

Ecological Interactions & Dynamics

Principles in Fisheries Science

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Who am I?

- MSc in Applied Marine and Fisheries Ecology, Aberdeen UK
- PhD in Marine Ecology, theoretical population and community ecology
- Postdoc at SLU on spatiotemporal aspects of cod-flounder interactions
- max.lindmark@slu.se

Who are you ... ?

Plan for today

- Theoretical
 - 1: Brief recap on population ecology
 - 2: Species interactions!
- “Empirical”
 - 3: Quantifying species interactions in natural systems
 - 4: Species interactions in fisheries ecology

Plan for today

- Have questions?
 - Just interrupt and ask, write in chat or ask during our break. Thanks!
- Slides can be found here: <https://github.com/maxlindmark/pfs>
- And on Canvas



Motivating questions

- We want to know what makes fish abundance vary through time and space...
 - For conservation
 - For sustainable management of marine resources
 - Because it is a basic scientific question (ecology is a young discipline!)

1. Brief recap on population ecology

Recap

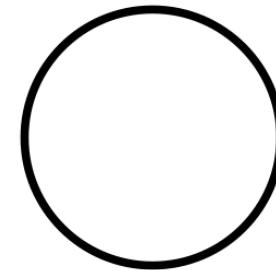
- **Population ecology**: how and why animal populations change in numbers over time and space
- **Community ecology**: how and why species abundance, composition, diversity and structure change over time and space
- **Food web ecology**: energy transfers (feeding links) between species in food webs

Population ecology

The branch of science that attempts to describe, understand, and predict the growth (positive and negative) of animal and plant populations

Why do we use models?

- Capture the essence of a process so that we can generalize across systems
- Simplest representation of a population:



- What do we assume in this model?

The simplest population model

Population size (numbers) at time t :

$$N(t)$$

Rate of change:

$$\frac{dN}{dt}$$

Per capita rate of change:

$$\frac{1}{N} \frac{dN}{dt}$$

The simplest population model

$$r = b - d$$

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

The simplest population model

- Solution to this first-order differential equation:

$$N(t) = N_0 e^{rt}$$

- Exponential growth for positive r and exponential decline for negative r

The simplest population model

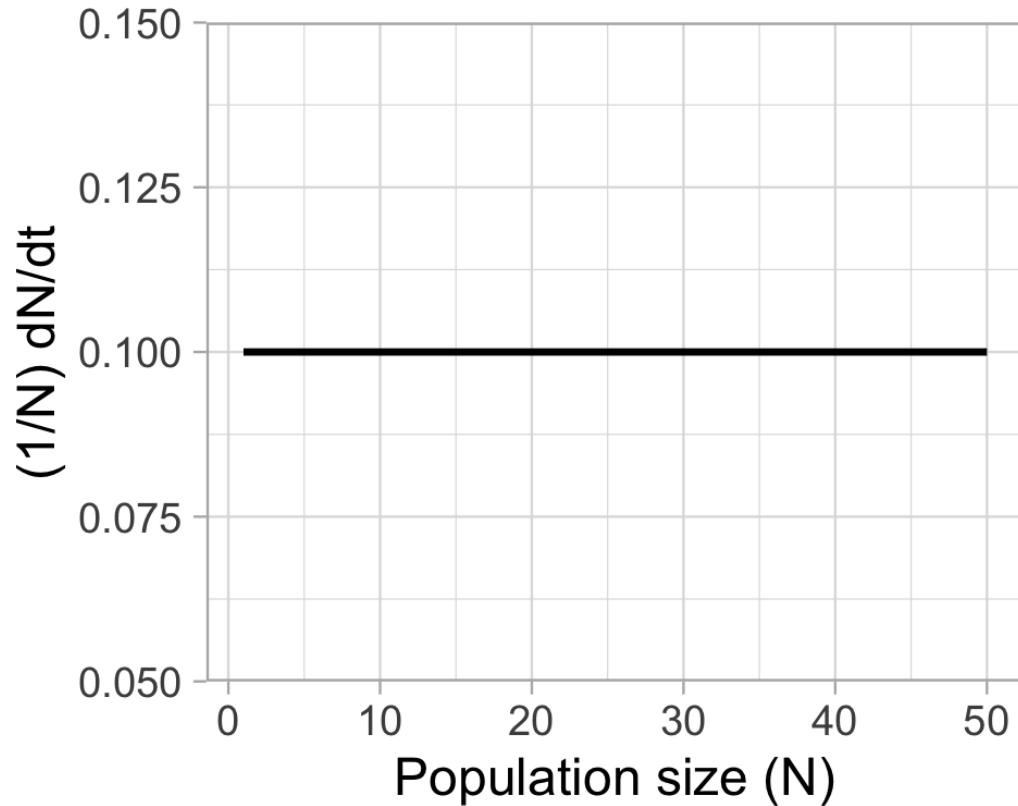
$$N(t) = N_0 e^{rt}$$

```
1 n <- 1:50
2 r <- 0.1
3 d <- data.frame(N = n) %>%
4   mutate(dNdDt = r*N,
5         pc_dNdDt = (r*N)/N)
```

The simplest population model

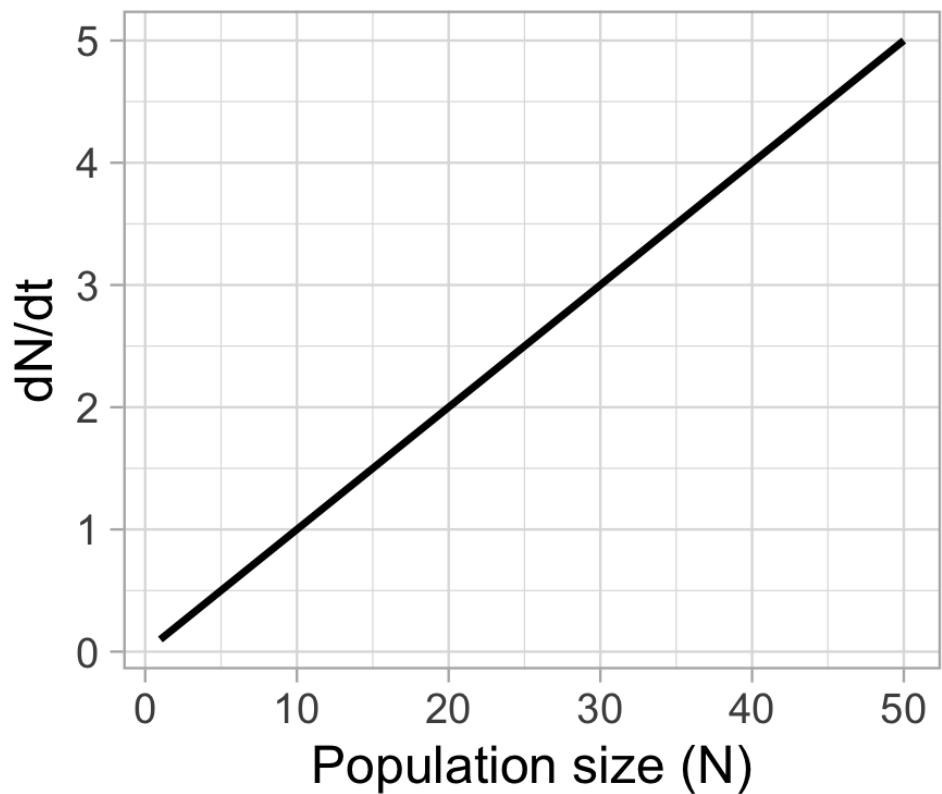
Per-capita growth rate

$r=0.1$



Population growth rate

$r=0.1$



- Per-capita growth rates unaffected by density
- Population growth rates increase with size!

The simplest population model

- Equilibrium?

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

The simplest population model

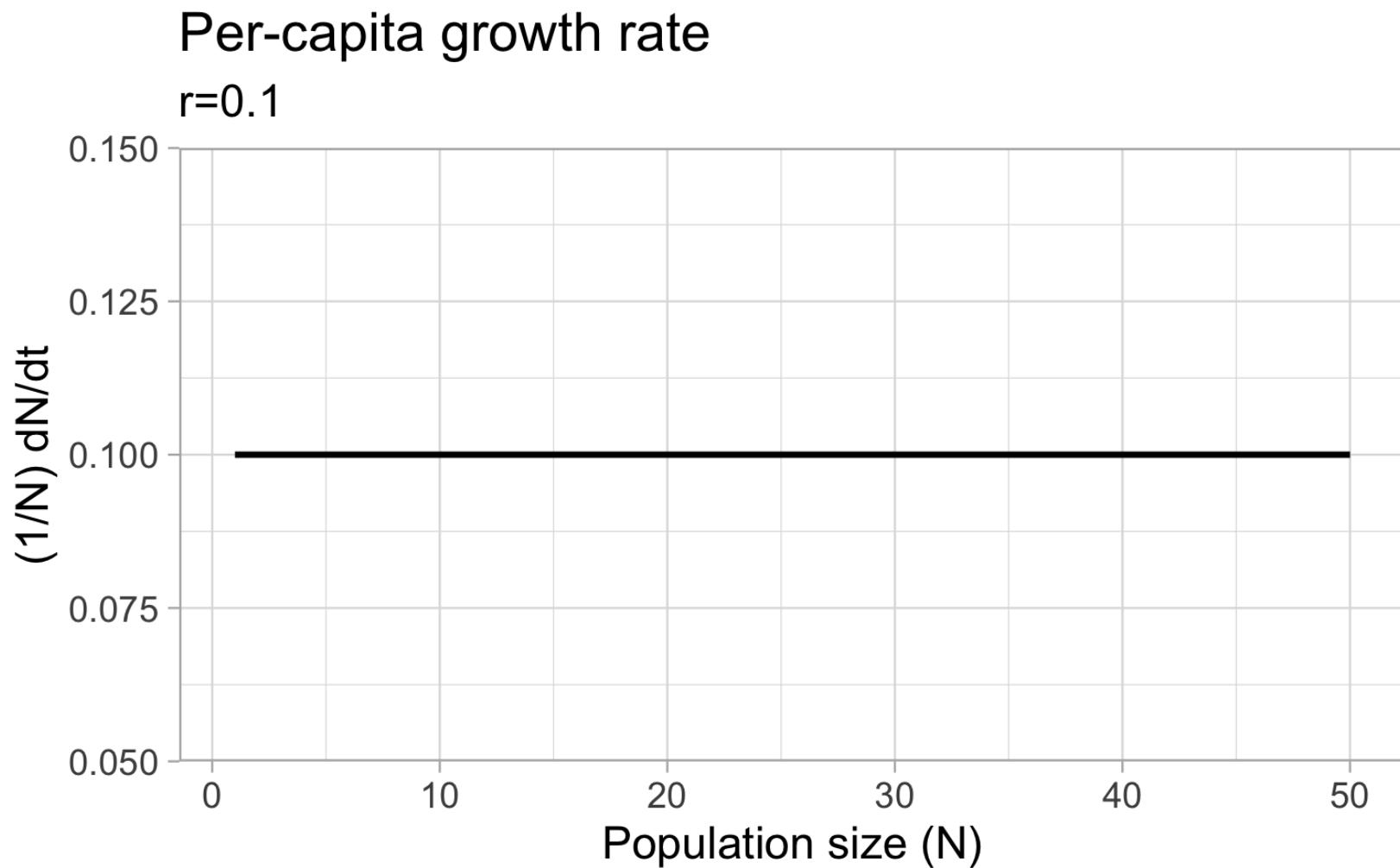
- What's wrong with this model?

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

Population regulation

- Density or density-independent factors?
- Strongly debated in the 1950's
- Any ideas for the simplest form of density dependence?

Population regulation



The logistic growth model

John Graunt (1662)

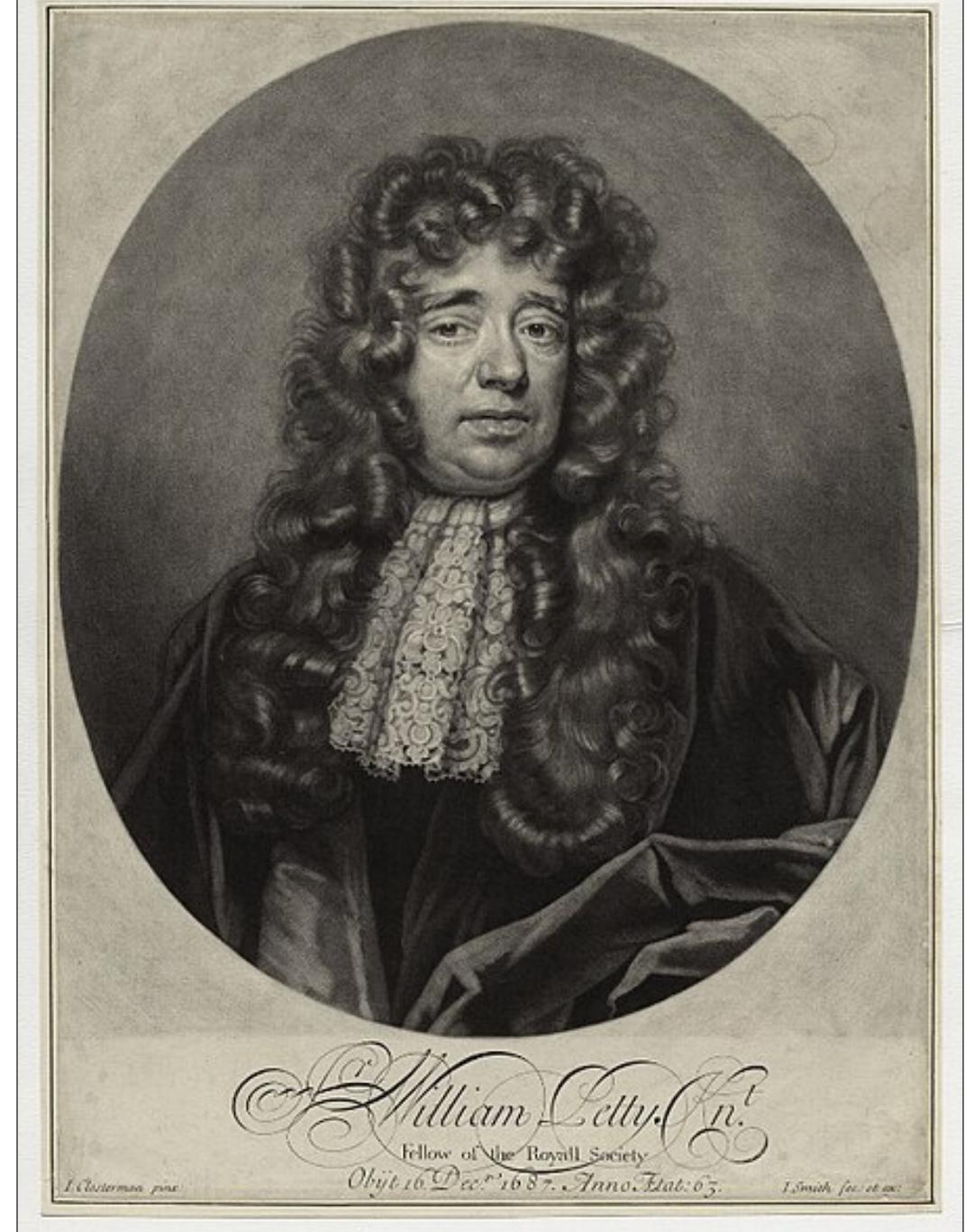
- Studied lists of births and deaths (demography) in London
- Adam and Eve: 6000 years ago... doubling time is 64 years...
- Should be *far* more people now than there is



The logistic growth model

Sir William Petty (1683)

- Fool, you haven't accounted for the biblical flood!
- Reduce doubling time, change start time



William Petty, Jr.

Fellow of the Royall Society

Died 16 Dec'r 1687 Anno. Ftab. 65.

J. Closterman p[ro]p[rietary]

J. Smith sculpsit





The logistic growth model

Reverend Thomas Robert Malthus (1798)

- *An Essay on the Principle of Populations*
 - If population grows faster than supply...
 - ... much human misery!



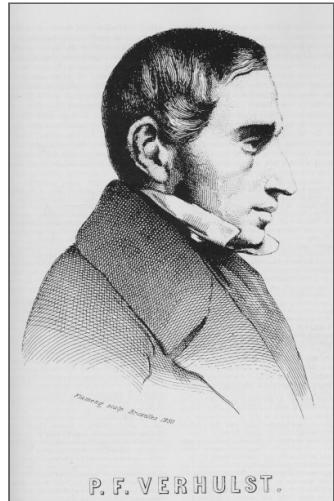
The logistic growth model

Pierre-Francois Verhulst (1845)

- Derived the logistic equation

Raymond Pearl and Lowell Reed (1920)

- Re-discovered it: Law of nature?



The logistic growth model

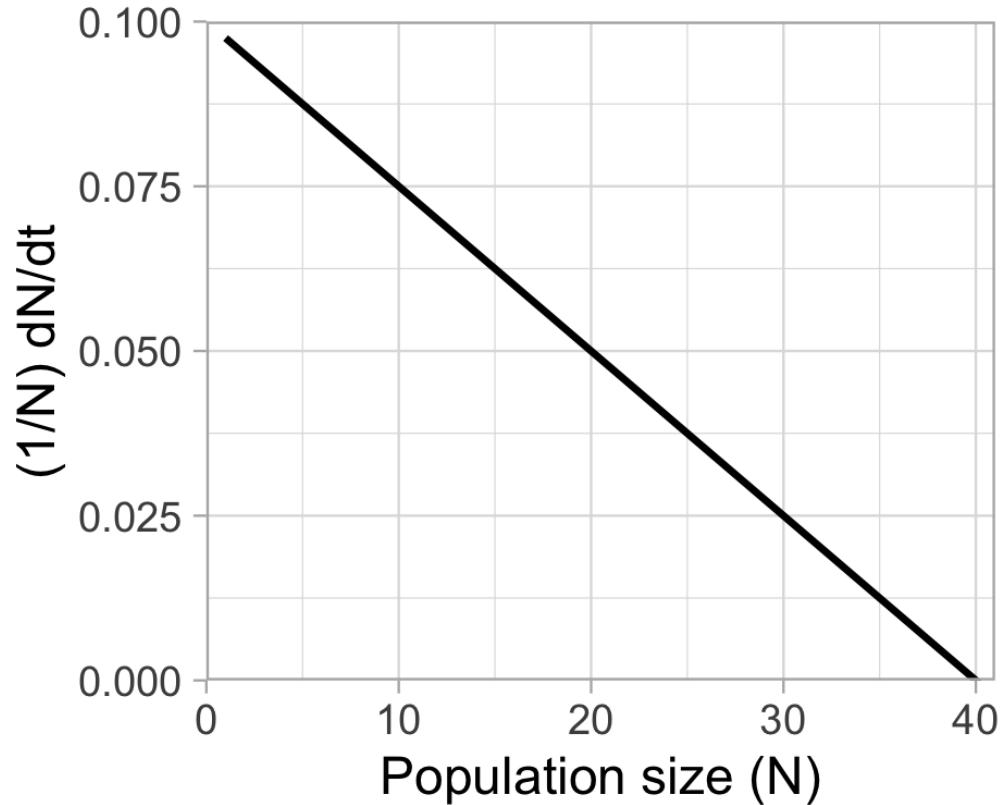
$$\frac{dN}{dt} = rN\left(1 - \frac{N}{K}\right)$$

```
1 n <- 0:50
2 K <- 40
3
4 d <- data.frame(N = n) %>%
5   mutate(dNd़t = r*N*(1 - N/K),
6         pc_dNd़t = dNd़t/N)
```

The logistic growth model

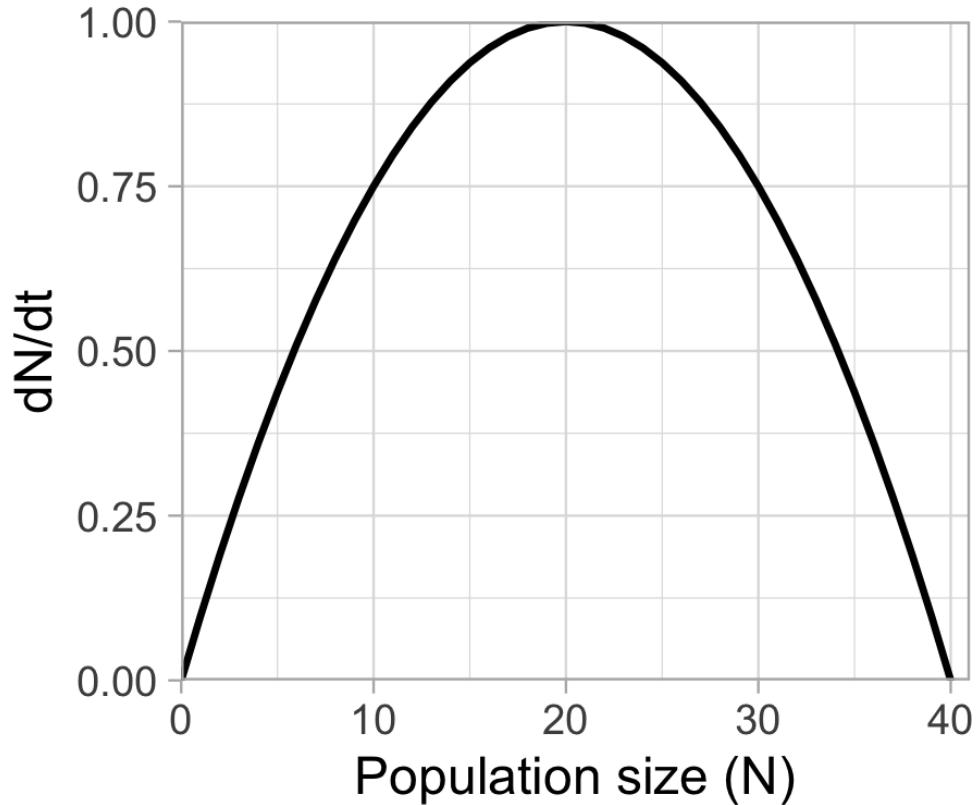
Per-capita growth rate

$r=0.1$



Population growth rate

$r=0.1$



The logistic growth model

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

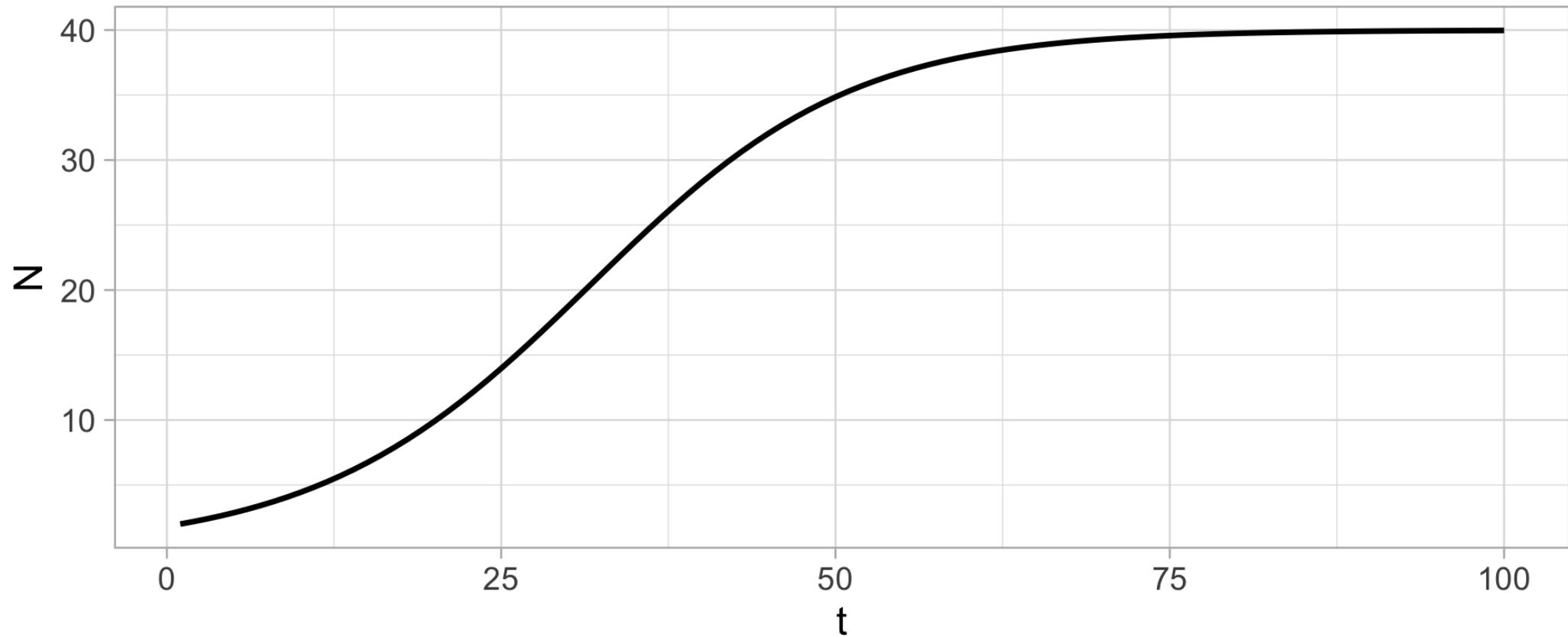
- How does the population grow?
- Can solve this... but also iteratively fill in N s'

```
1 r <- 0.1; K <- 40; N_ini <- 2; t <- 100
2 N <- rep(NA, t)
3 N[1] <- N_ini
4
5 for (i in 2:t) {
6   N[i] <- r * N[i-1] * (1-(N[i - 1]/K)) + N[i-1]
7 }
```

The logistic growth model

Logistic growth curve

$r = 0.1$ and $K = 40$



The logistic growth model

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

- Another useful technique is to find the equilibria with algebra
- Set $\frac{dN}{dt} = 0$

The logistic growth model

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

- Another useful technique is to find the equilibria with algebra
- set $\frac{dN}{dt} = 0$
- $N_1^* = 0$
- $N_2^* = K$

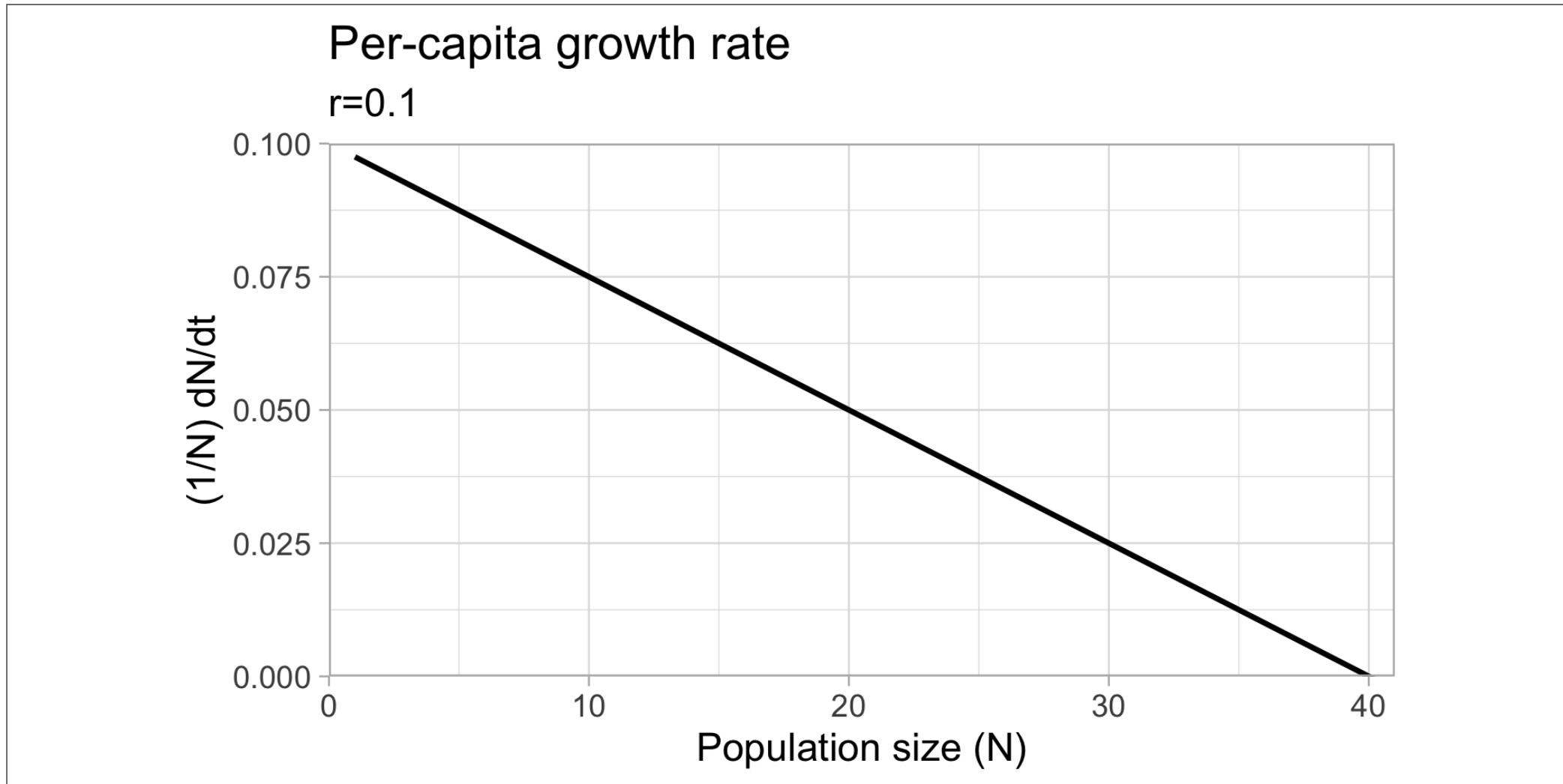
The logistic growth model

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

- One can also conduct stability analysis, but we will skip that

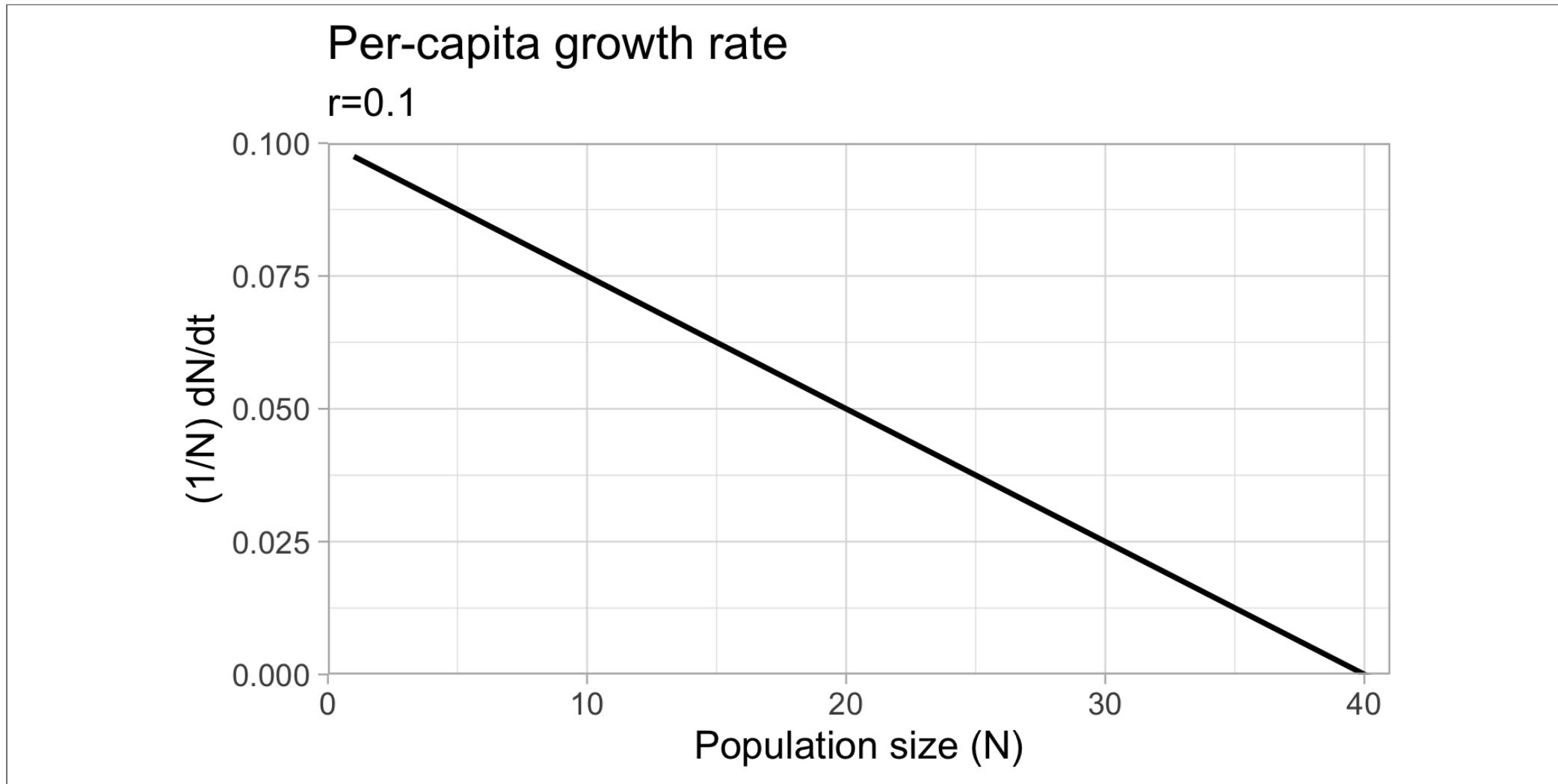
The logistic growth model

- Is it really a law of nature?



The logistic growth model

- ... There are other models where growth depends on population size, e.g., Gompertz, and it may of course have different shape than the linear!



2. Species interactions

2. Species interactions

- **Predation]**[parasitism] (-, +)
- **Competition** (-, -)
- Mutualism (+, +)
- Amensialism (0, -)
- Commensalism (0, +)

Predation



Hieronymus Bos.
inventor

ECCE

COCK EXCV - 1557

Petrus
Merica
Siet sone dit hebbe ik zeer langhe ghetweten / dat die groote vissen de cleynen eten

The original predator-prey model

- Lotka-Volterra
- Published independently by Alfred J. Lotka and Vito Volterra in 1925 & 1926
- Widely used and analyzed today

The original predator-prey model



Alfred J. Lotka



Vito Volterra

The original predator-prey model



Alfred J. Lotka



Vito Volterra



Umberto D'Ancona

The original predator-prey model



Fish Market, Marina, Valletta – MALTA



The original predator-prey model

- Volterra wrote down these eqns to Umberto's:

$$\frac{dN}{dt} = \alpha N - \beta NP$$

$$\frac{dP}{dt} = \delta \beta NP - \gamma P$$

- How does the prey grow in absence of predators? How does the predator population decline in the absence of prey? What is β and δ ?

Lotka-Volterra model

- Let's break it down

$$\frac{dN}{dt} = \alpha N - \beta NP$$

$$\frac{dP}{dt} = \delta \beta NP - \gamma P$$

Lotka-Volterra model

- Zero-net growth isoclines
- set $\frac{dN}{dt}$ or $\frac{dP}{dt} = 0$, break out P and N

$$\frac{dN}{dt} = \alpha N - \beta NP$$

$$\frac{dP}{dt} = \delta \beta NP - \gamma P$$

Prey zero growth isoclines

$$\frac{dN}{dt} = \alpha N - \beta NP$$

$$0 = \alpha N - \beta NP$$

$$0 = \alpha - \beta P$$

$$P = \frac{\alpha}{\beta}$$

Predator zero growth isoclines

$$\frac{dP}{dt} = \delta\beta NP - \gamma P$$

$$0 = \delta\beta NP - \gamma P$$

$$0 = \delta\beta N - \gamma$$

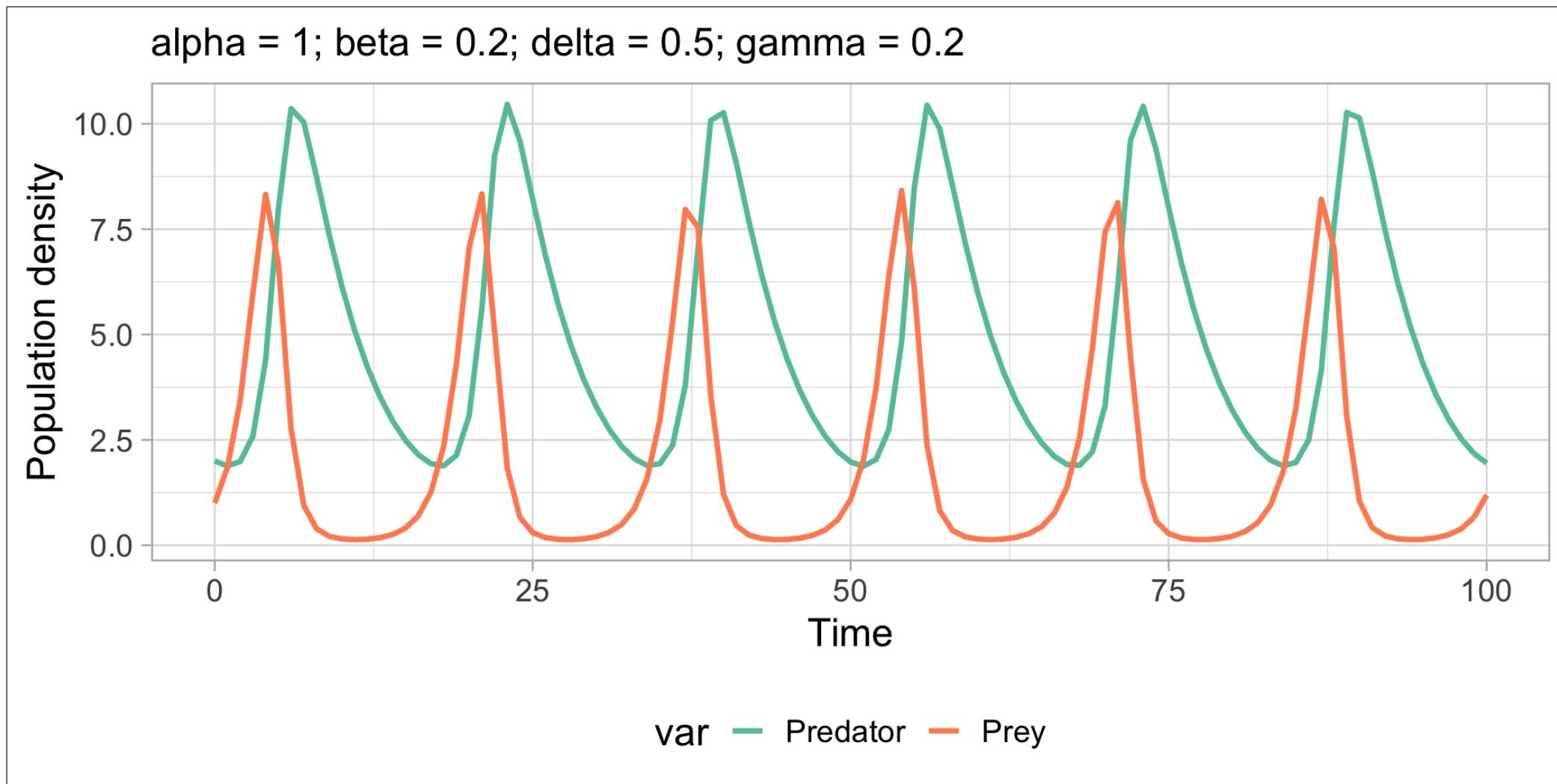
$$P = \frac{\gamma}{\delta\beta}$$

Lotka-Volterra model

```
1 # https://strimas.com/post/lotka-volterra/
2 # parameters
3 pars <- c(alpha = 1, beta = 0.2, delta = 0.5, gamma = 0.2)
4 # initial state
5 init <- c(x = 1, y = 2)
6 # times
7 times <- seq(0, 100, by = 1)
8
9 deriv <- function(t, state, pars) {
10   with(as.list(c(state, pars)), {
11     d_x <- alpha * x - beta * x * y
12     d_y <- delta * beta * x * y - gamma * y
13     return(list(x = d_x, y = d_y)))
14   })
15 }
16
17 lv_results <- ode(init, times, deriv, pars)
```

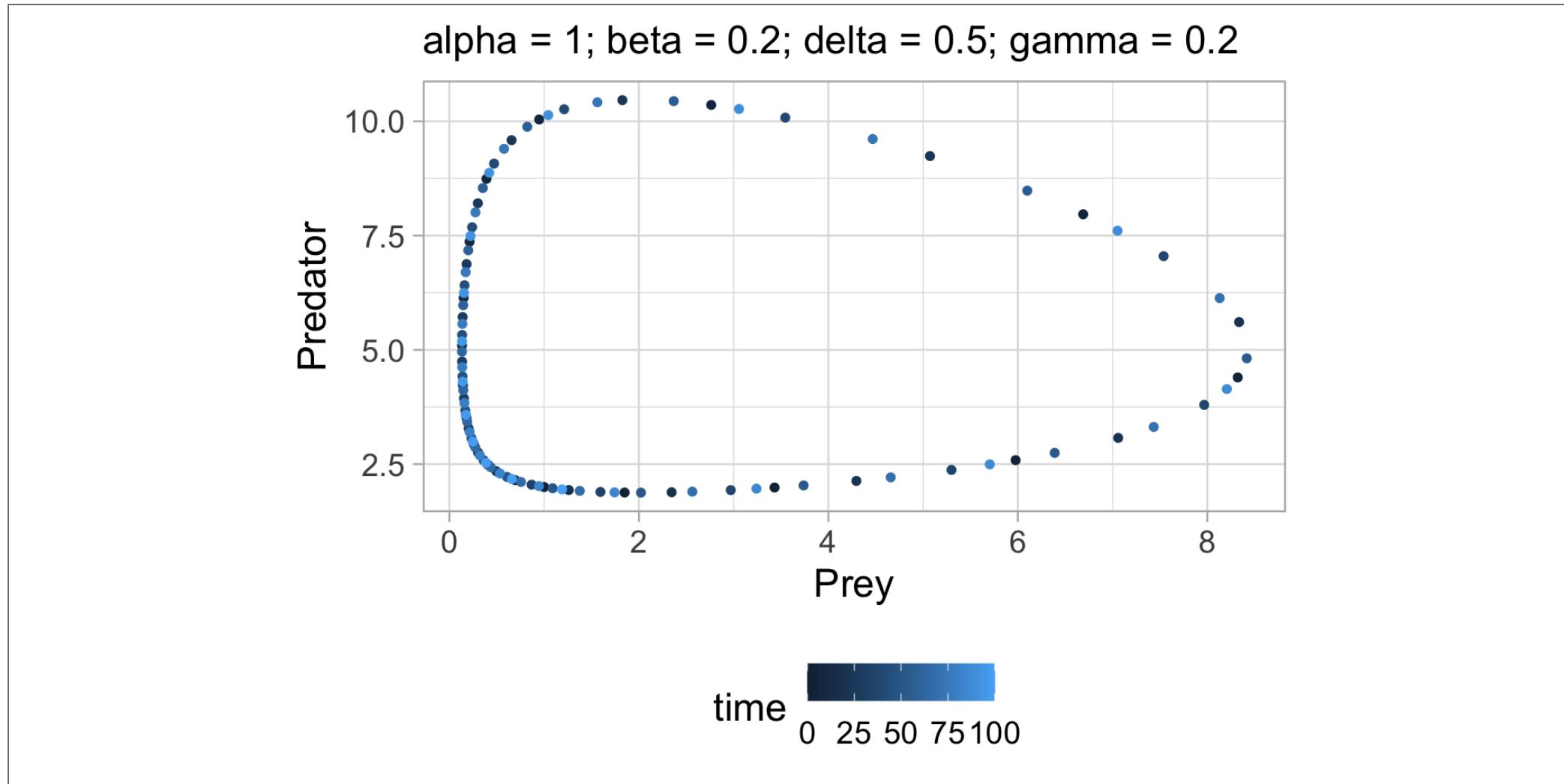
Lotka-Volterra model

- A cyclic model



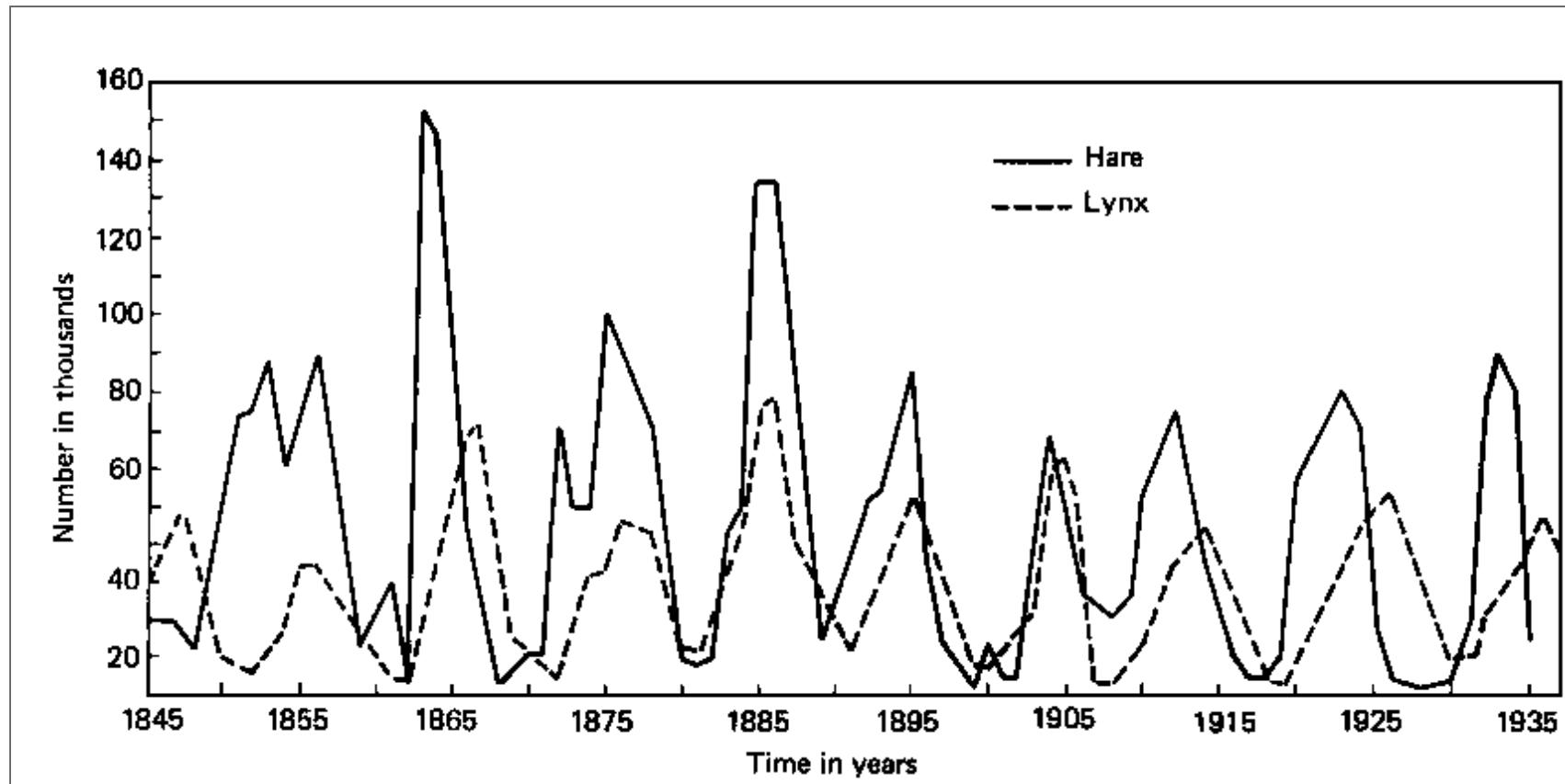
Lotka-Volterra model

- A cyclic model: phase plot



A famous example

- Lynx and hare data compiled by Elton¹



Other predator-prey models

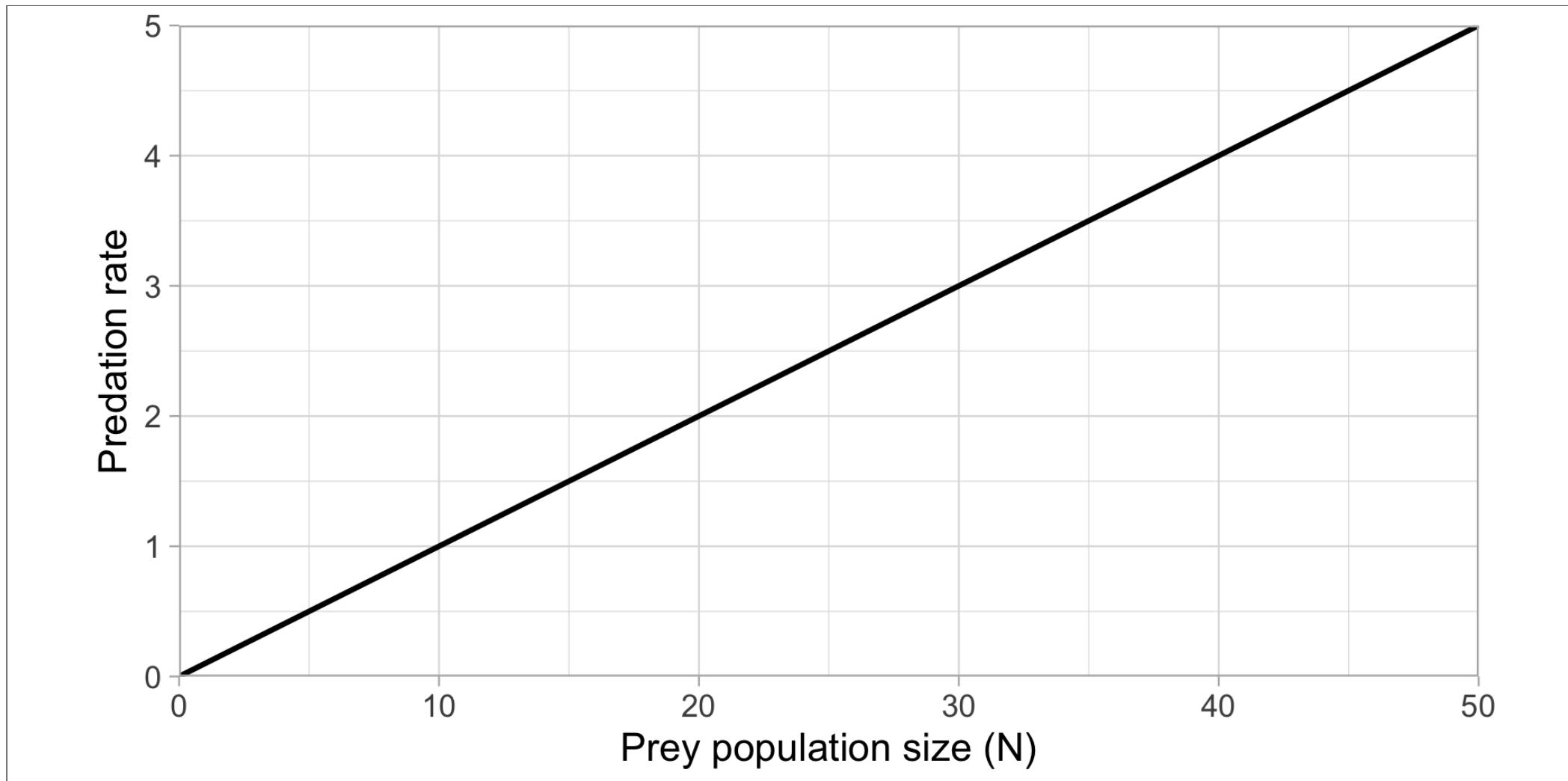
- How can we incorporate more realism into the Lotka-Volterra model?

Functional response

- “Kill rate”, in the LV model given by:

$$\beta N$$

- We call this a Type I functional response

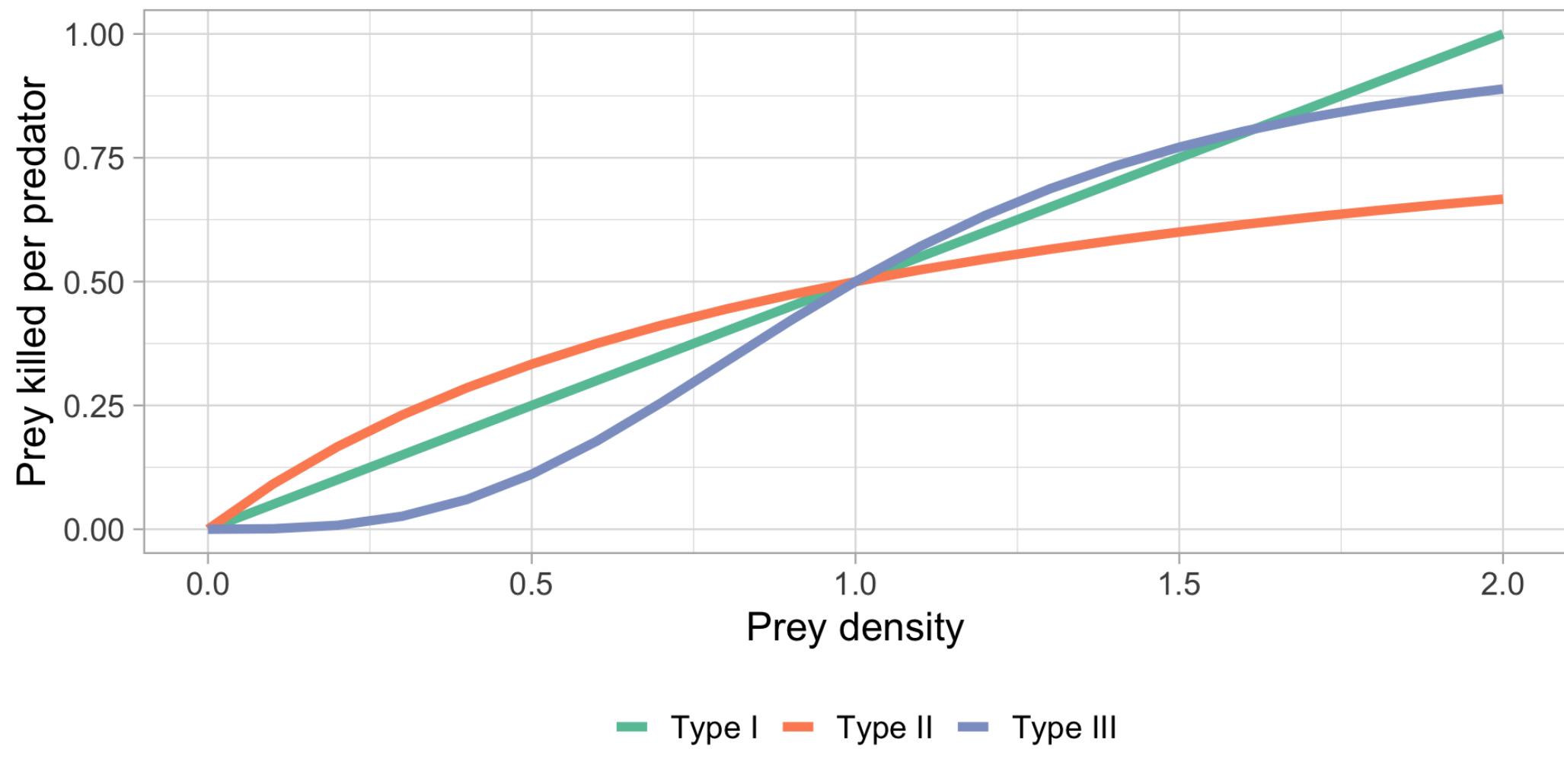


Other functional responses!

- Type I: αN
- Type II: $\frac{\alpha N}{1+\alpha hN}$
- Type III: $\frac{\alpha N^c}{1+\alpha hN^c}$

Other functional responses!

```
1 n <- seq(0, 2, 0.1); a <- 0.5; b <- 1; c <- 3
2
3 d <- data.frame(N = n) %>%
4   mutate("Type I" = a*N,
5         "Type II" = N / (b + N),
6         "Type III" = N^c / (b + N^c)) %>%
7   pivot_longer(2:4)
```



Other numerical responses!

- I.e., the how the predators population growth rate varies with N , or dP/dt vs. N .

Other predator-prey models

- Endless possibilities
- Let's look at the Rosenzweig and MacArthur model

Rosenzweig and MacArthur

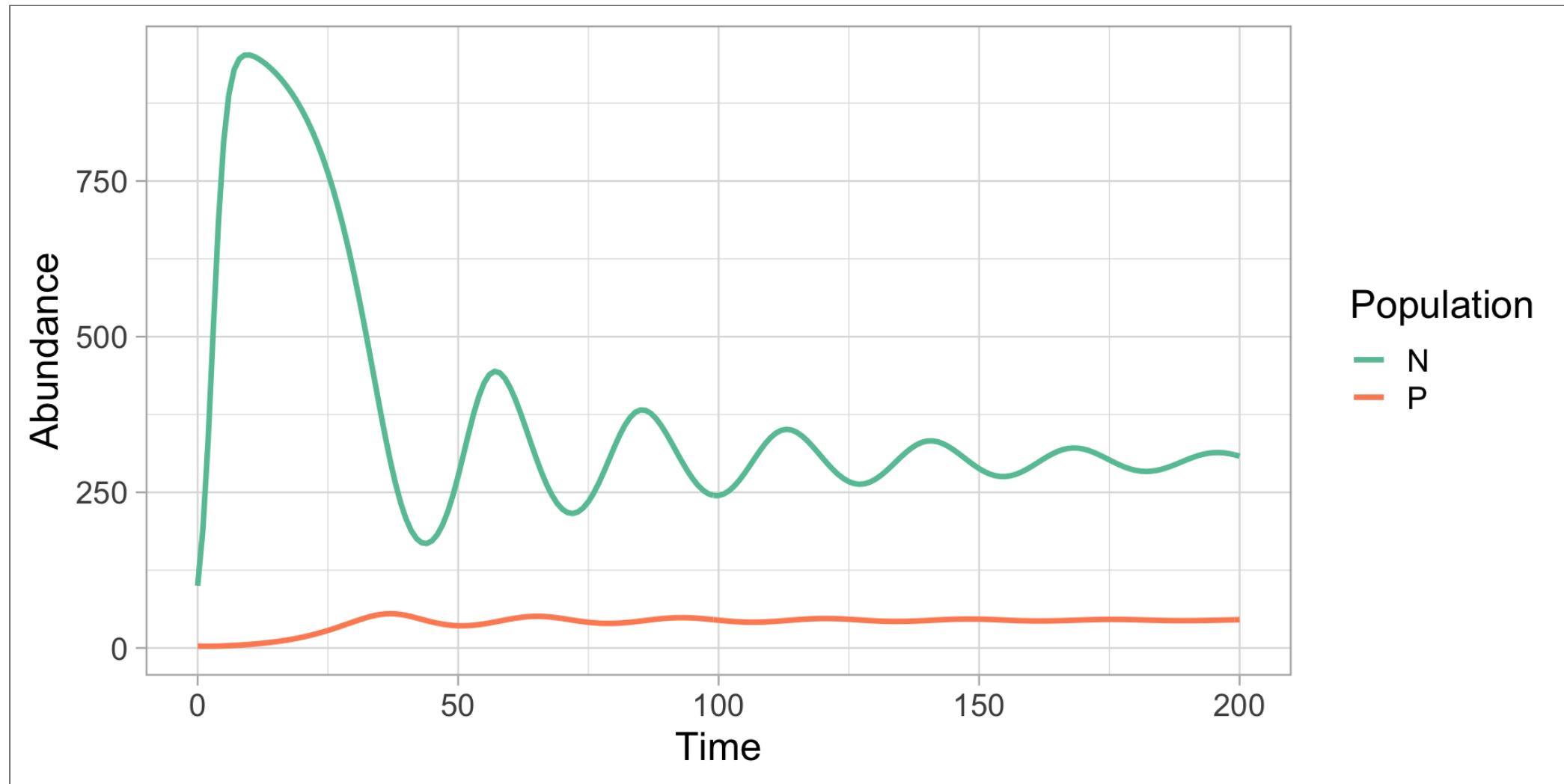
$$\frac{dN}{dt} = rN(1 - \alpha N) - \frac{\alpha N}{1 + \alpha hN} P$$

$$\frac{dP}{dt} = e \frac{\alpha N}{1 + \alpha hN} P - mP$$

Rosenzweig and MacArthur

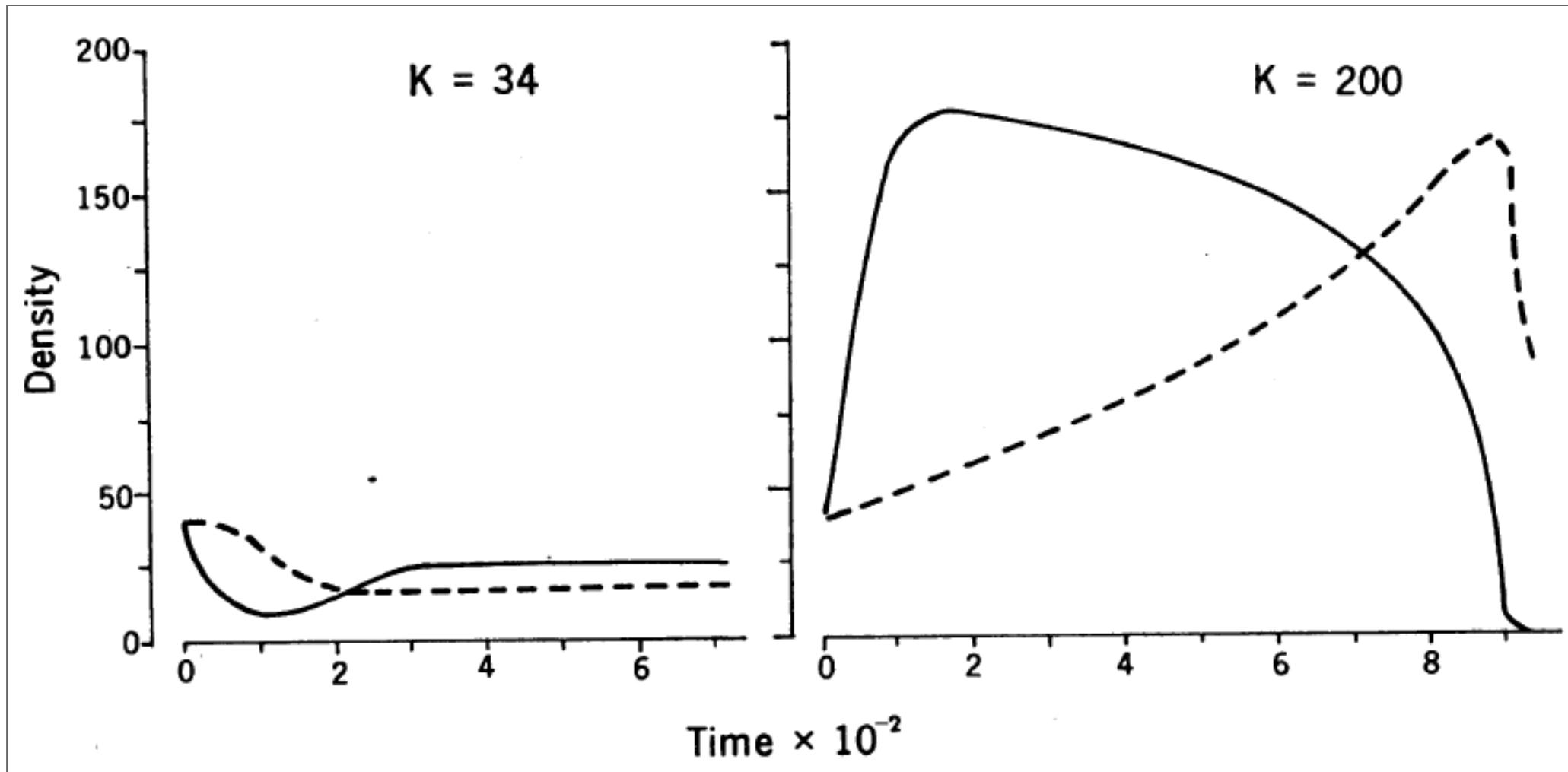
```
1 # https://hankstevens.github.io/Primer-of-Ecology/cr.html
2 cr_RM_pred <- function(time, y, p){
3   N <- y[1]
4   P <- y[2]
5   with(as.list(p), {
6     Ndot <- r*N*(1 - alpha*N) - a*N*P/(1 + a*h*N) # prey
7     Pdot <- e*a*N*P/(1 + a*h*N) - m*P # predator
8     return(list(c(Ndot, Pdot)))
9   })
10 }
11
12 t <- 0:200
13 y0 <- c(N = 100, P = 3)
14
15 p <- list(r = 0.8, alpha = 0.001, a = 0.02, e = 0.04, m = .15, h =
16
17 outdf <- as.data.frame(ode(y0, t, cr_RM_pred, p) ) %>%
18   pivot_longer(-time, names_to = "Population", values_to = "Abundan
```

Rosenzweig and MacArthur



Rosenzweig and MacArthur

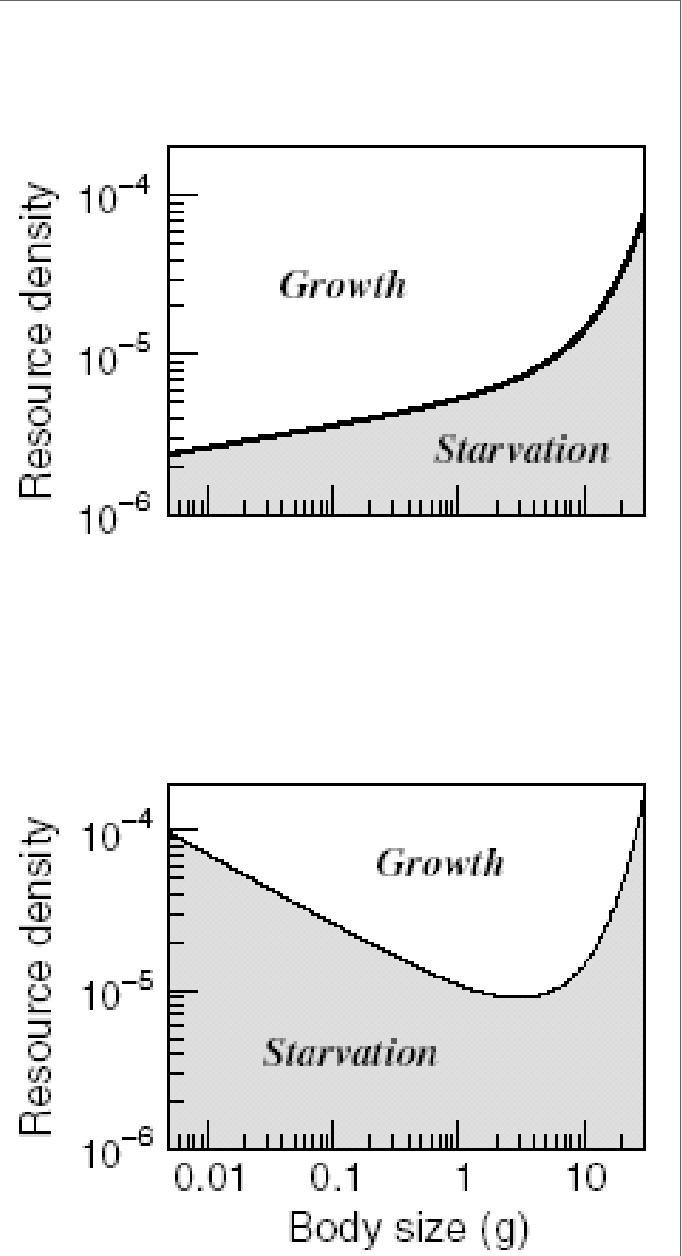
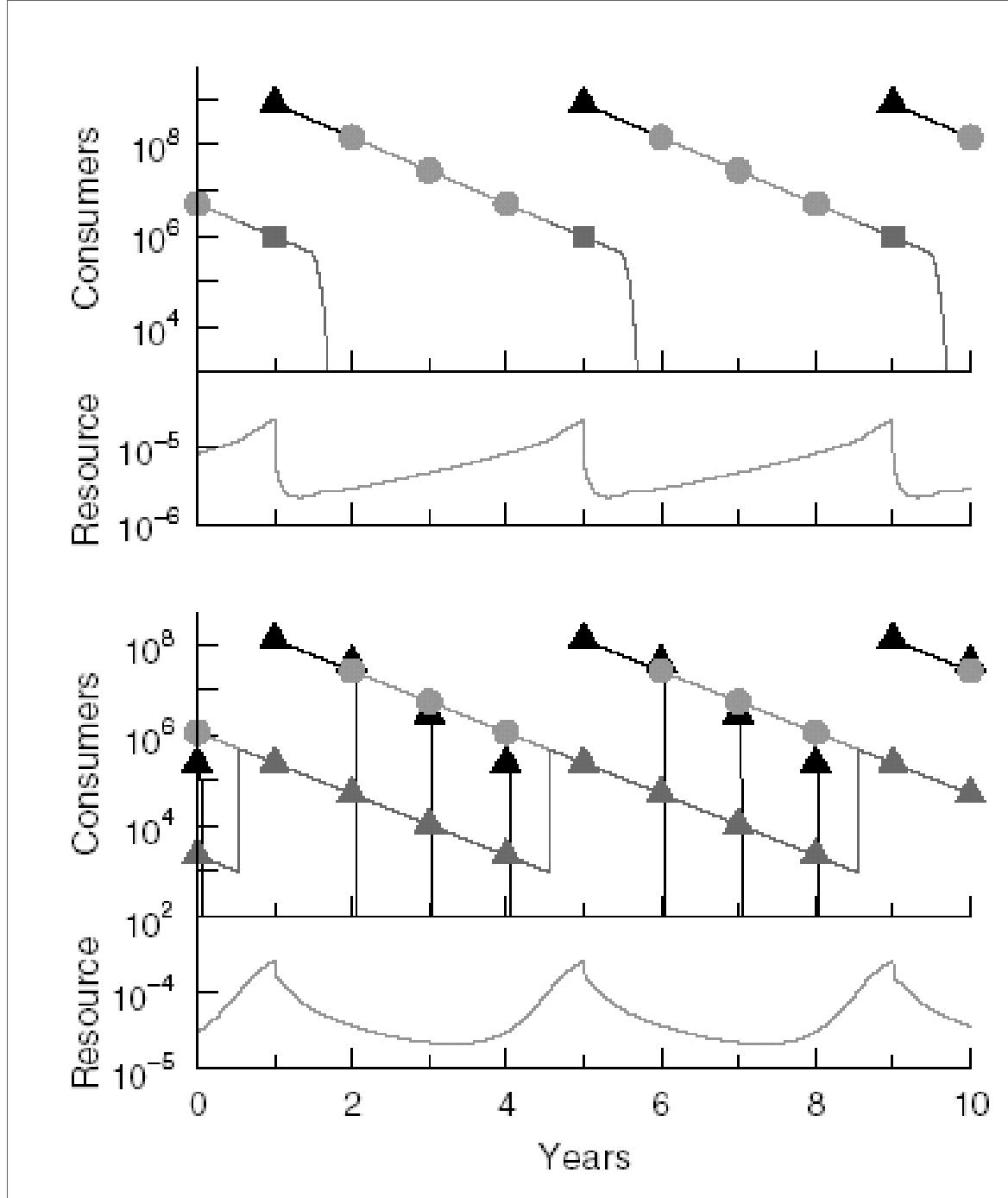
- Paradox of enrichment!



Other types of cycles...

- We have seen predator-prey cycles, but populations can also cycle for other reasons!

Cohort-cycles



Competition

- Interference
- Scramble / Exploitation





L-V competition model

$$\frac{dN_1}{dt} = r_1 N_1 \left(\frac{K_1 - N_1 - \alpha_{12} N_2}{K_1} \right)$$

$$\frac{dN_2}{dt} = r_2 N_2 \left(\frac{K_2 - N_2 - \alpha_{21} N_1}{K_2} \right)$$

L-V competition model

- Find the zero-growth isocline for species N_1

$$\frac{dN_1}{dt} = r_1 N_1 \left(\frac{K_1 - N_1 - \alpha_{12} N_2}{K_1} \right)$$

$$0 = r_1 N_1 \left(\frac{K_1 - N_1 - \alpha_{12} N_2}{K_1} \right)$$

$$0 = \frac{K_1 - N_1 - \alpha_{12} N_2}{K_1}$$

$$N_1 = K_1 - \alpha_{12} N_2$$

L-V competition model

- Find the zero-growth isocline for species N_2

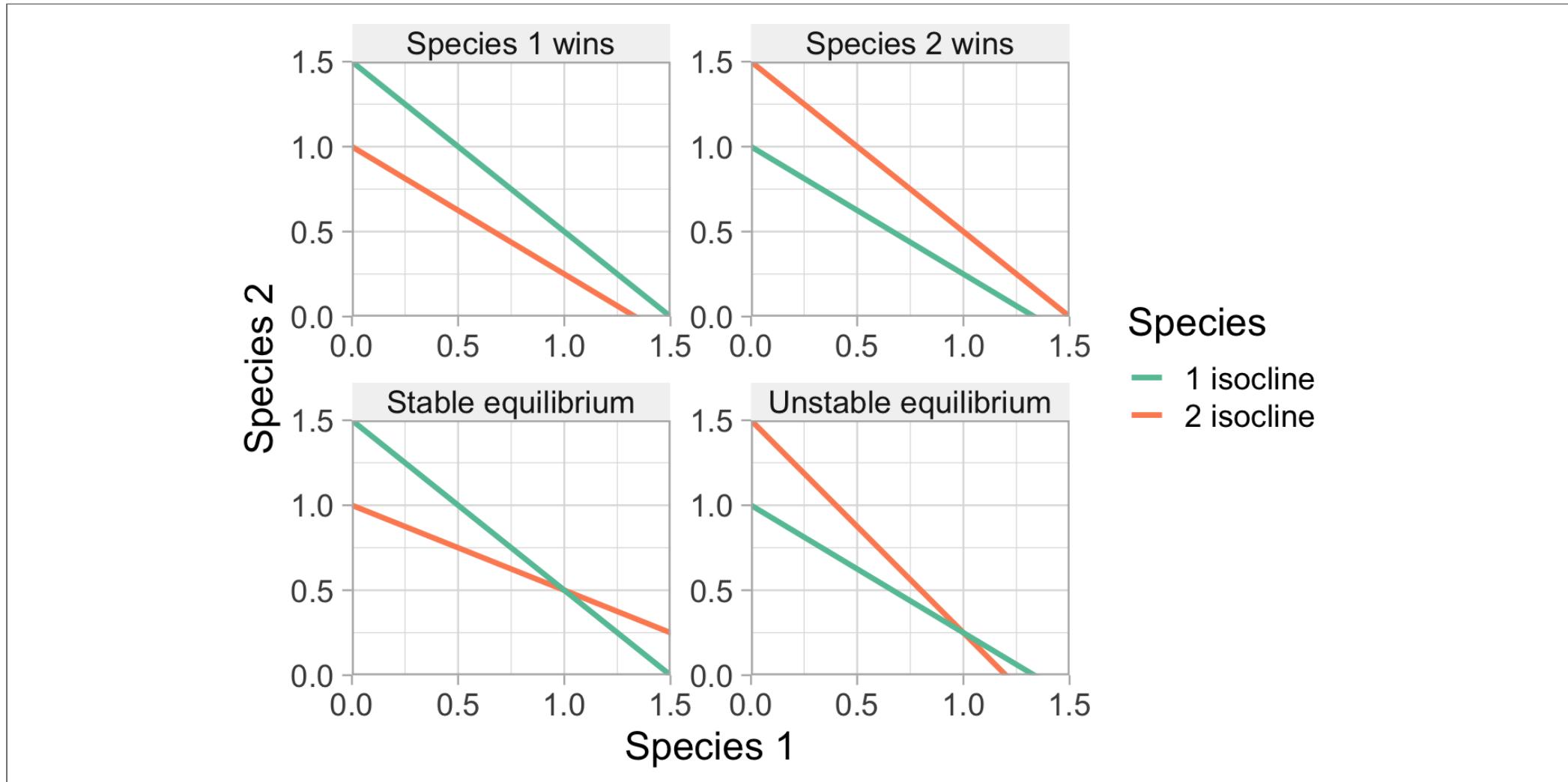
$$\frac{dN_2}{dt} = r_2 N_1 \left(\frac{K_2 - N_2 - \alpha_{21} N_1}{K_2} \right)$$

$$N_2 = K_2 - \alpha_{21} N_1$$

L-V competition model

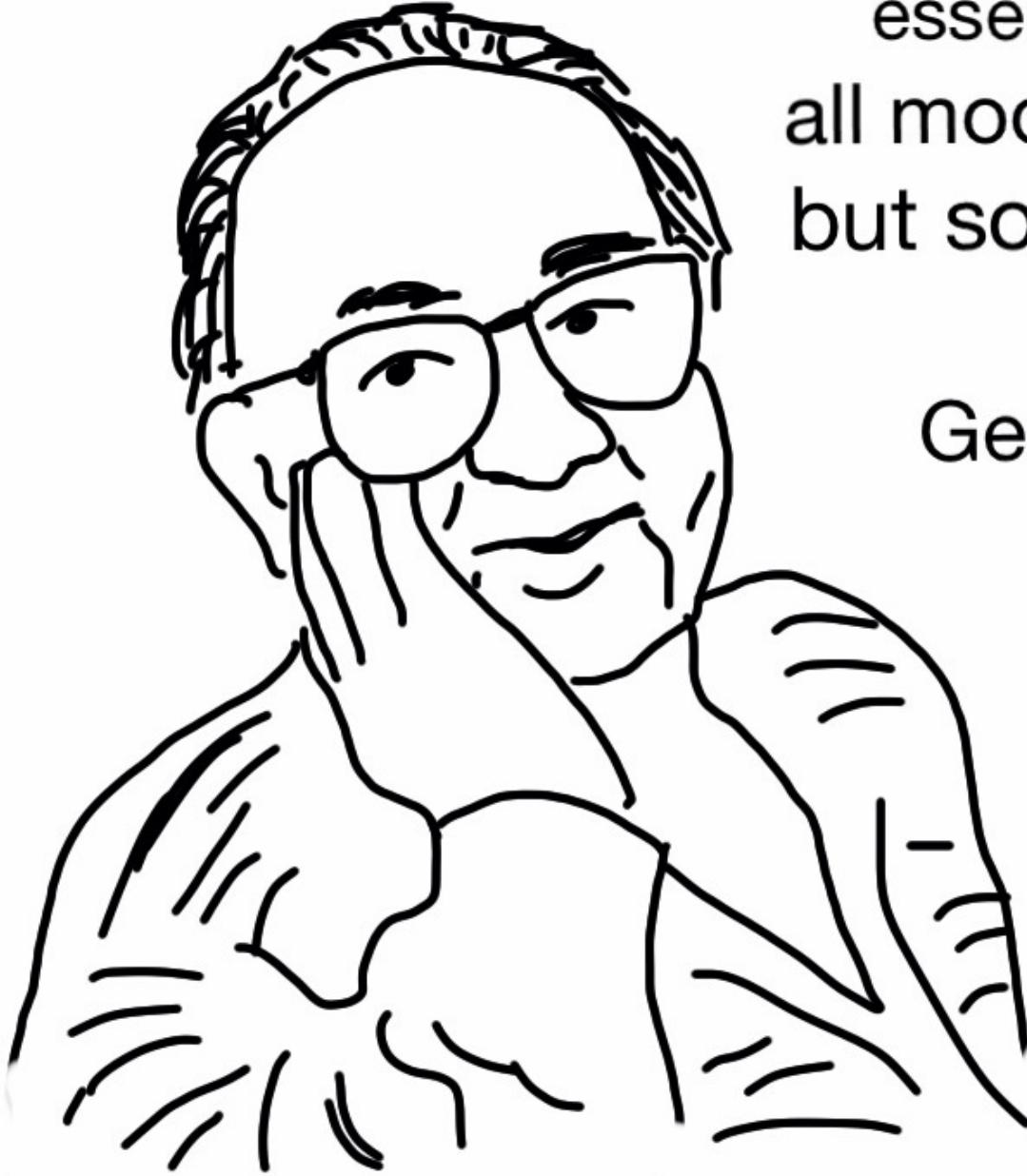
```
1 N <- 0:20
2
3 # Species 1 wins
4 a_21 <- 0.75
5 a_12 <- 1
6 K_1 <- 1.5
7 K_2 <- 1
8
9 d1 <- data.frame(N = N) %>%
10   mutate(N2_iso = K_2 - a_21*N,
11         N1_iso = K_1 - a_12*N,
12         scenario = "Species 1 wins")
```

L-V competition model



Epilogue

- If models keep being still are too unrealistic even after adding realistic features, why do we use them?



essentially,
all models are wrong,
but some are useful

George E. P. Box

freshspectrum.com

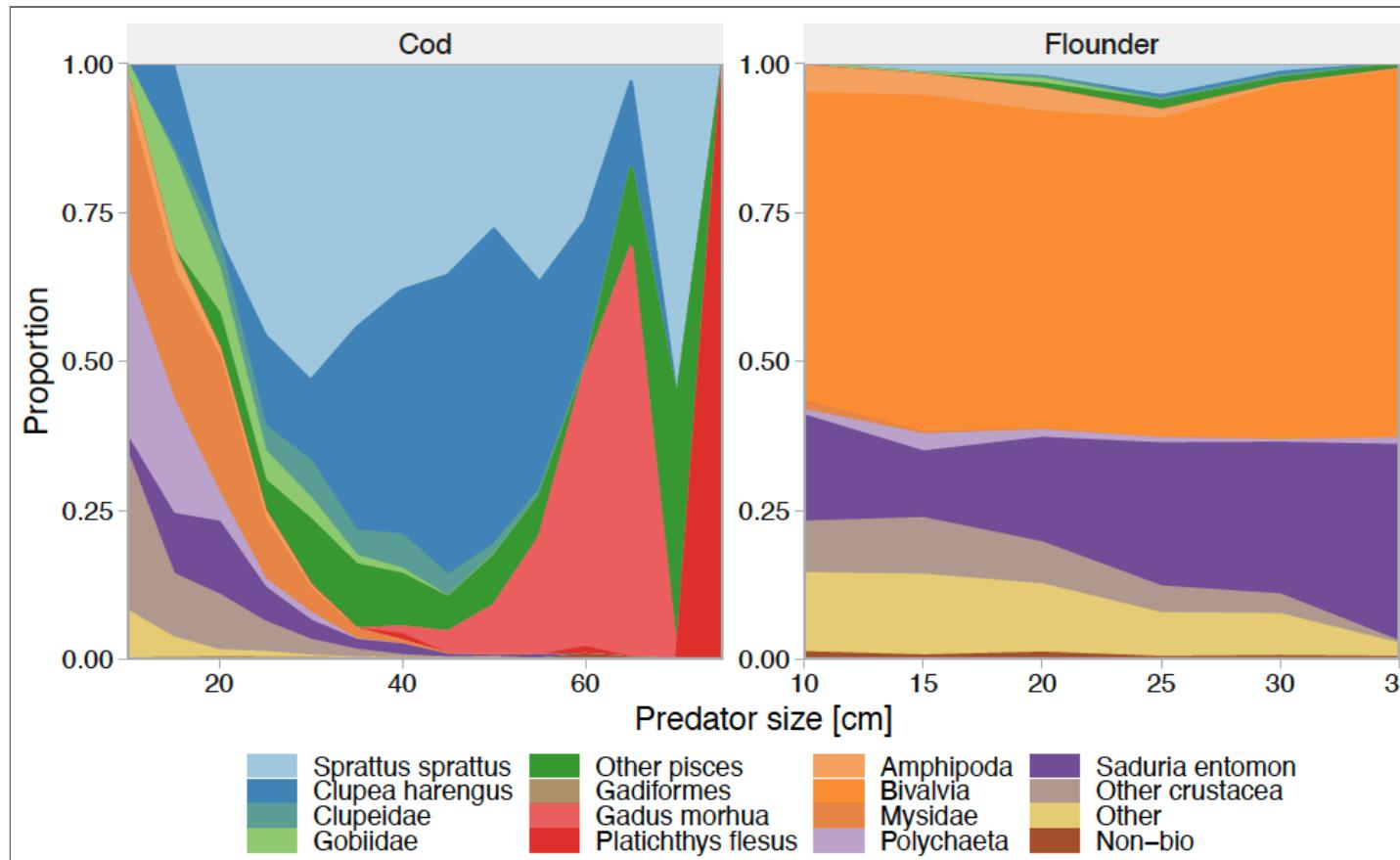
3. Quantifying species interactions in natural systems

3. Quantifying species interactions in natural systems

- We know how some ideas on how to model interactions mathematically
- How do we determine if and what species interactions occur in the wild?

Diet data

- We collect stomach content data for key species (read: commercial)



Diet data: example Baltic cod

Diet data: example Baltic cod

- Bioenergetic models + diet information = cod grow worse today

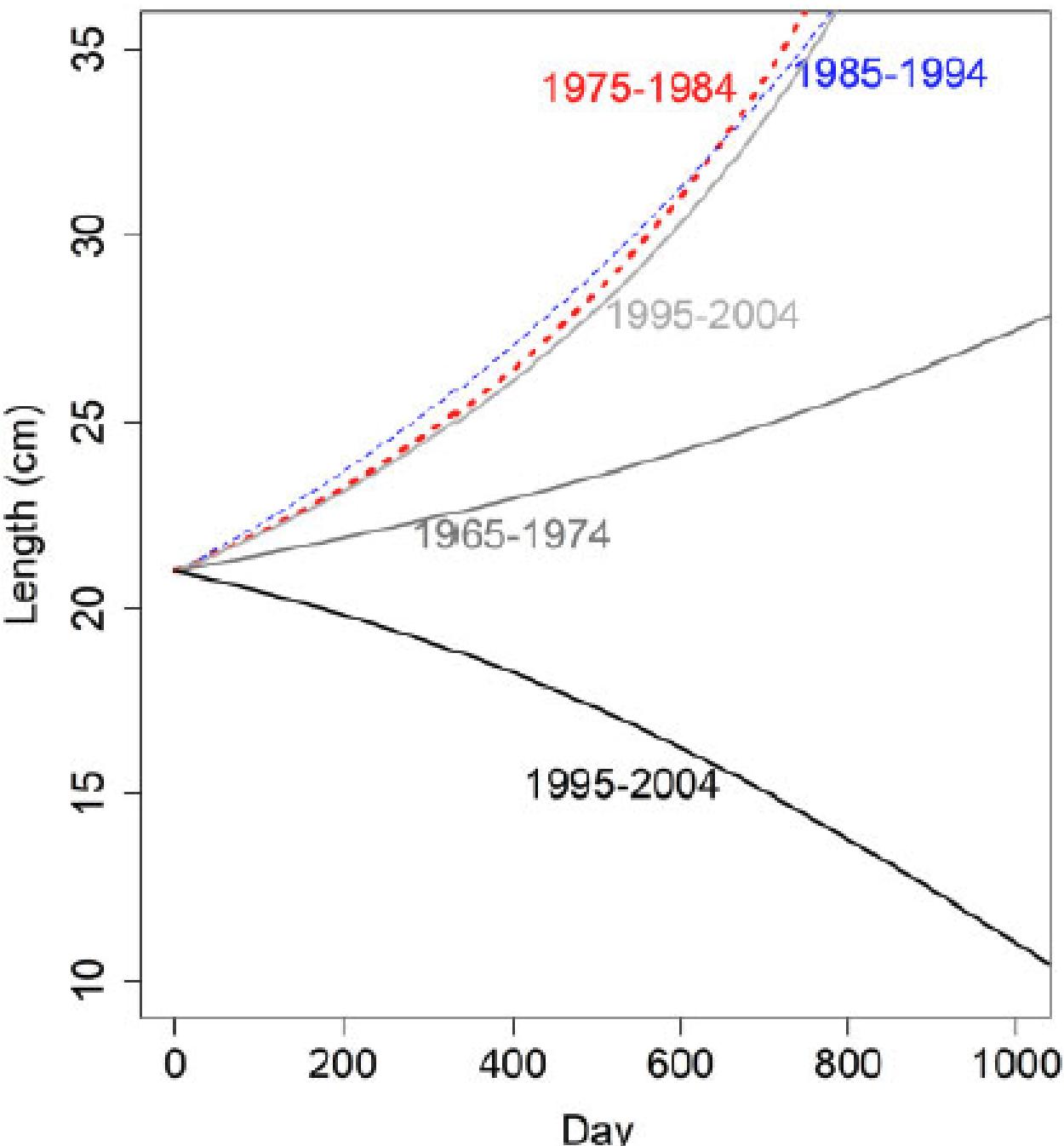
$$C = 24 \rho_0 L^{1.30} e^{0.083T} E^{0.15} \sqrt{S}.$$

$$C_{\max} = 0.223 e^{(0.104T - 0.000112T^3)} W^{0.802}$$

$$P_B = \kappa f C_{\max} - R_S - R_A$$

Diet data: example Baltic cod

- Bioenergetic models + diet information = cod grow worse today

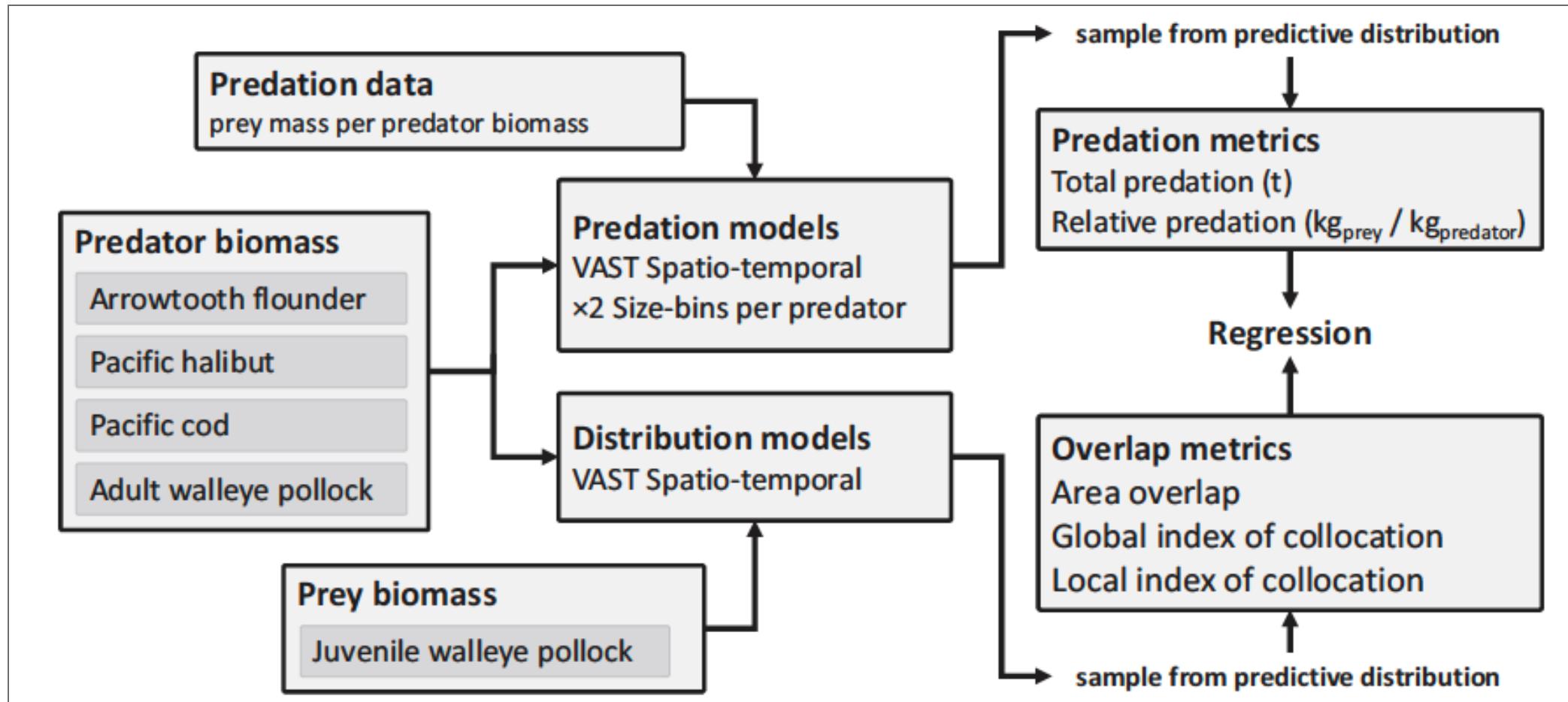


Diet data: example Baltic cod



Predation in space!

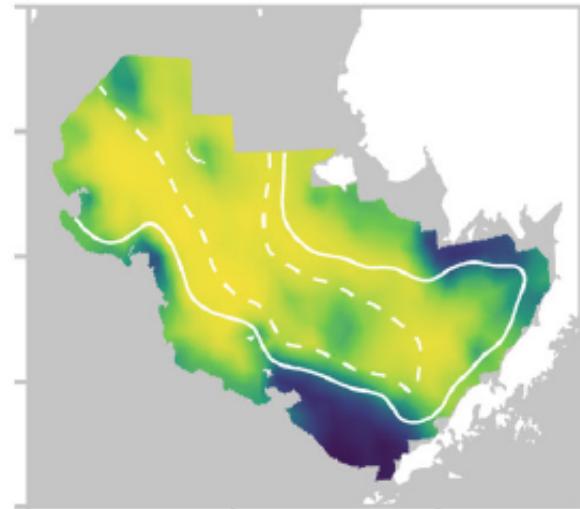
- Diets, predators, and prey vary in space



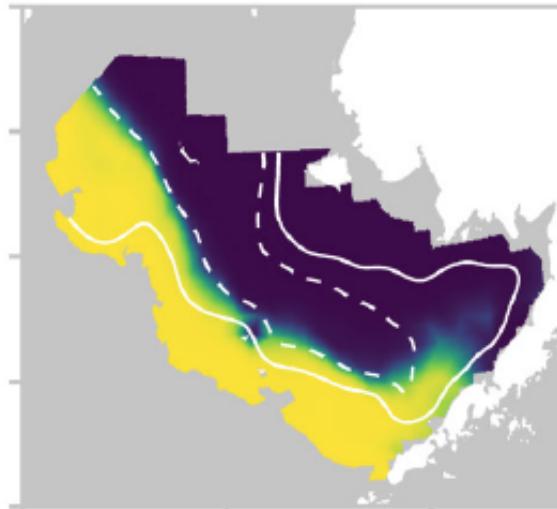
Predation in space!

- Diets, predators, and prey vary in space

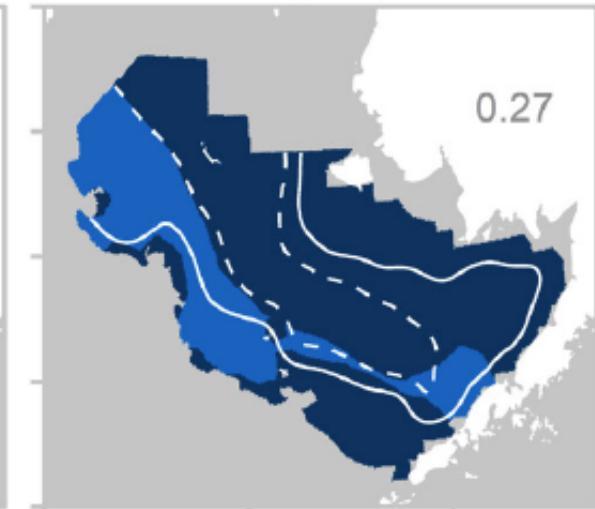
(b) Juvenile pollock 2009



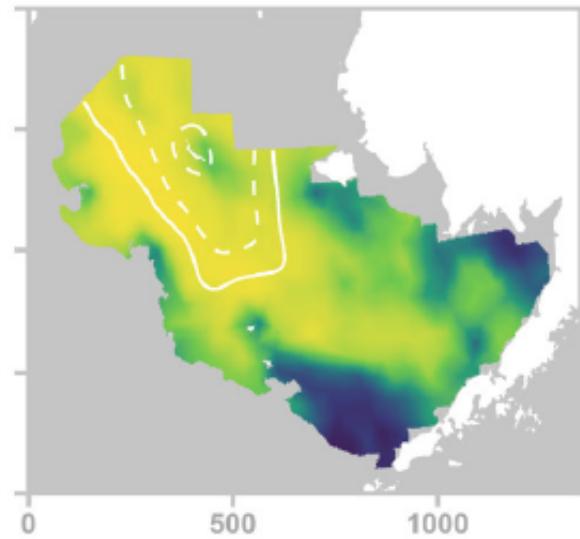
(c) Flounder 2009



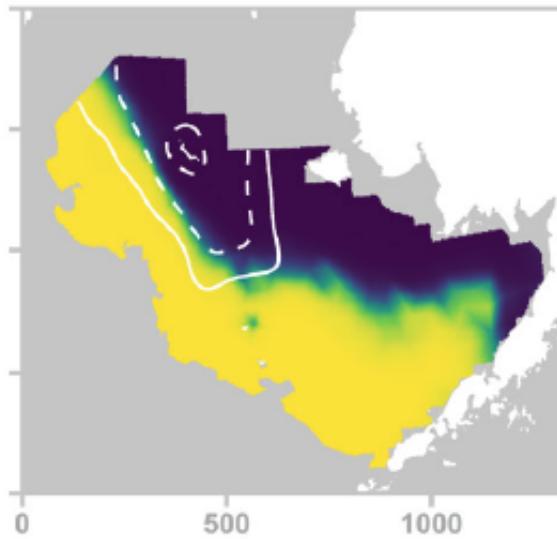
(d) Area overlap 2009



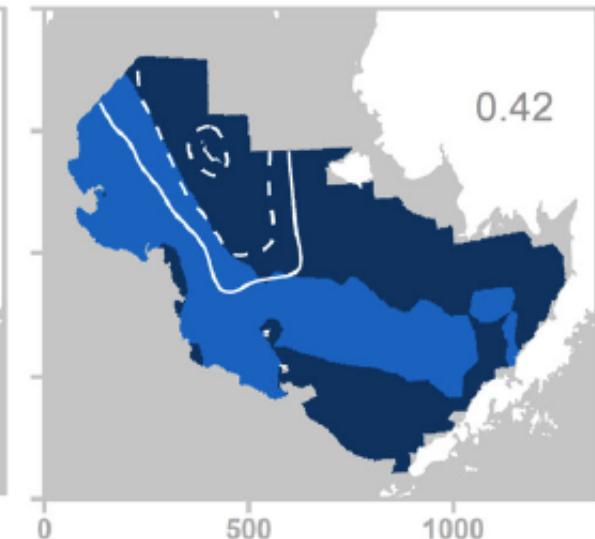
(f) Juvenile pollock 2015



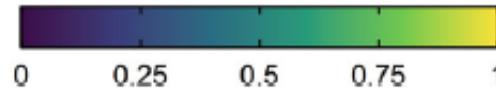
(g) Flounder 2015



(h) Area overlap 2015

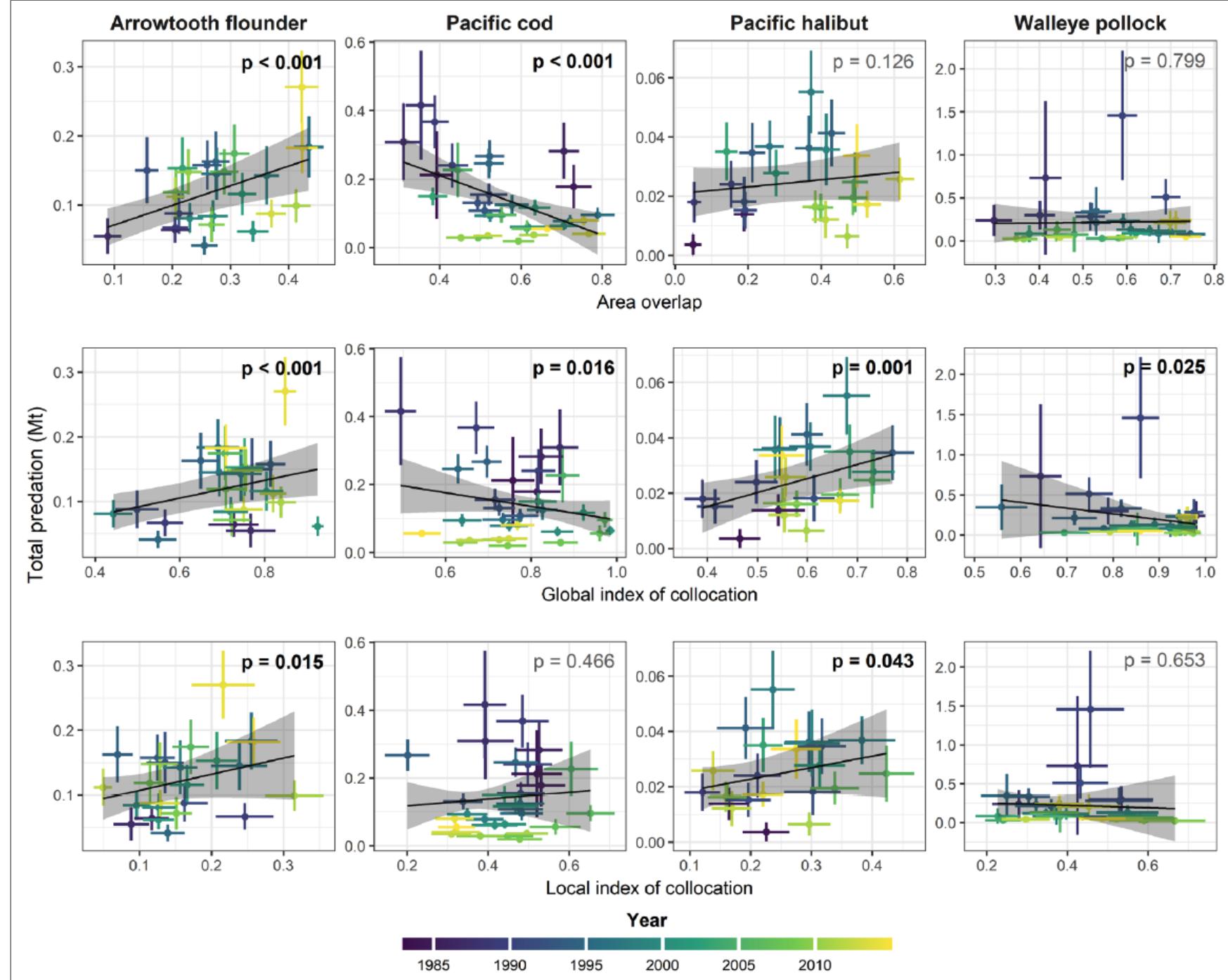


Probability of encounter



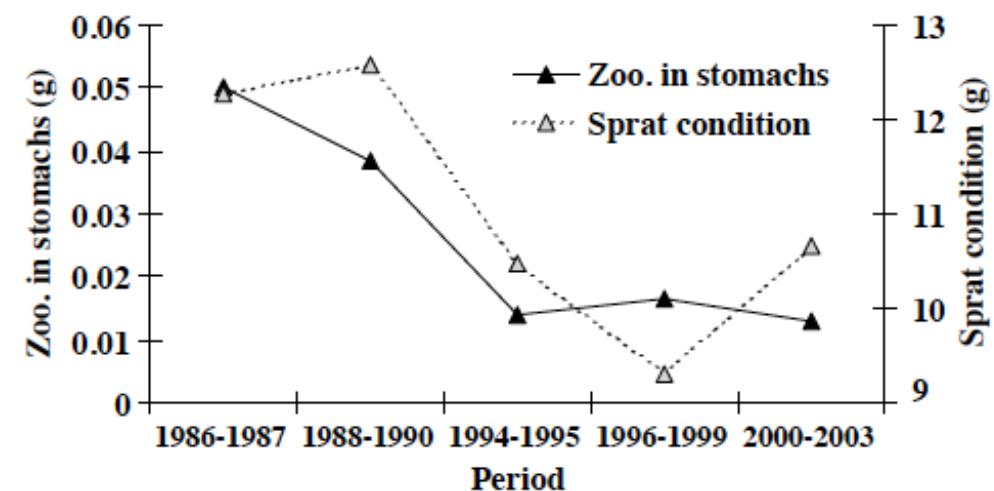
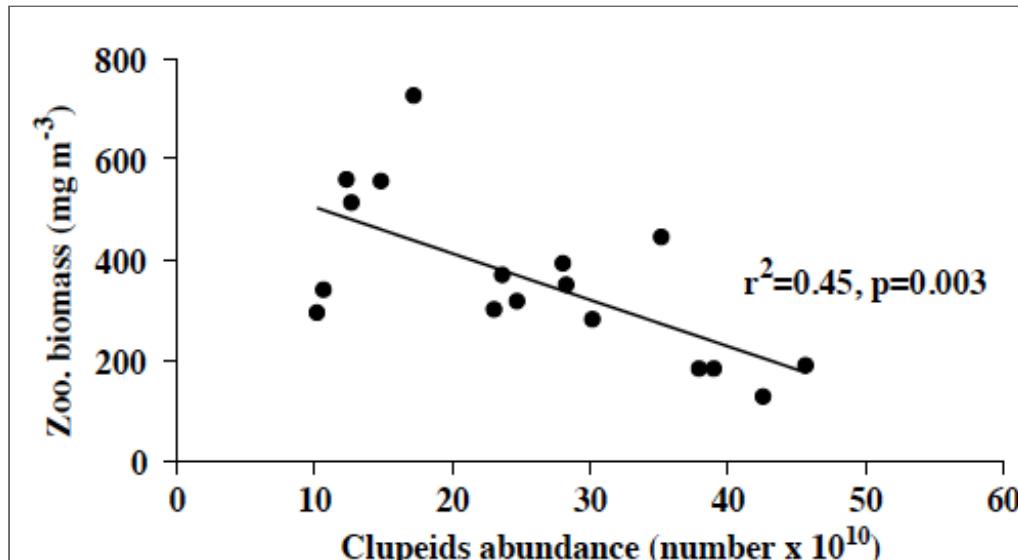
Predation in space!

- Diets, predators, and prey vary in space



Competition

- Sprat and herring affect the abundance of zooplankton
- In sprat, zooplankton in stomachs correlated with condition



4. Species interactions in fisheries research

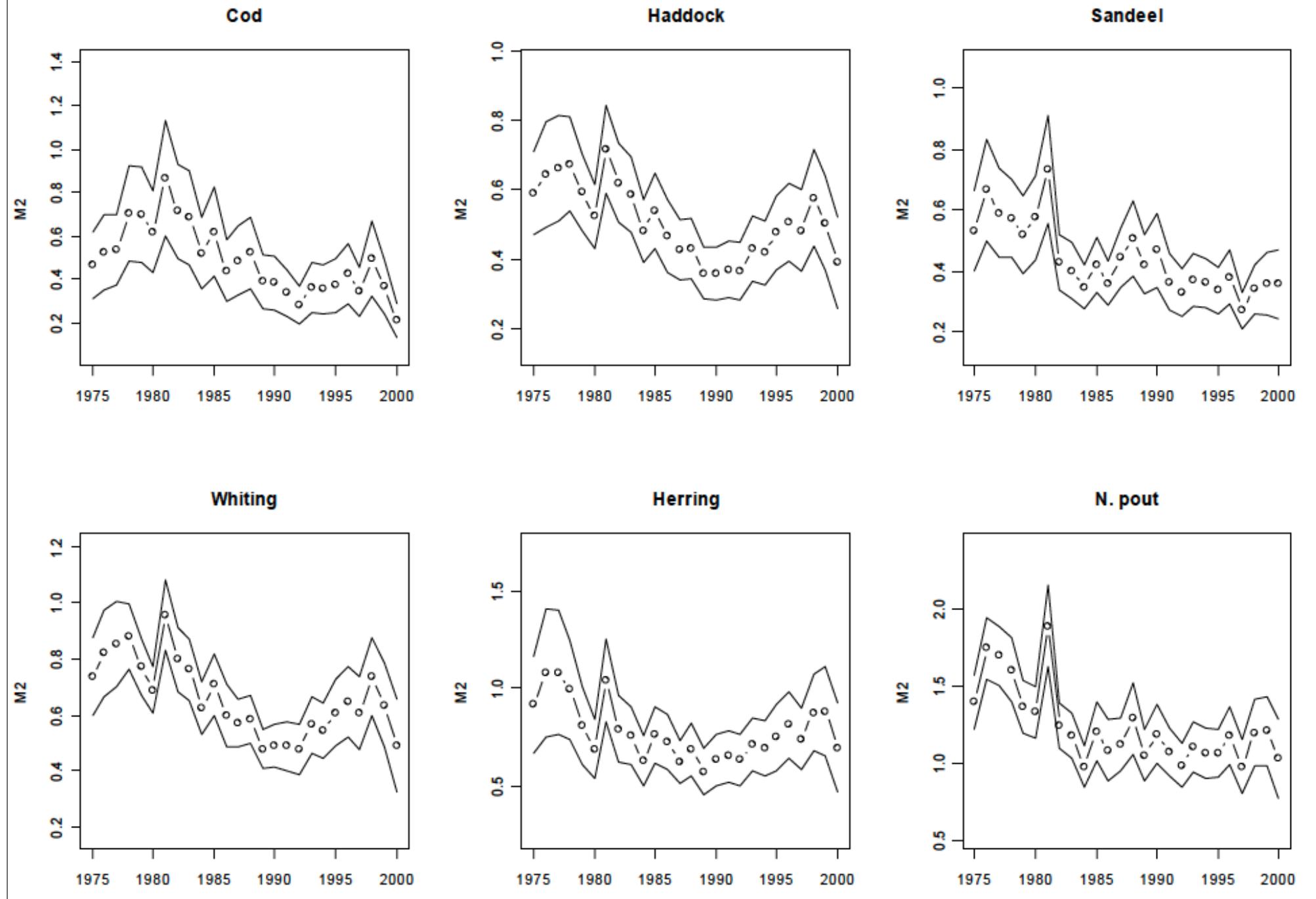
4. Species interactions in fisheries research

- Statistical or Mathematical approaches

In stock assessment

- Mainly in terms of predation (natural mortality), not on growth parameters (competition!)
- SMS model: catch-at-age, survey abundance, stomach data
- (statistical approach)

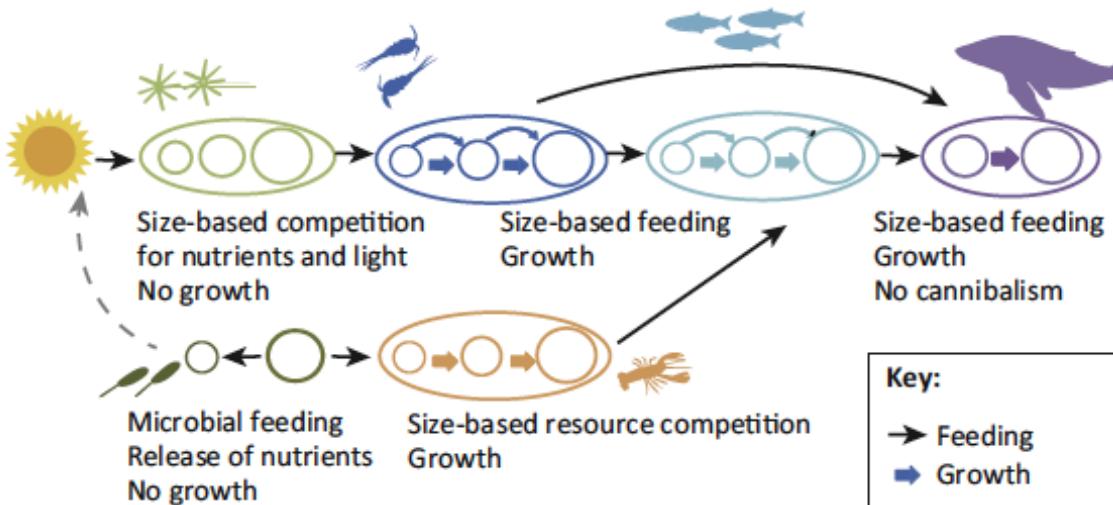
Natural mortality rates



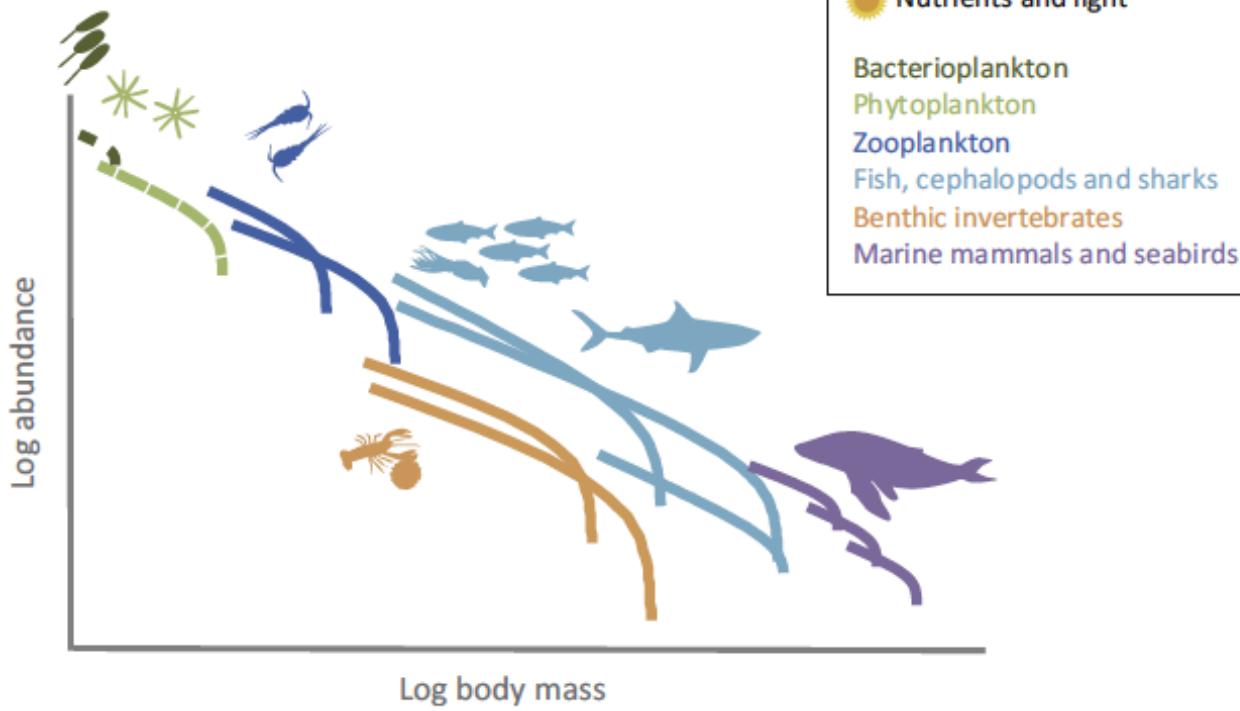
Food web models: strategic advice

- Size-spectrum models

(A)

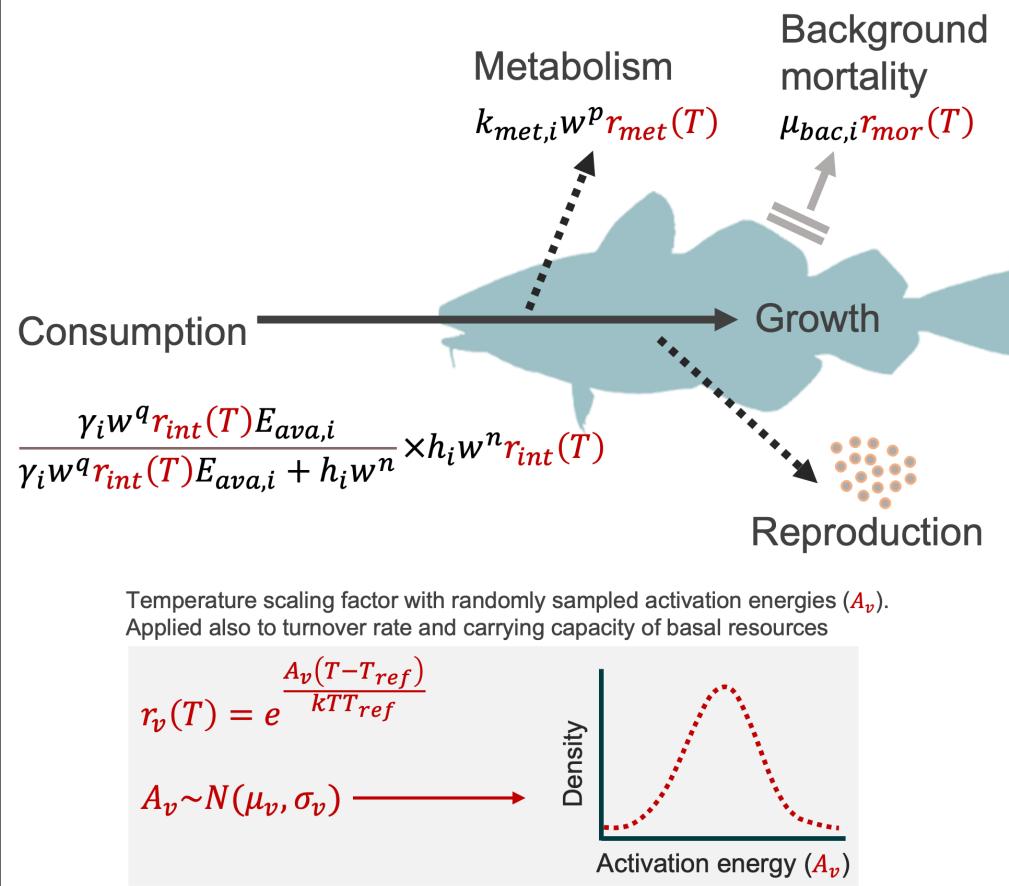


(B)

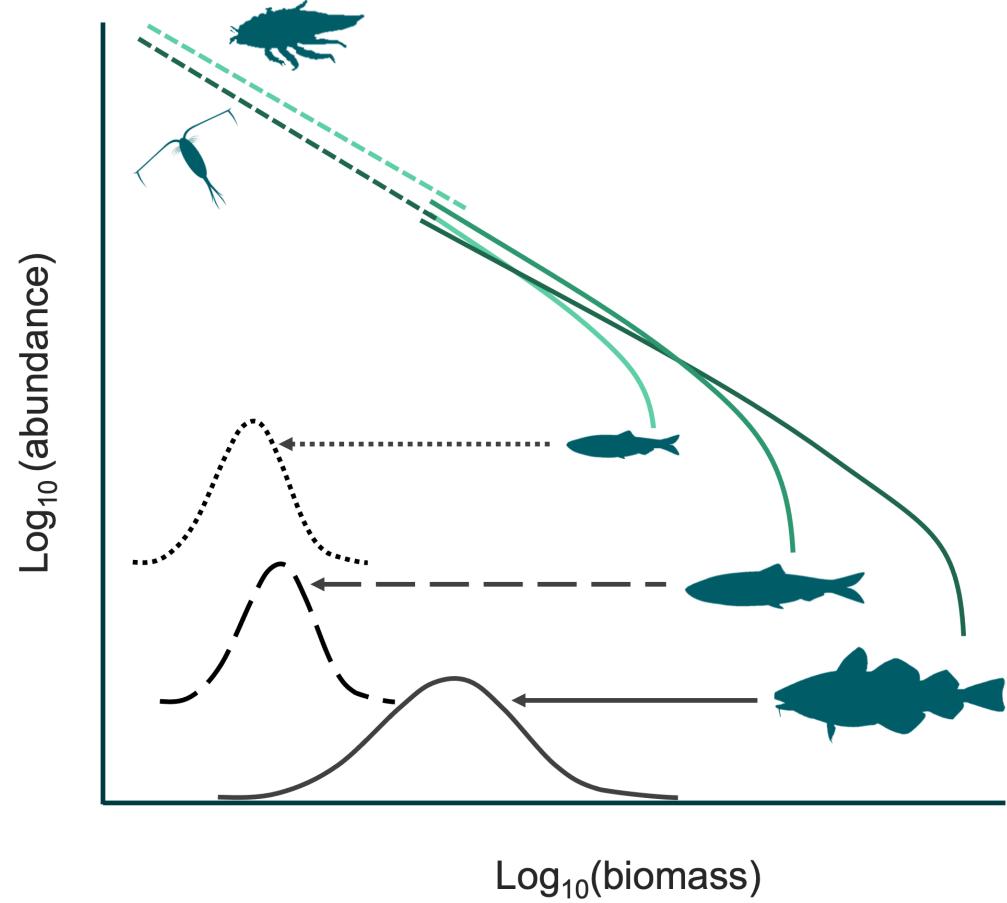


Food web models: strategic advice

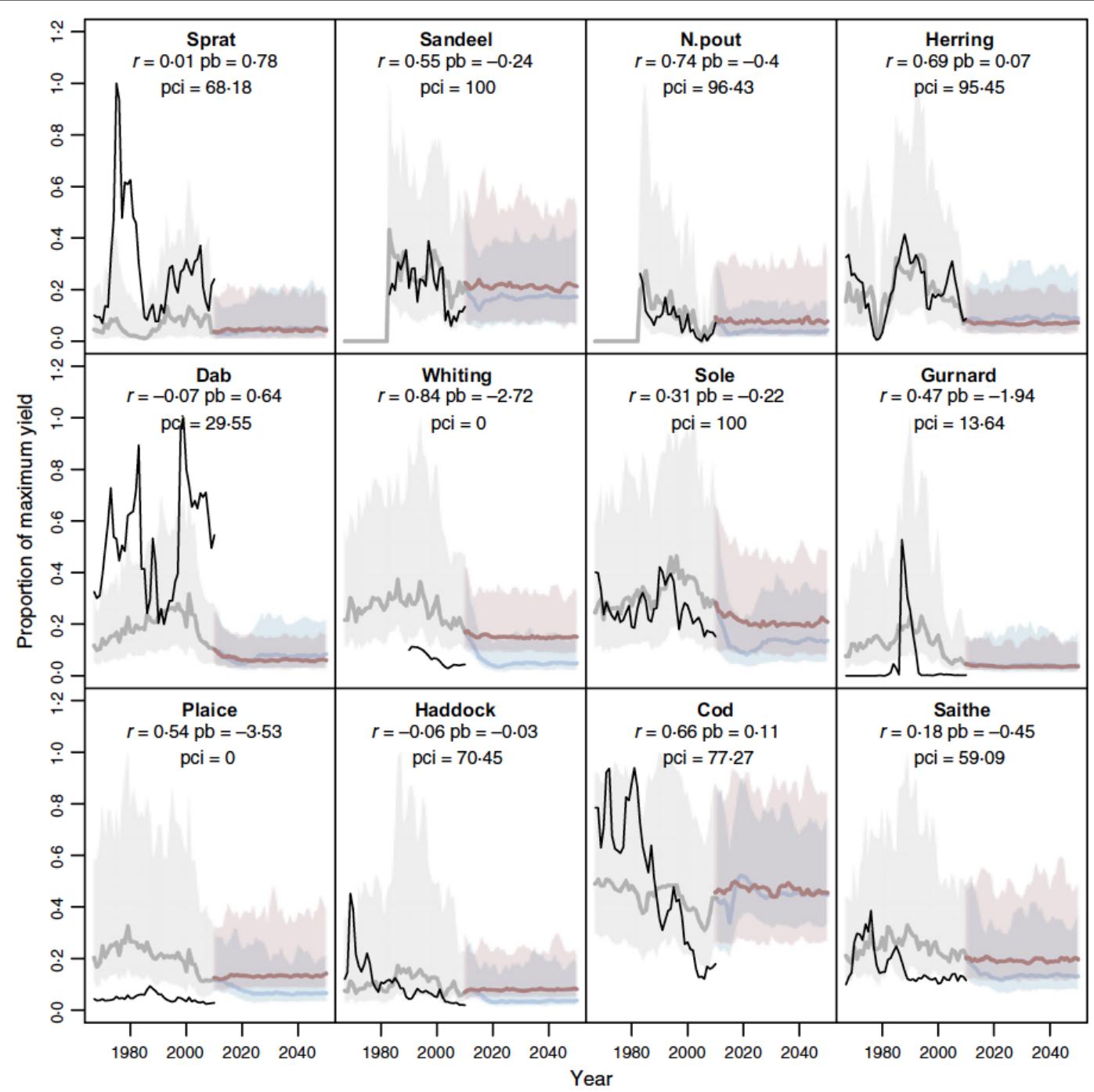
A



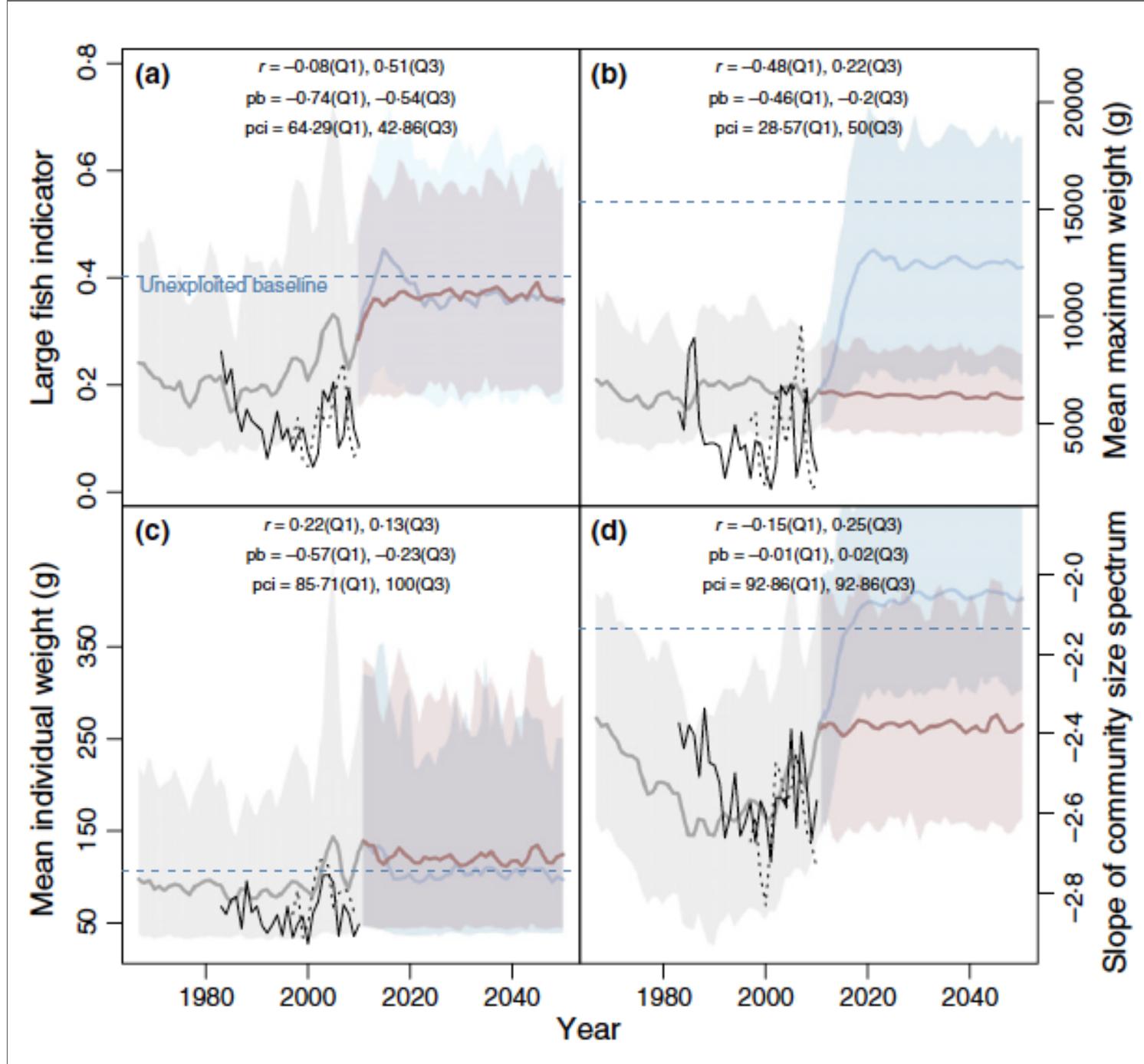
B



Food web models: strategic advice



Food web models: strategic advice



Mathematical or statistical?

WHY NOT BOTH?



makeameme.org

Question time!

