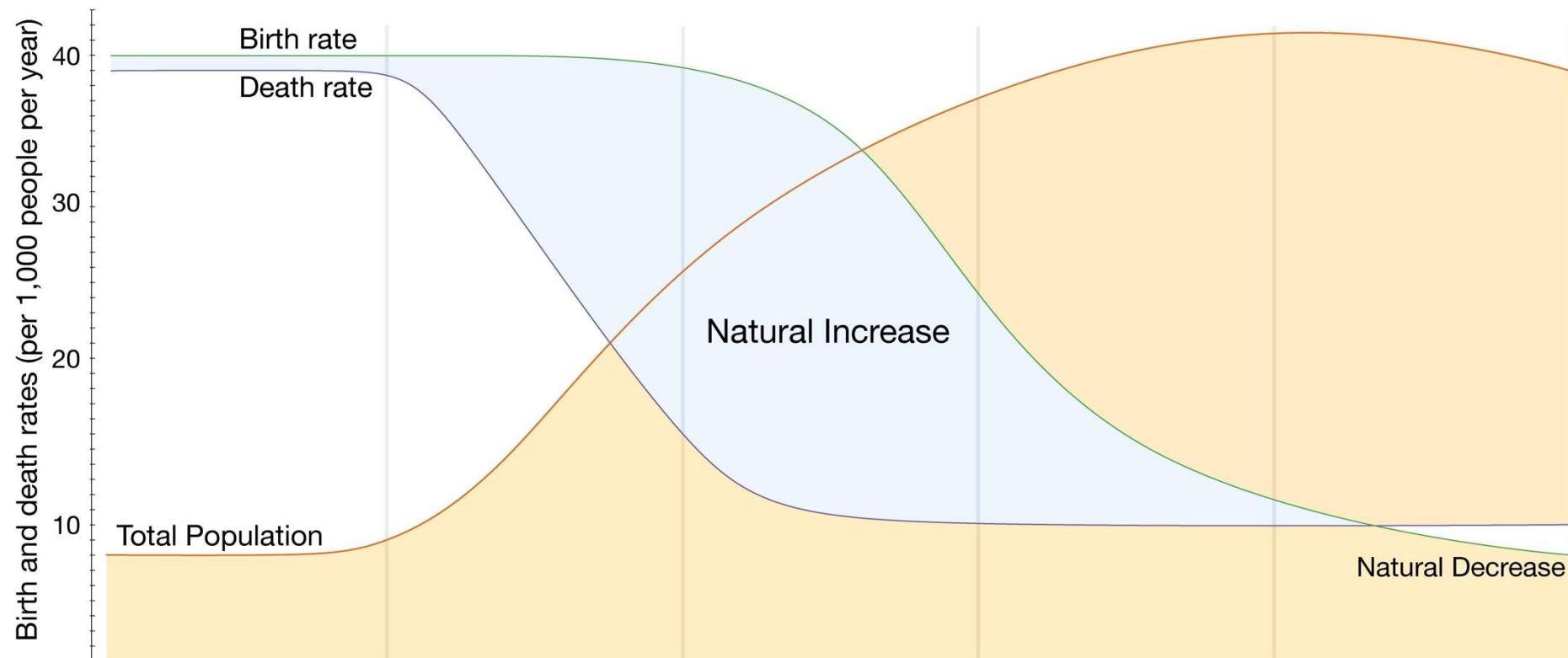
A. $F_2N_2 + F_3N_3 + F_4N_4$

SEE MORE



0%

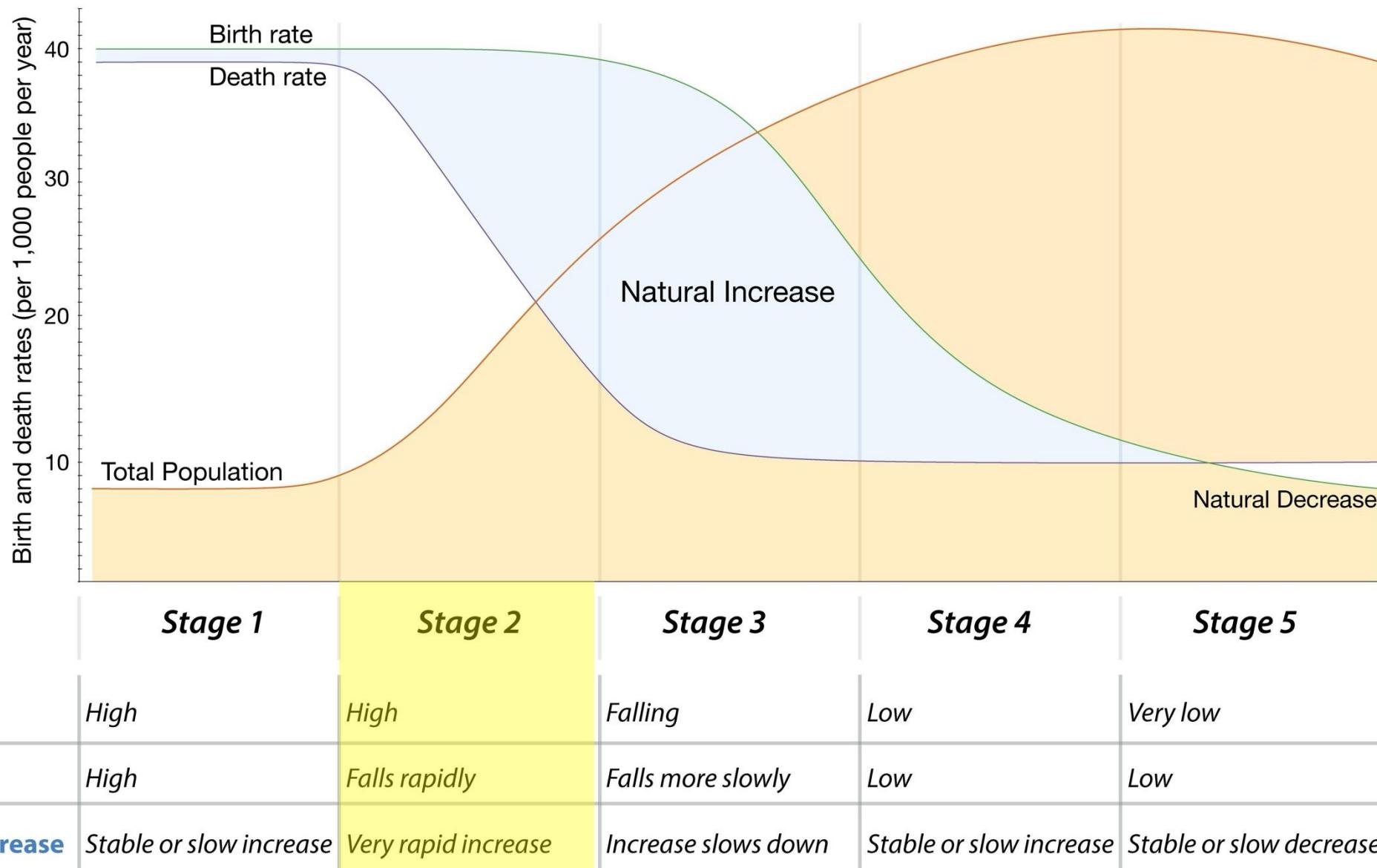
Demographic transition



	<i>Stage 1</i>	<i>Stage 2</i>	<i>Stage 3</i>	<i>Stage 4</i>	<i>Stage 5</i>
Birth rate	High	High	Falling	Low	Very low
Death rate	High	Falls rapidly	Falls more slowly	Low	Low
Natural increase	Stable or slow increase	Very rapid increase	Increase slows down	Stable or slow increase	Stable or slow decrease

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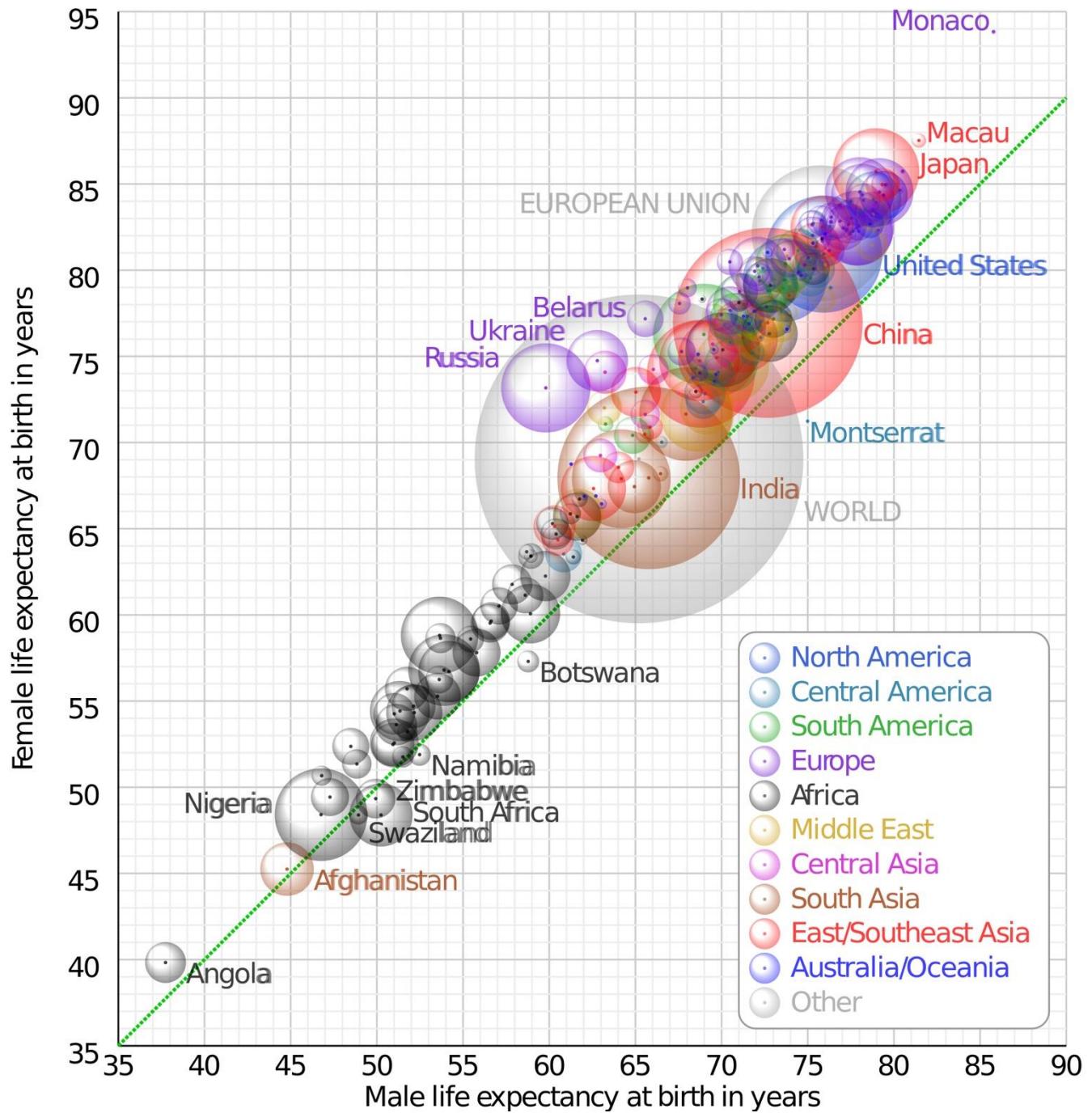
Demographic transition



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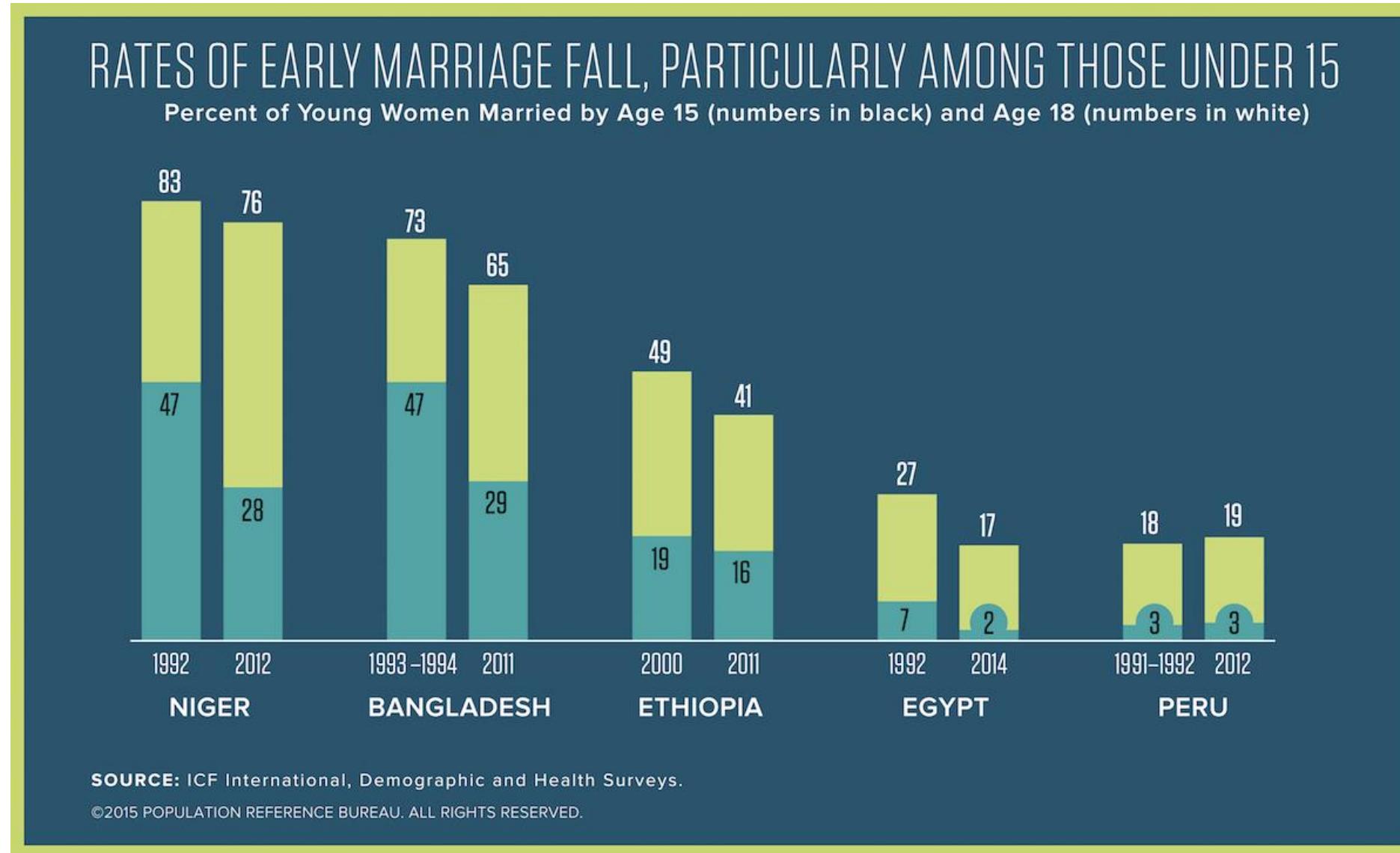
Demographic transition

Death rates are falling globally...

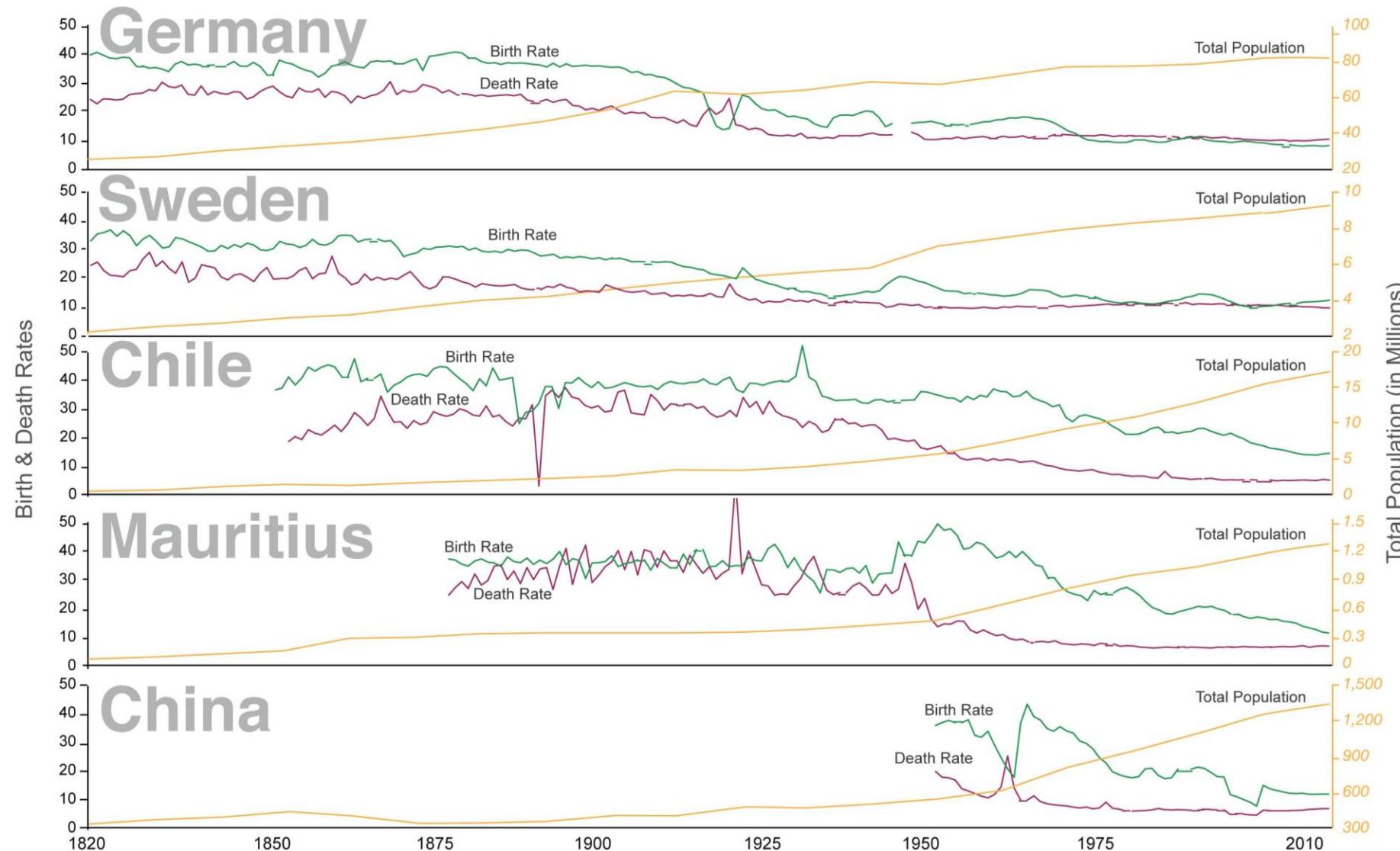


Demographic transition

And birth rates
are also falling...



Demographic transition



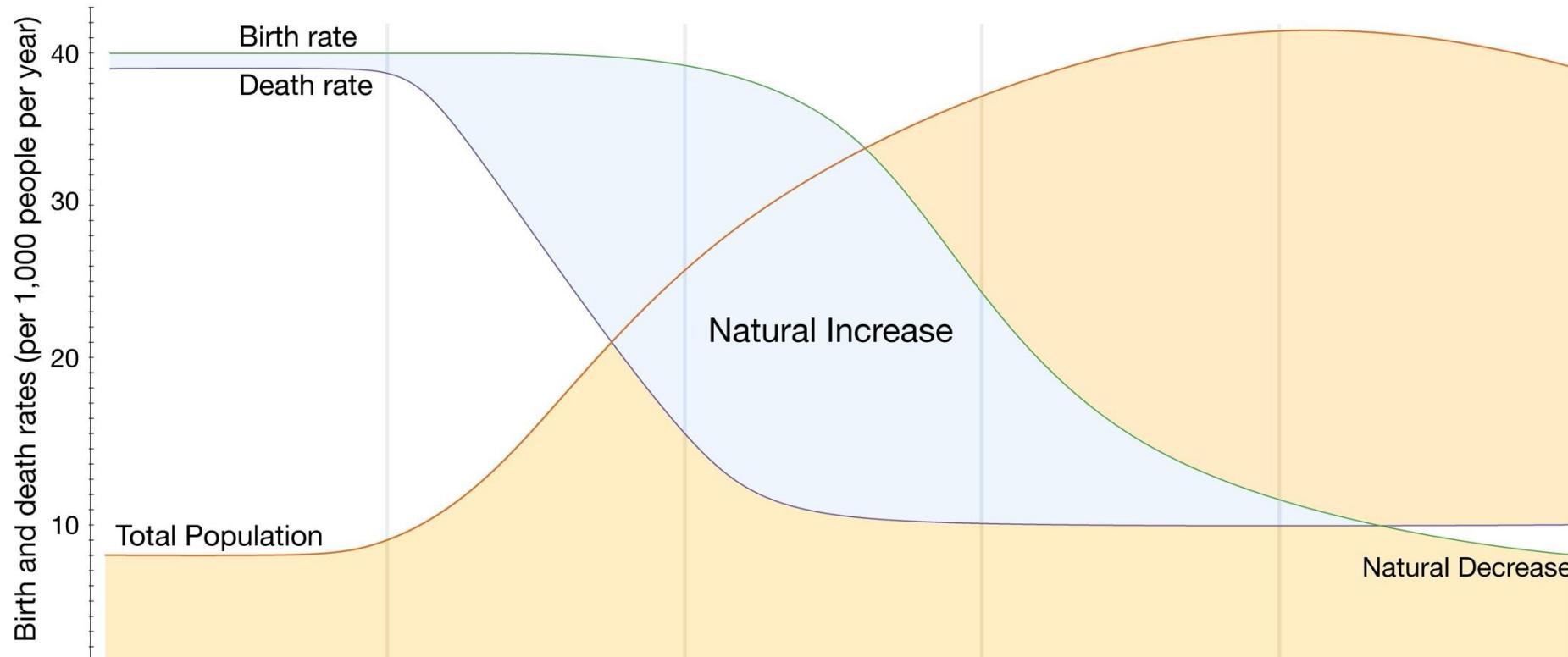
Data source: The data on birth rates, death rates and the total population are taken from the International Historical Statistics, edited by Palgrave Macmillan (April 2013).

The interactive data visualisation is available at OurWorldInData.org. There you find the raw data and more visualisations on this topic.

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Demographic transition

How does age structure predict population growth?

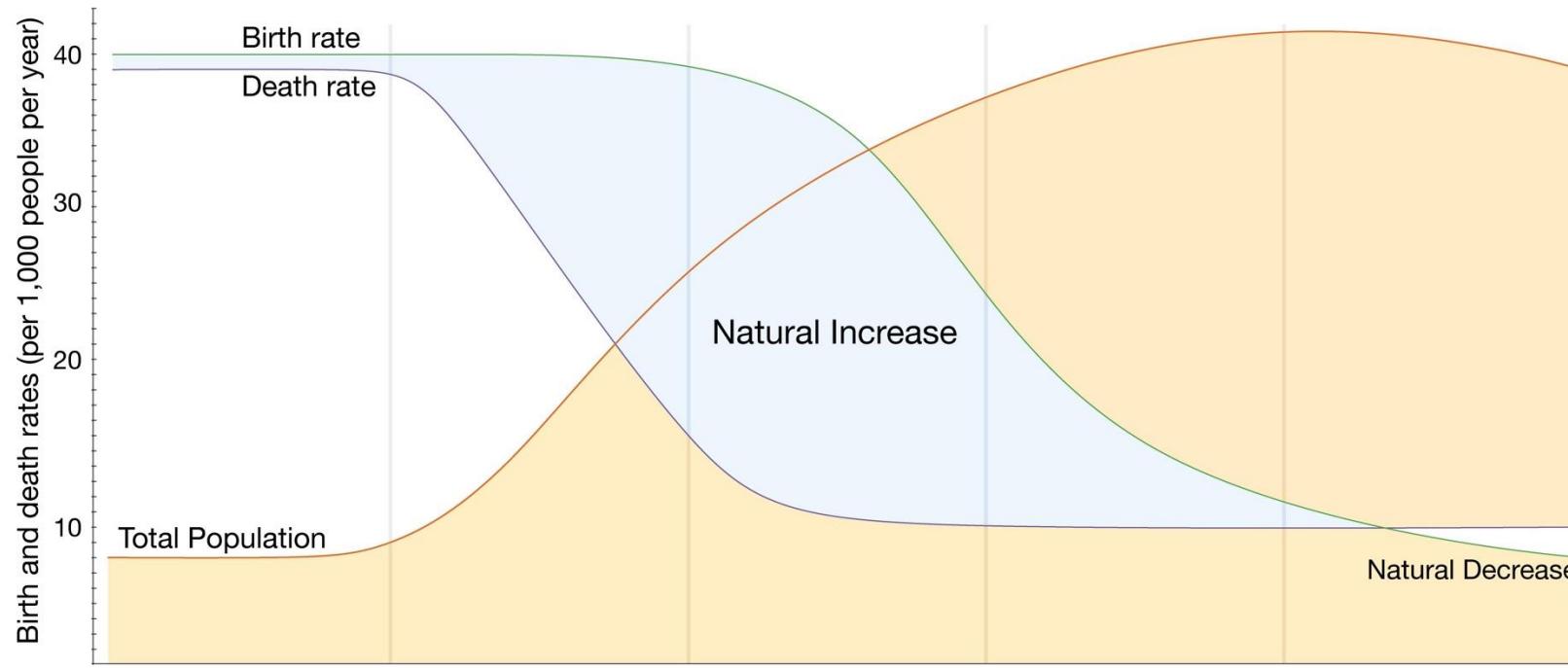


	Stage 1	Stage 2	Stage 3	Stage 4	Stage 5
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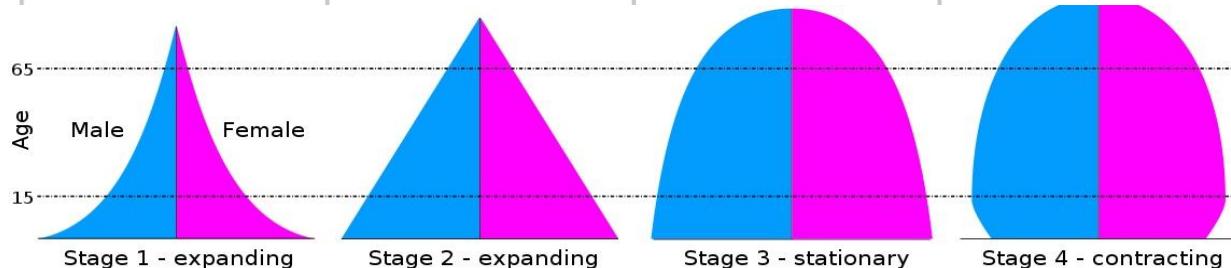
The author Max Roser licensed this visualisation under a CC BY-SA license. You are welcome to share but please refer to its source where you find more information: <http://www.OurWorldInData.org/data/population-growth-vital-statistics/world-population-growth>

Demographic transition

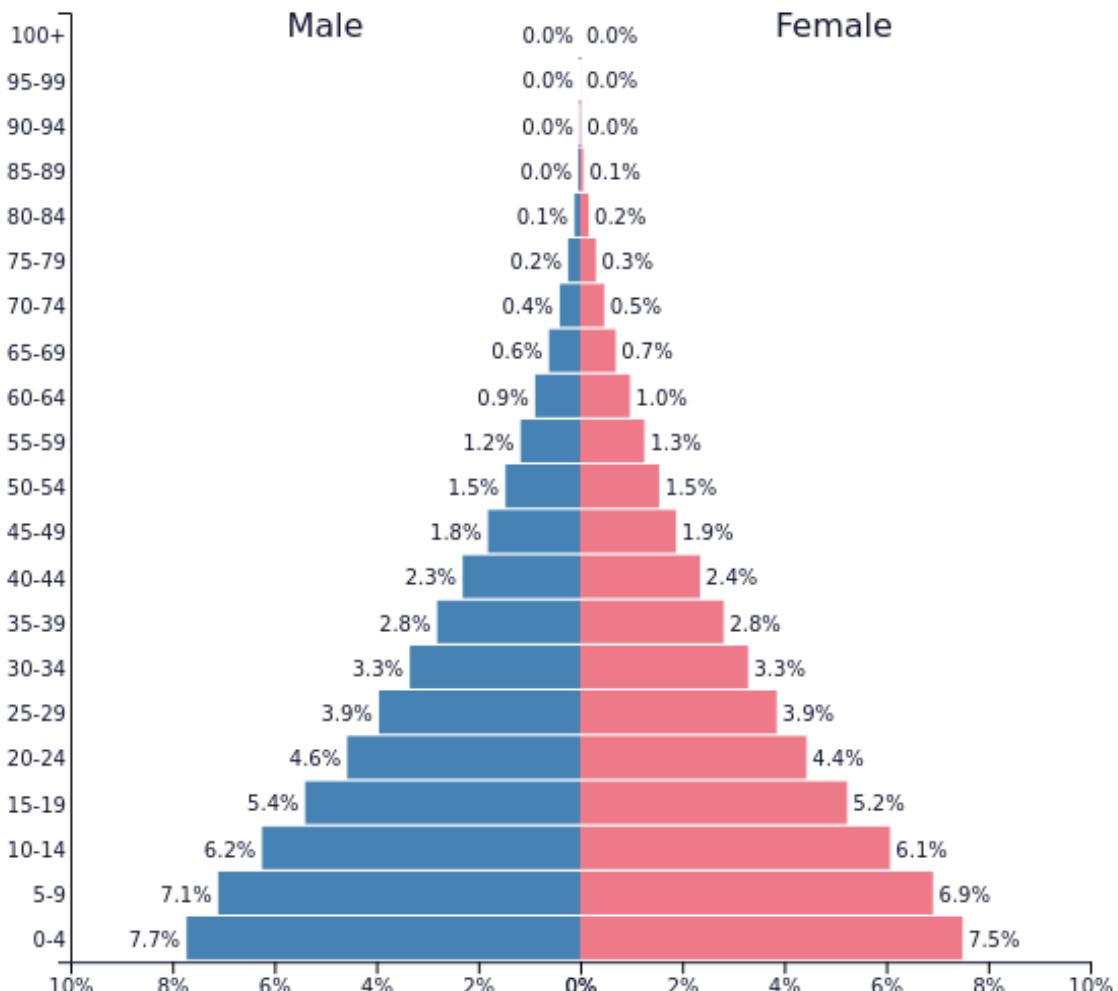
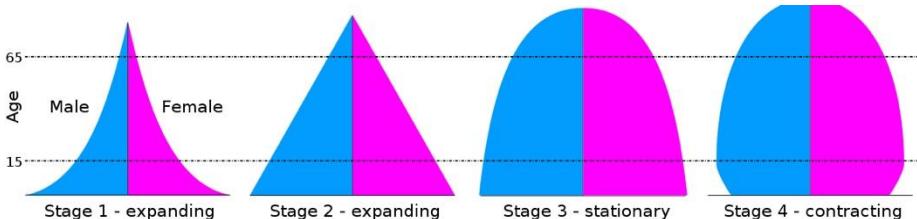
How does age structure predict population growth?



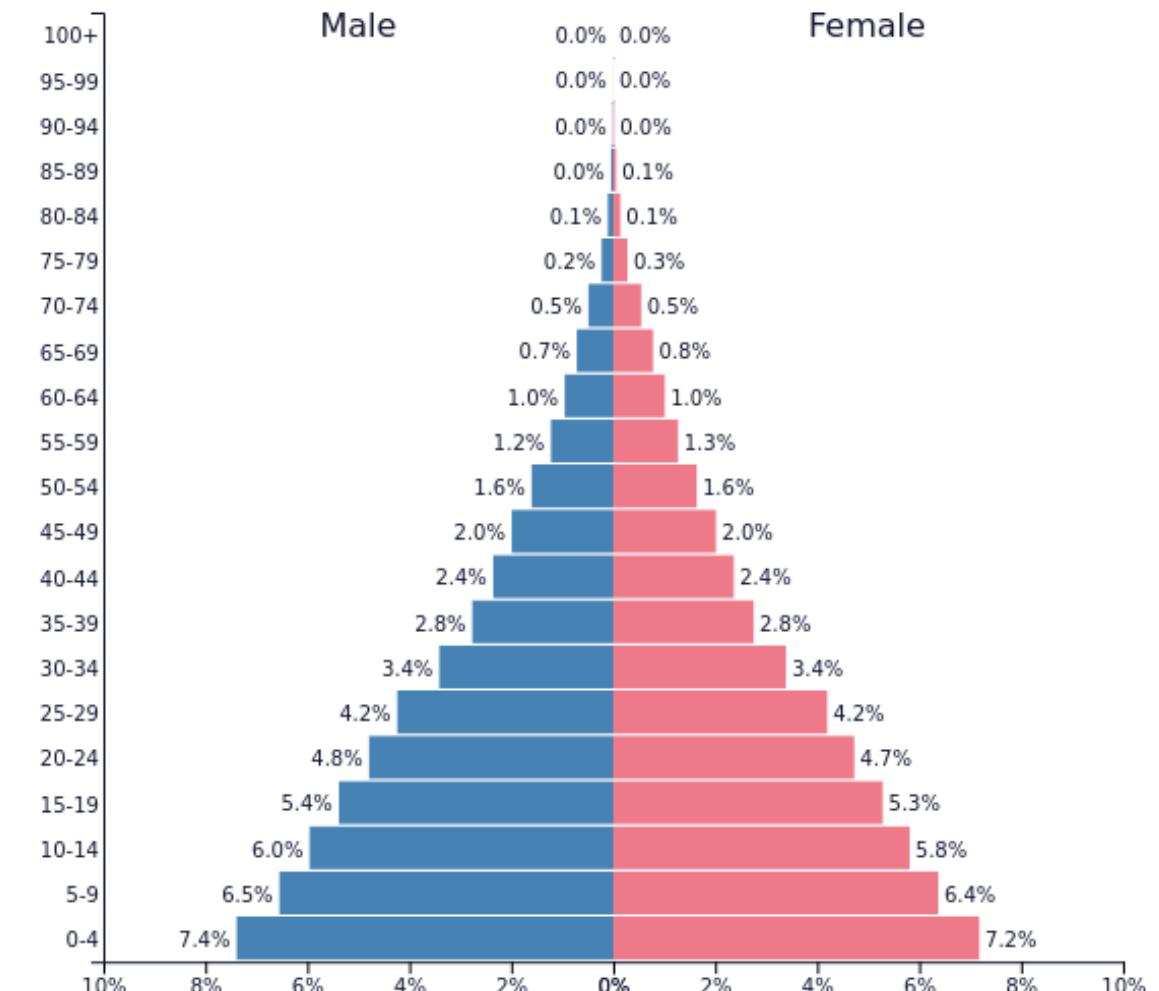
	Stage 1	Stage 2	Stage 3	Stage 4	Stage 5
Birth rate	High	High	Falling	Low	Very low
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Where are we globally?

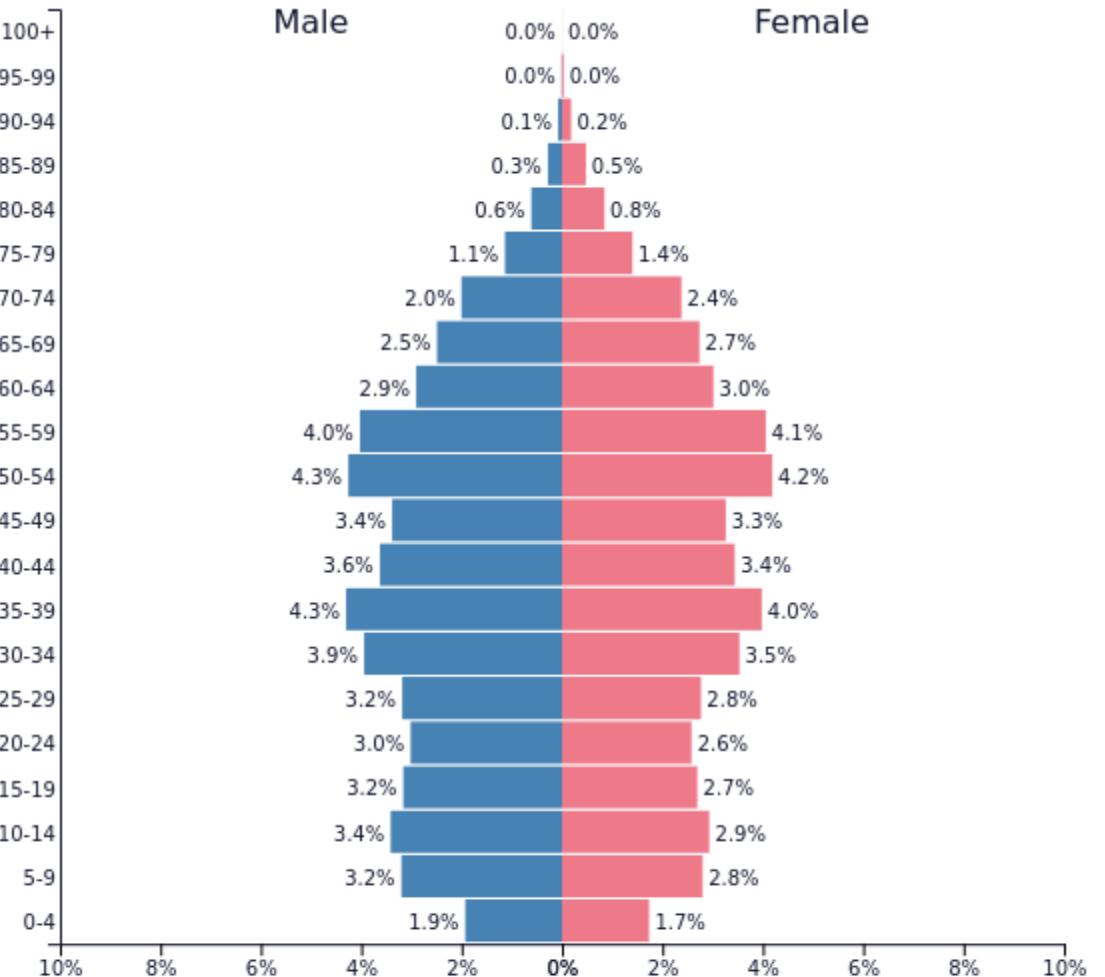
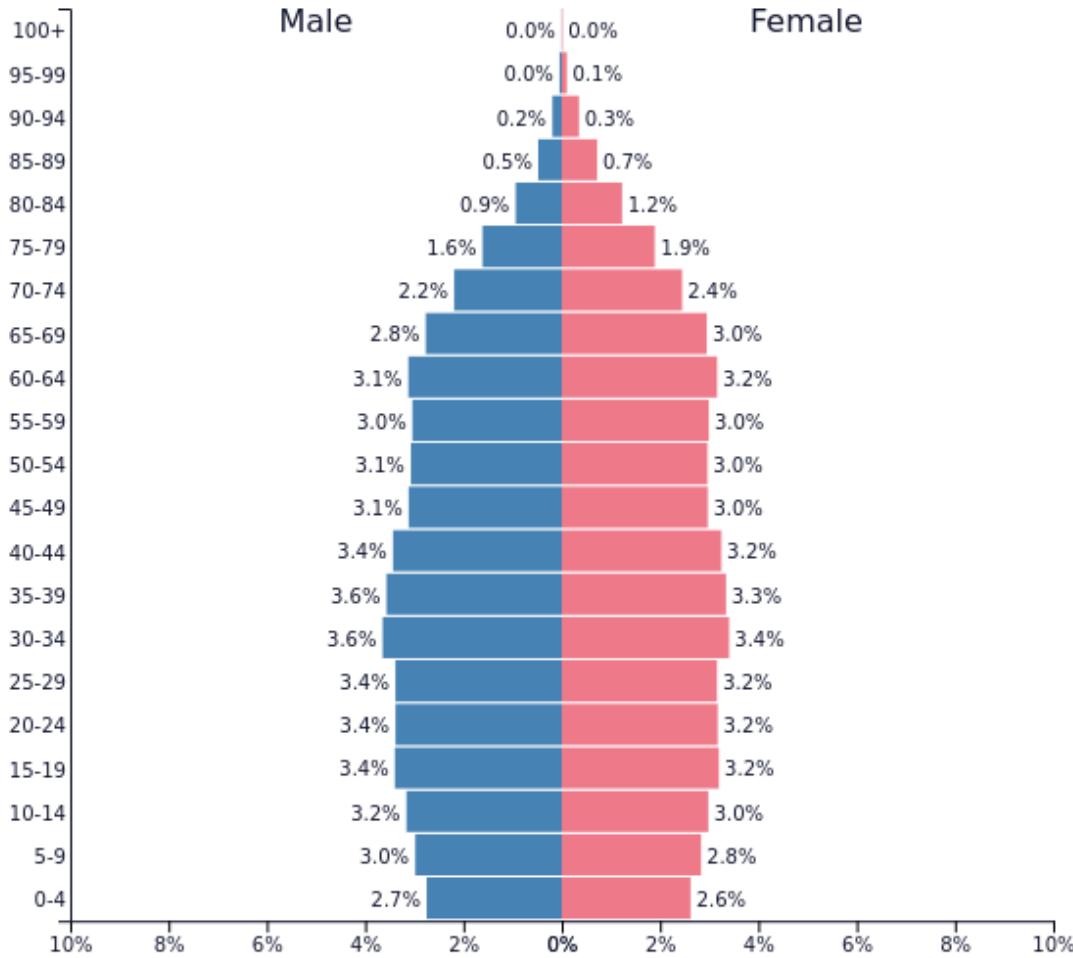
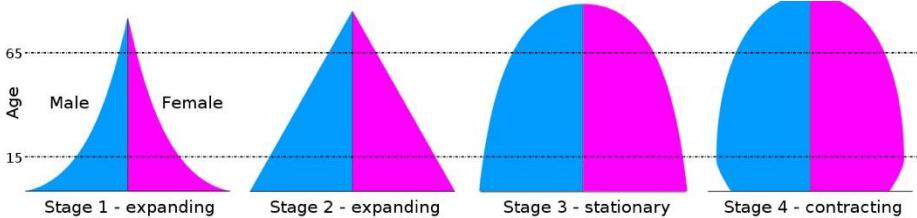


Benin - 2024

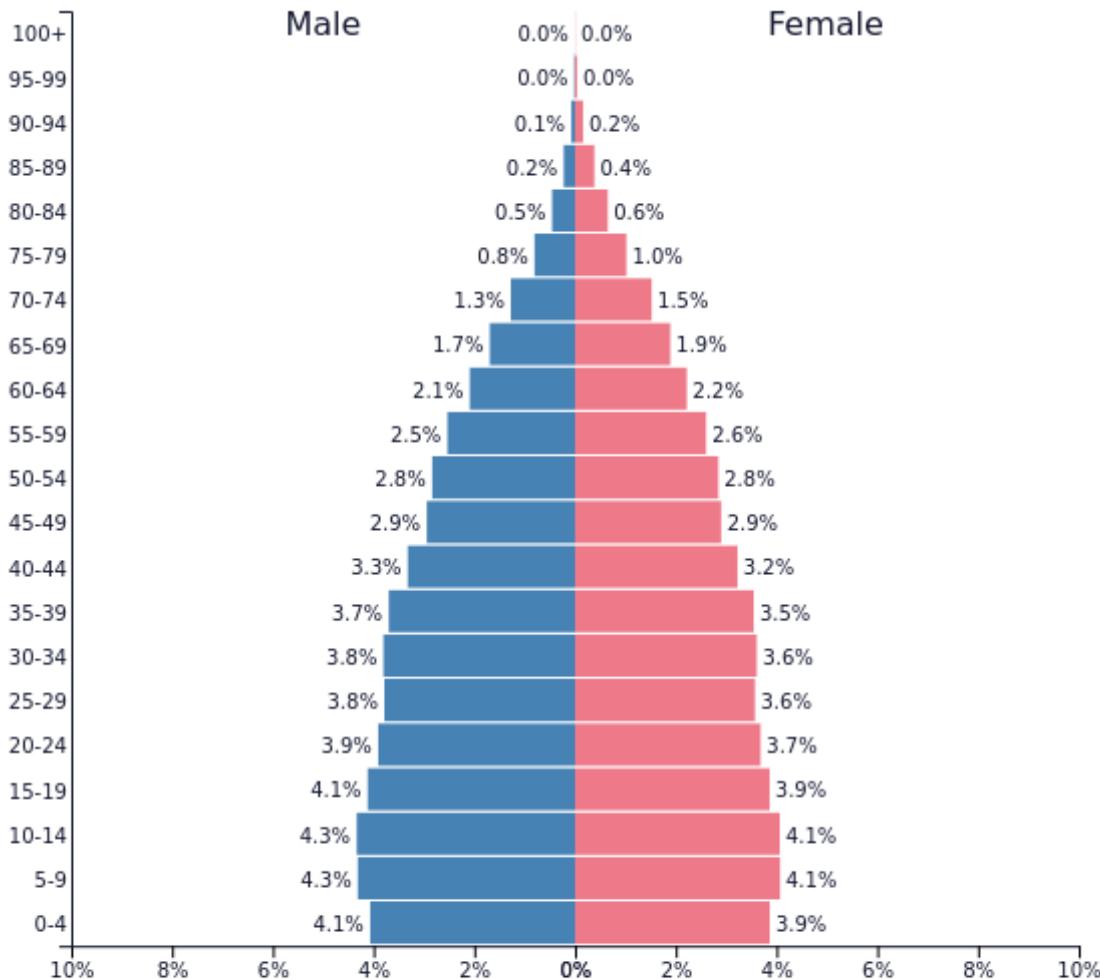
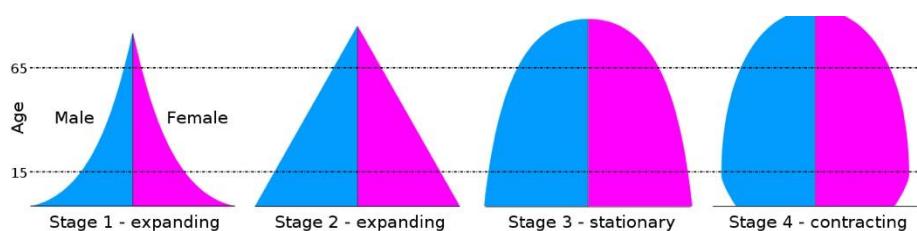


Madagascar - 2024

Where are we globally?



Where are we globally?



WORLD - 2024

Population: **8,161,972,572**

00

< Wk5-Lec2-Feb6



Visual settings



Edit



A population with this pyramid is likely:

80 +
75 - 79
70 - 74
65 - 69
60 - 64



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