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
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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

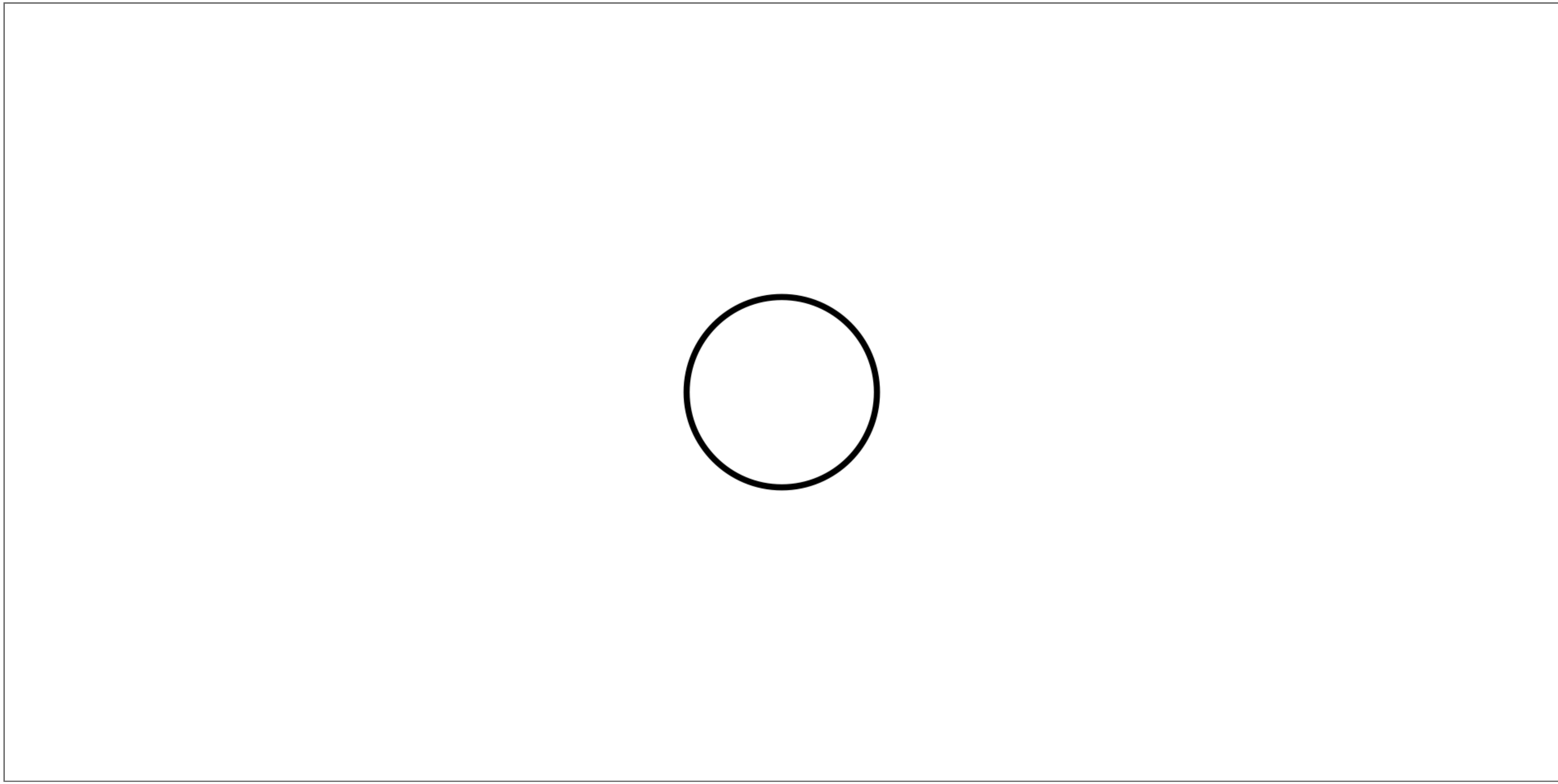
- **Population ecology**: how and why animal populations change in numbers over time and space
- **Community ecology**: how and why species abundance, composition, diversity and structure change over time and space
- **Food web ecology**: energy transfers (feeding links) between species in food webs

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:

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

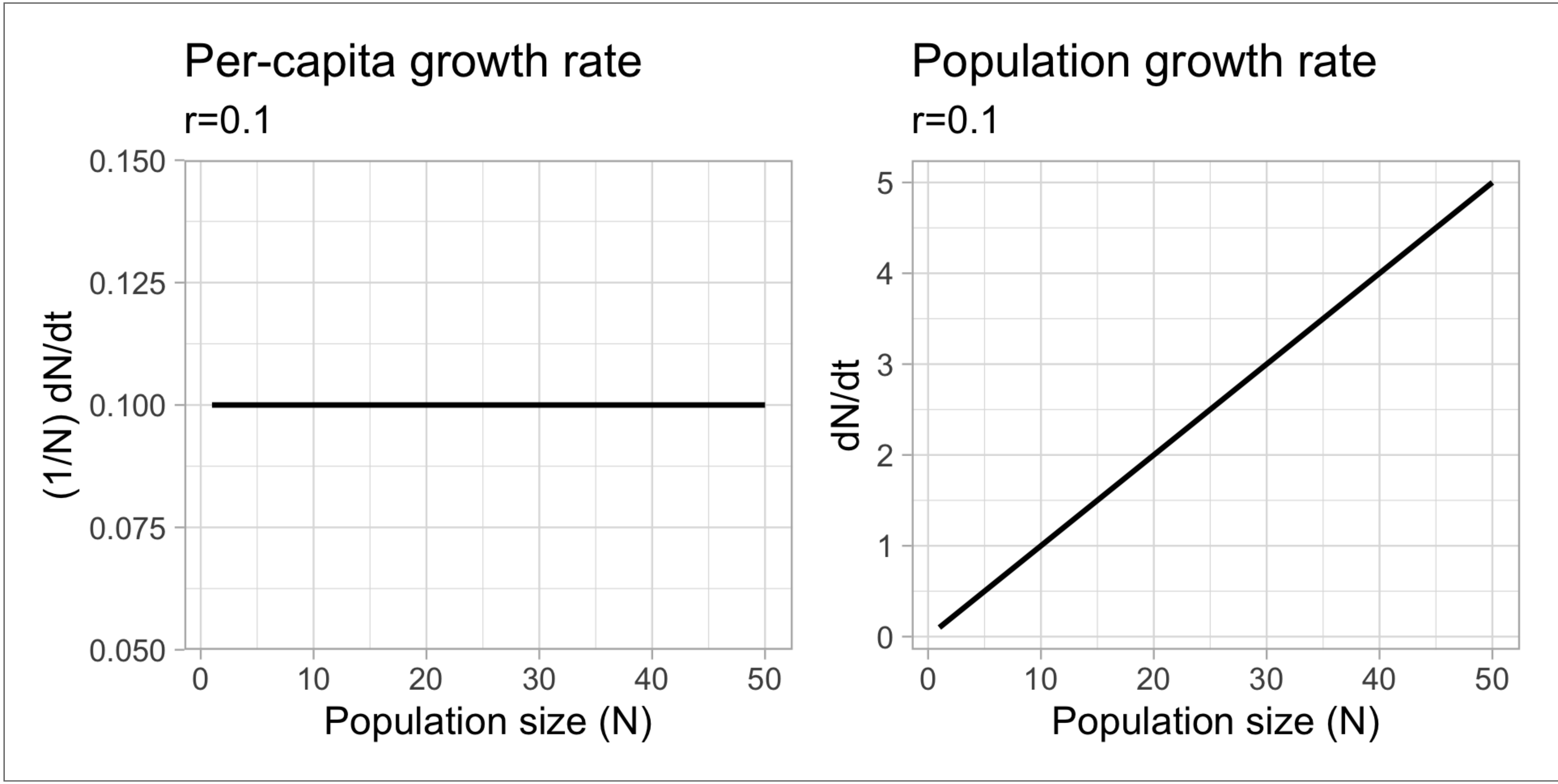
- Exponential growth for positive r and exponential decline for negative r

The simplest population model

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

```r
n <- 1:50
r <- 0.1
d <- data.frame(N = n) %>%
  mutate(dNdt = r*N,
         pc_dNdt = (r*N)/N)
```

The simplest population model



- 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

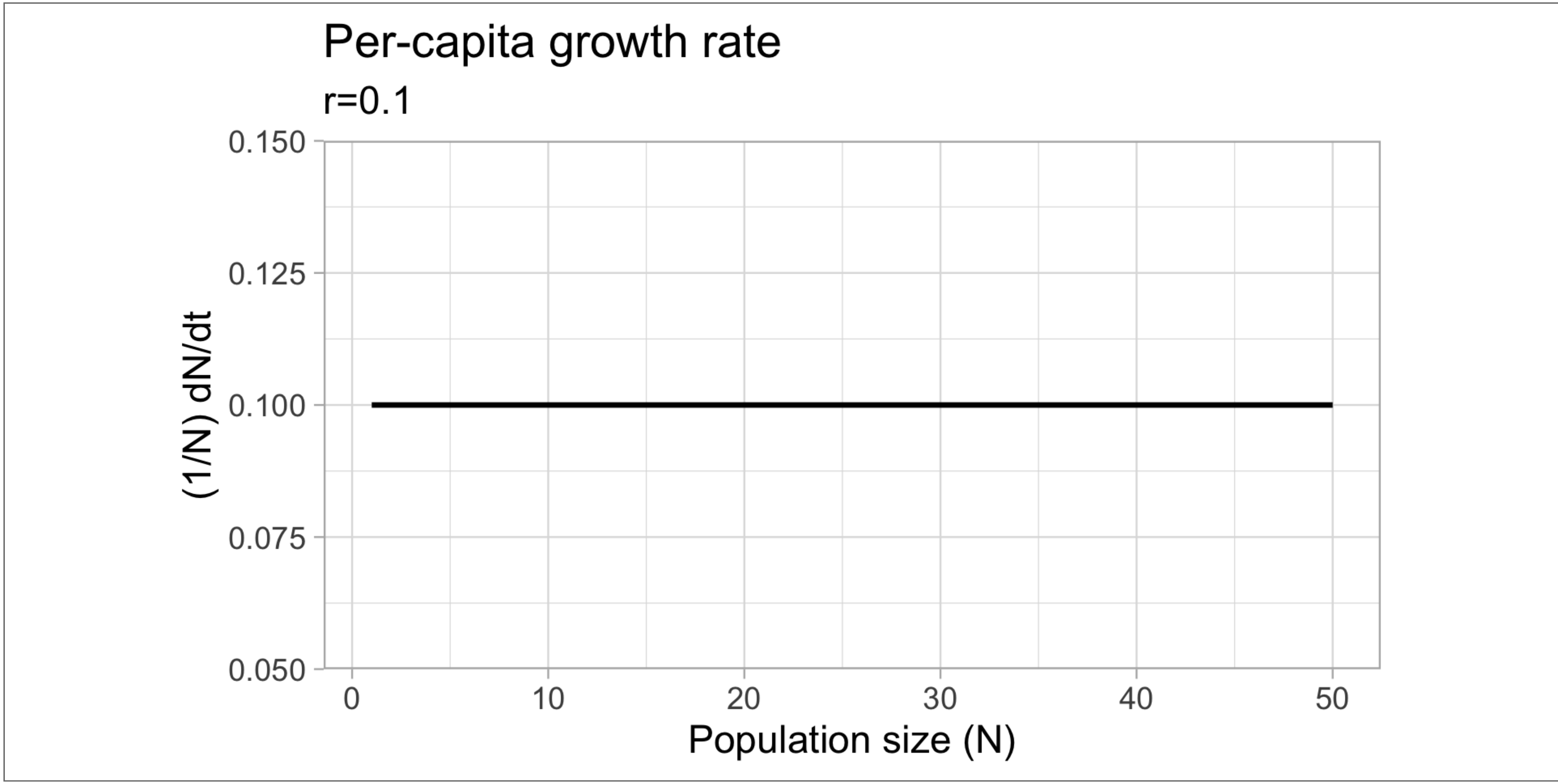
- What's wrong with this model?

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

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


Sr. William Petty Knt.
Fellow of the Royall Society
Obyt 16 Decr. 1687. Anno Ætat: 63.

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!

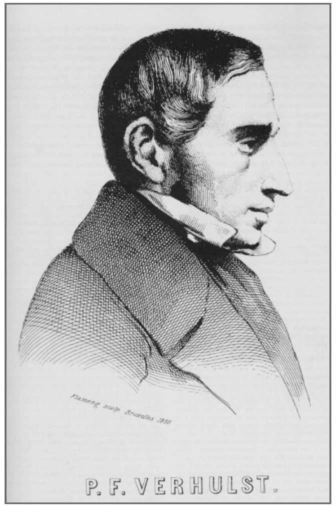
The logistic growth model

Pierre-Francois Verhulst (1845)

- Derived the logistic equation

Raymond Pearl and **Lowell Reed (1920)**

- Re-discovered it: Law of nature?

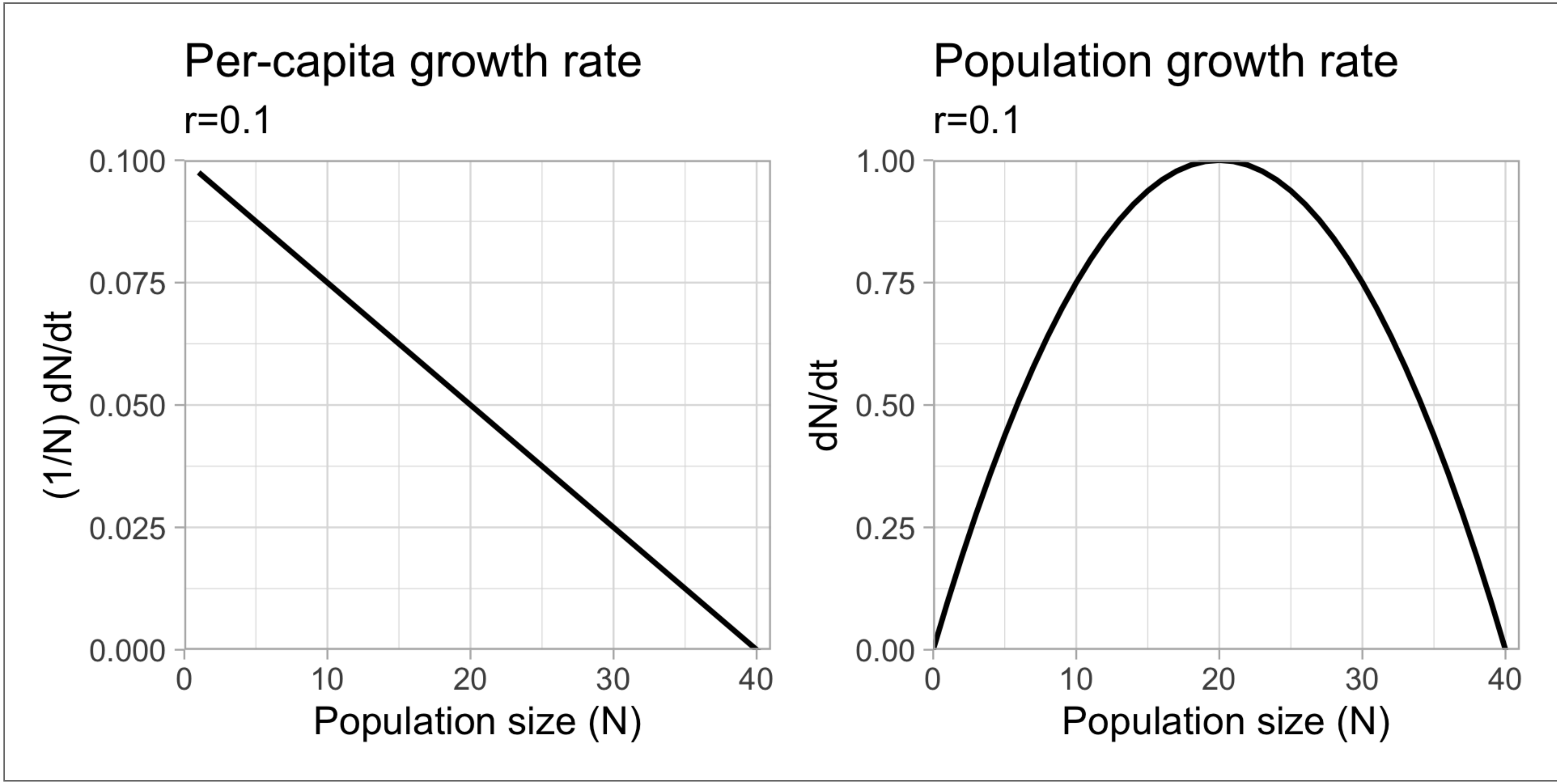


The logistic growth model

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

```
n <- 0:50
K <- 40

d <- data.frame(N = n) %>%
  mutate(dNdt = r*N*(1 - N/K),
         pc_dNdt = dNdt/N)
```

The logistic growth model



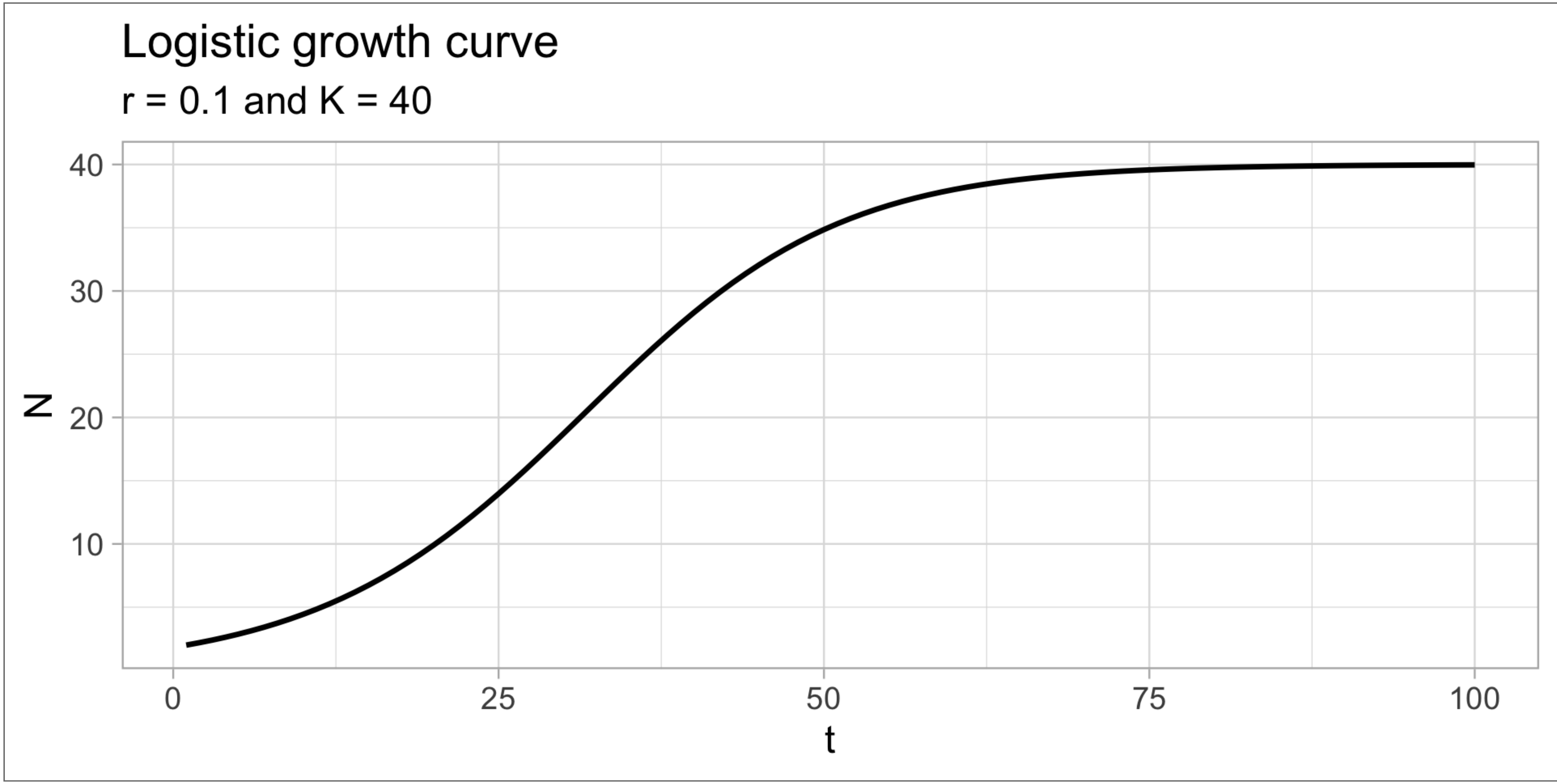
The logistic growth model

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

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

```
r <- 0.1; K <- 40; N_ini <- 2; t <- 100
N <- rep(NA, t)
N[1] <- N_ini

for (i in 2:t) {
N[i] <- r * N[i-1] * (1-(N[i - 1]/K)) + N[i-1]
}
```

The logistic growth model



The logistic growth model

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

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

The logistic growth model

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

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

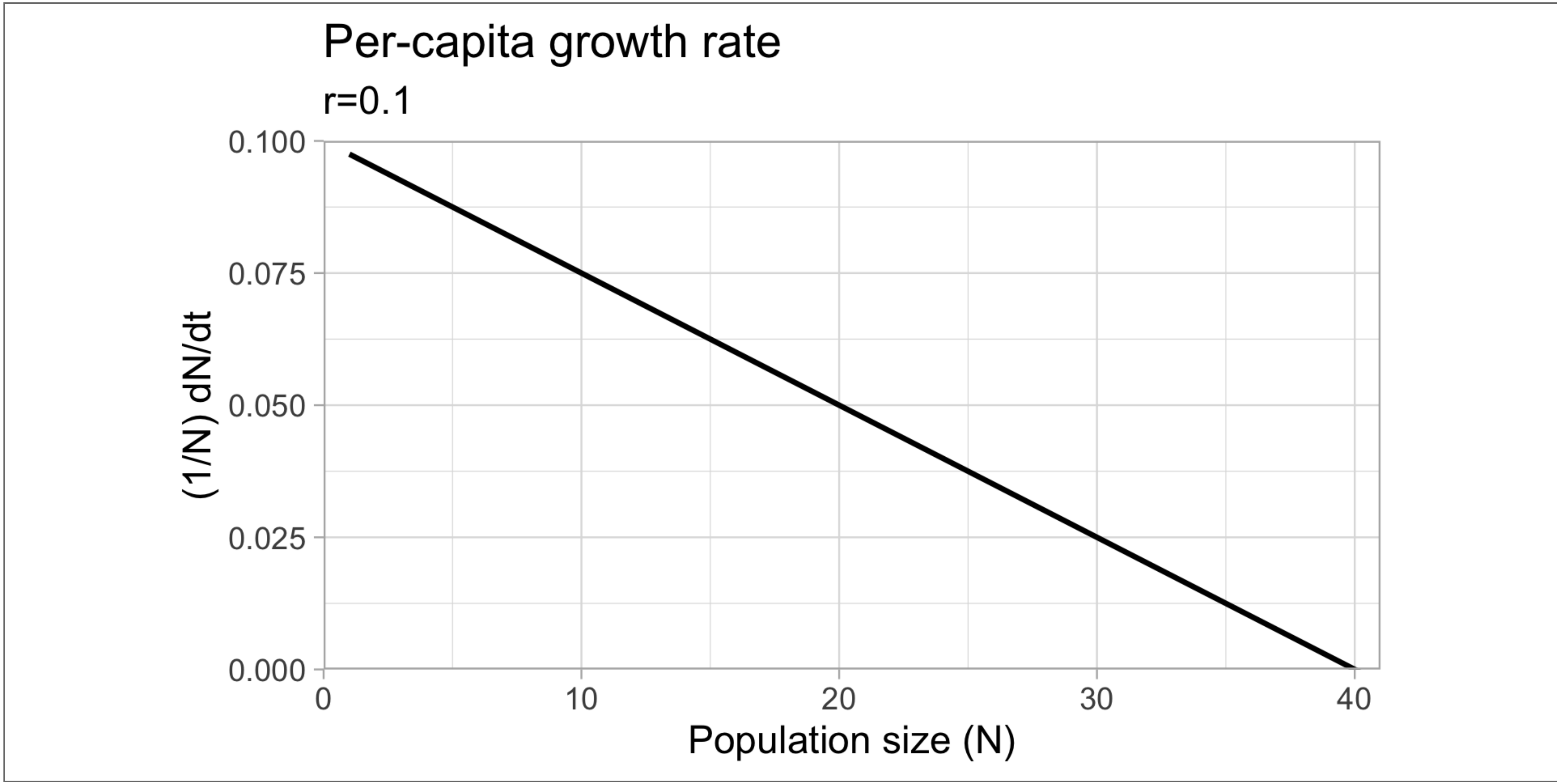
The logistic growth model

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

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

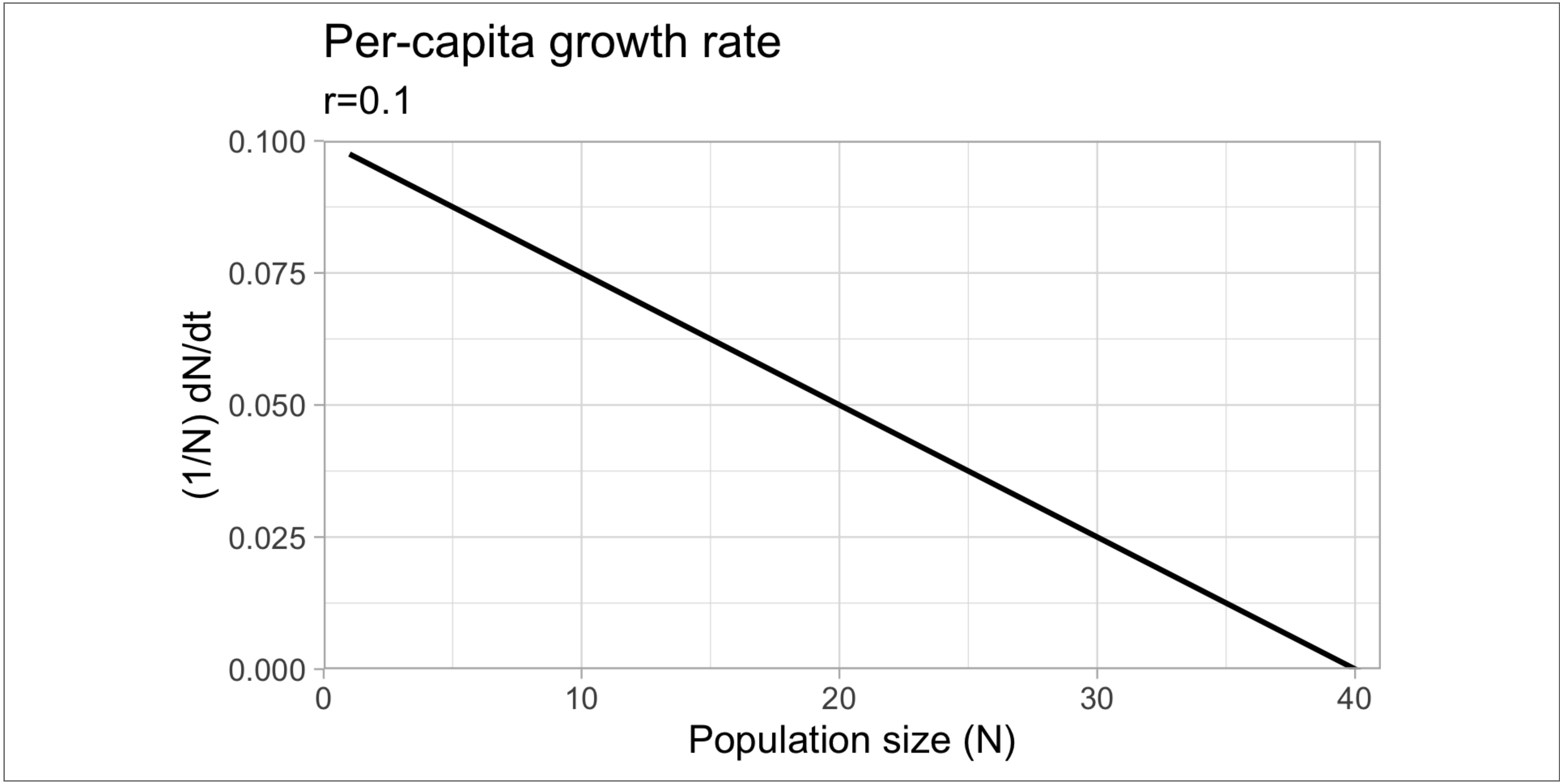
The logistic growth model

- 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 the linear!



2. Species interactions

2. Species interactions

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

Predation

GRANDIBVS EXIGVI SVNT PISCES PISCIBVS ESCA·
Petrus
merica
Siet sone dit hebbe ick zeer langhe ghewéten / dat die groote vissen de cleyne 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

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

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

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

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

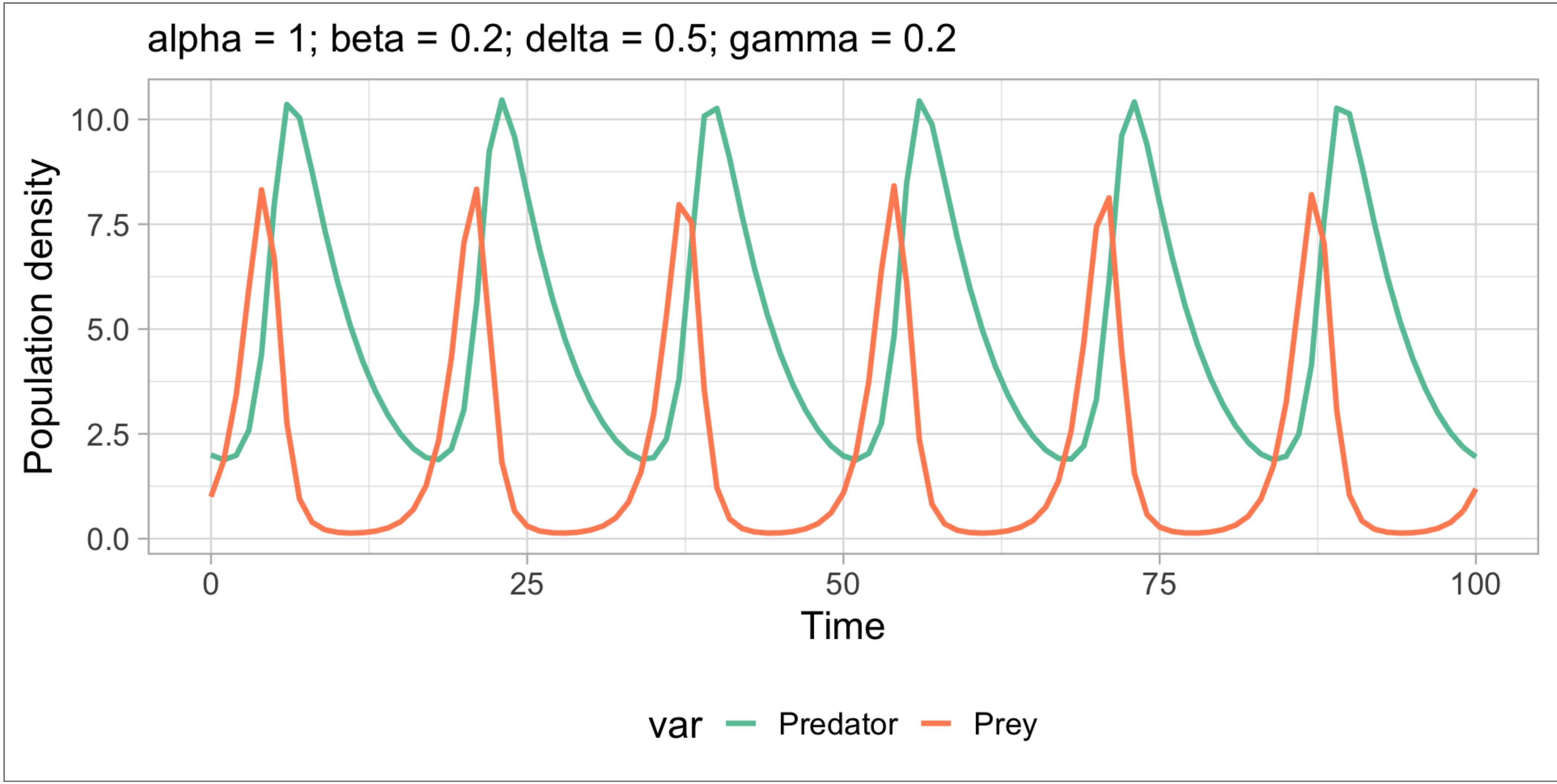
$$P = \frac{\gamma}{\delta\beta}$$

Lotka-Volterra model

```r
# https://strimas.com/post/lotka-volterra/
# parameters
pars <- c(alpha = 1, beta = 0.2, delta = 0.5, gamma = 0.2)
# initial state
init <- c(x = 1, y = 2)
# times
times <- seq(0, 100, by = 1)

deriv <- function(t, state, pars) {
  with(as.list(c(state, pars)), {
    d_x <- alpha * x - beta * x * y
    d_y <- delta * beta * x * y - gamma * y
    return(list(c(x = d_x, y = d_y)))
  })
}

lv_results <- ode(init, times, deriv, pars)
```

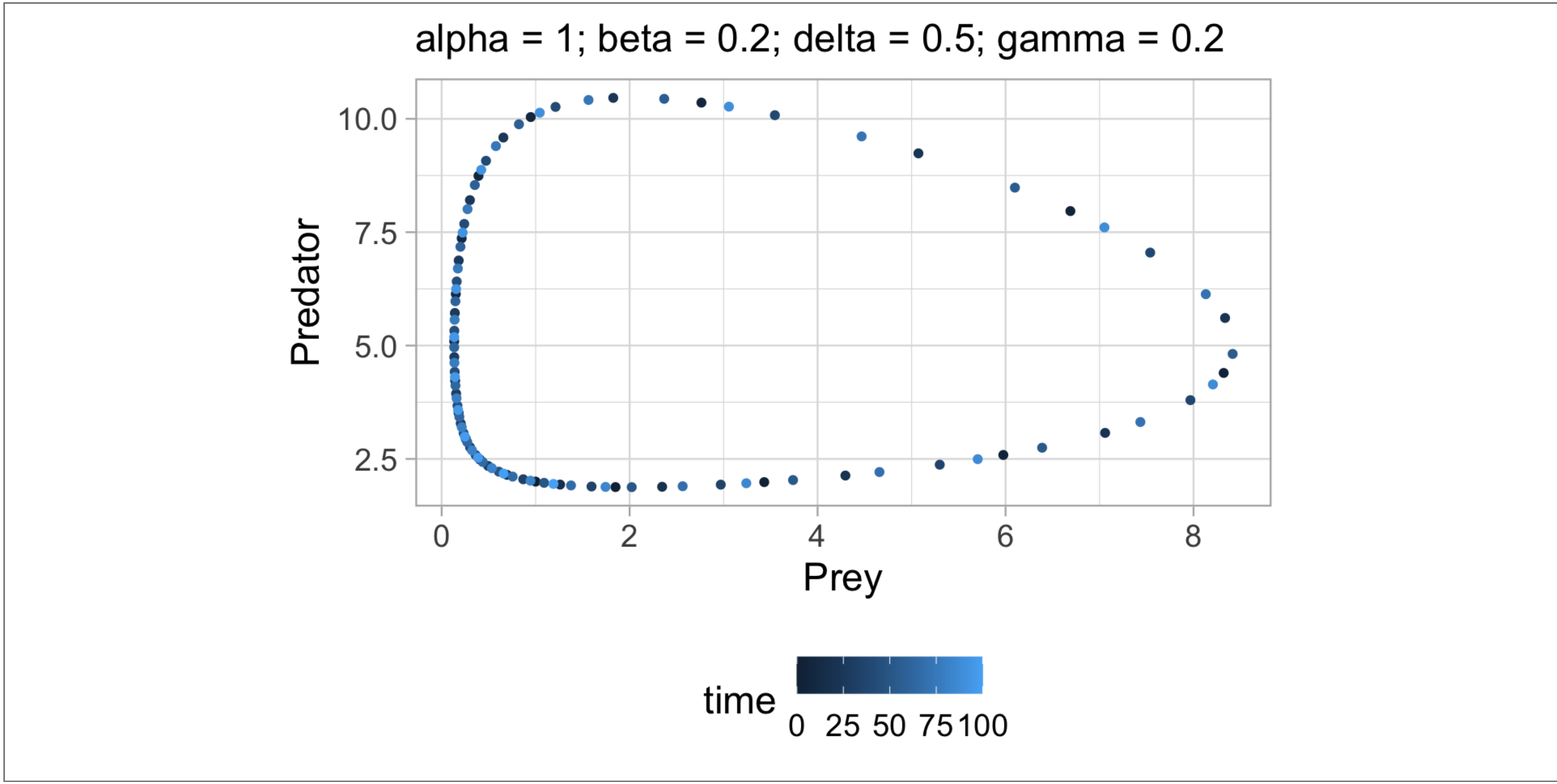
Lotka-Volterra model

- A cyclic model



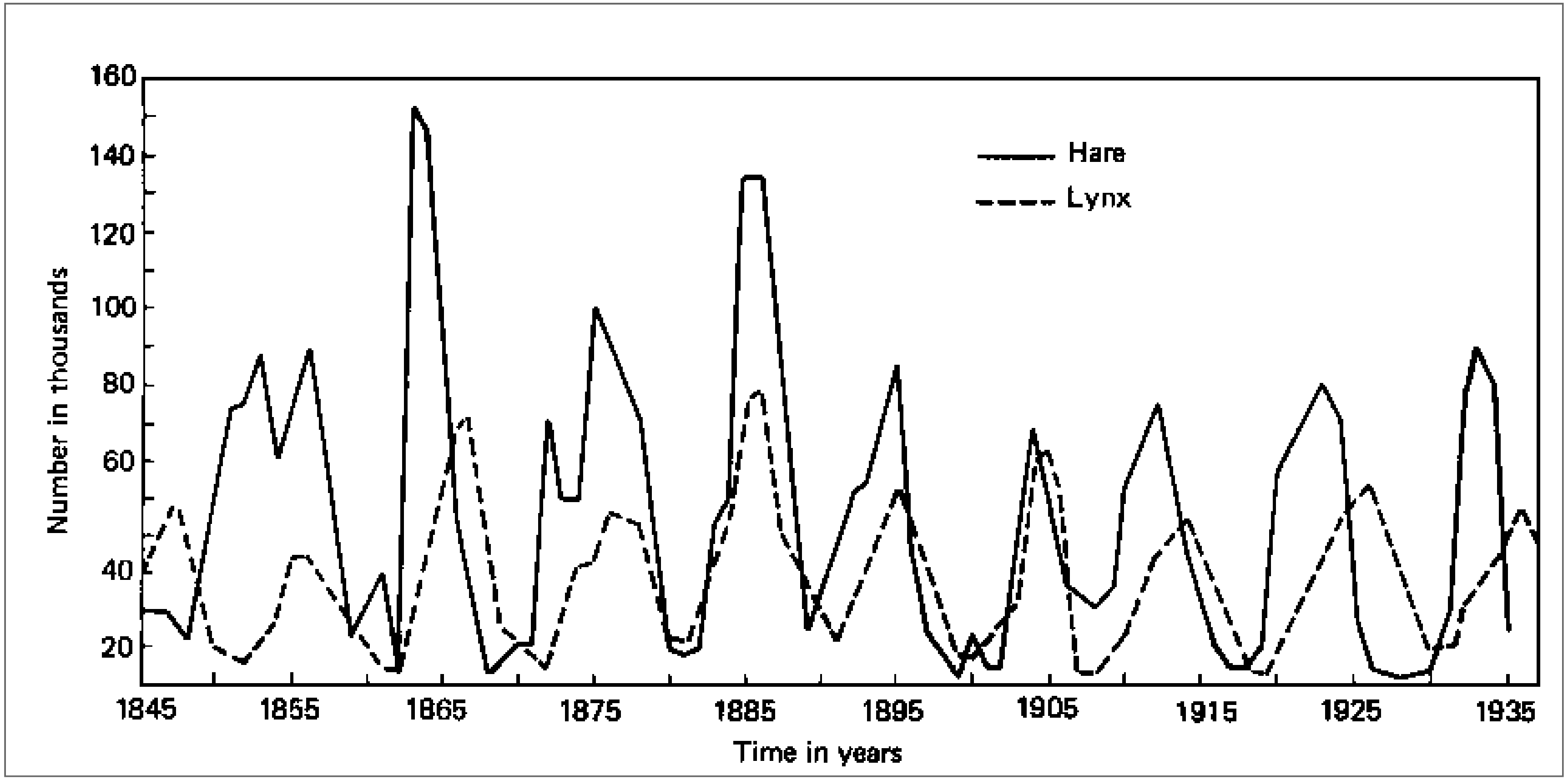
Lotka-Volterra model

- A cyclic model: phase plot



A famous example

- Lynx and hare data compiled by Elton[1]



Other predator-prey models

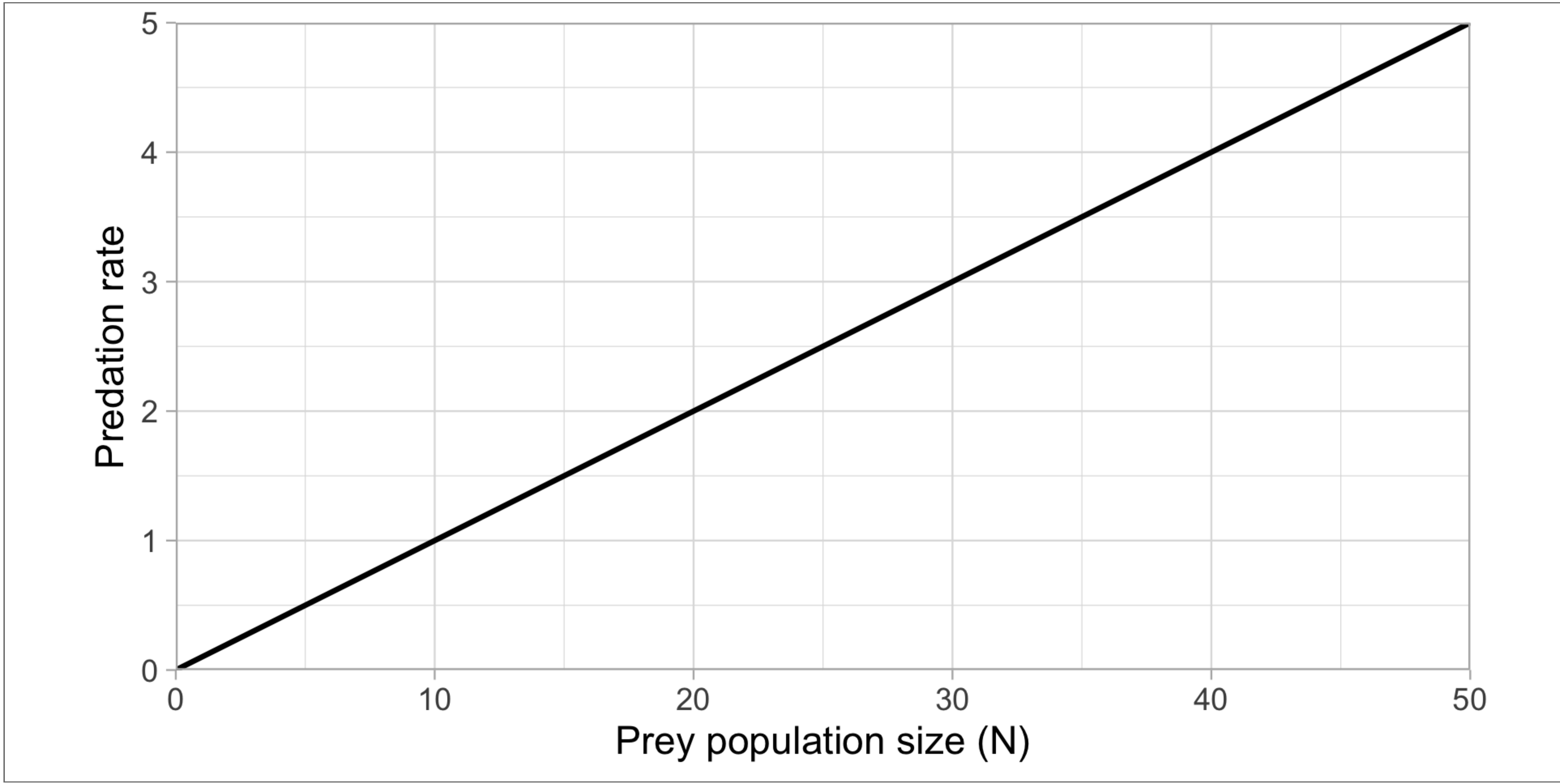
- How can we incorporate more realism into the Lotka-Volterra model?

Functional respose

- "Kill rate", in the LV model given by:

βN

- We call this a Type I functional response

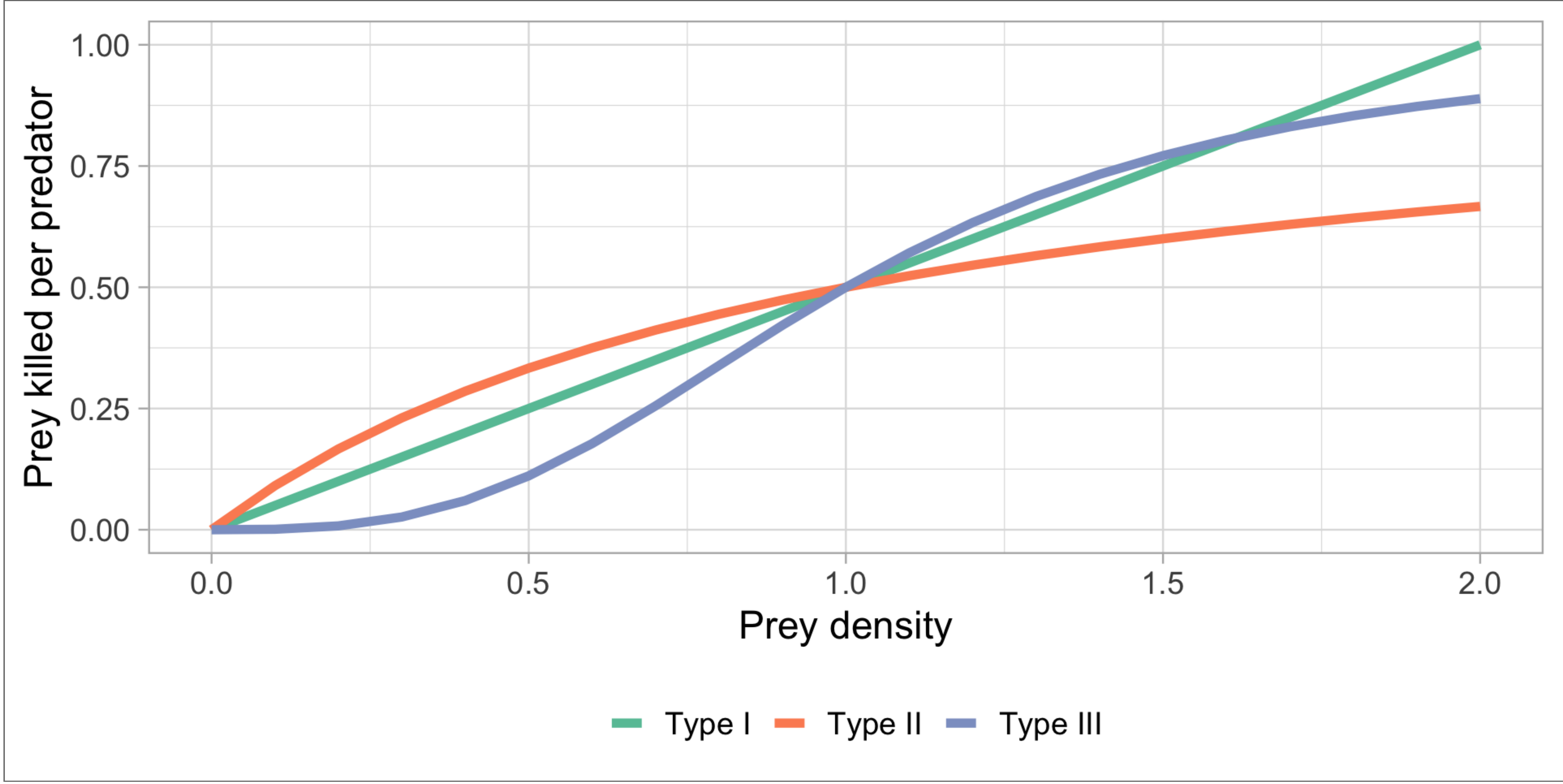


Other functional responses!

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

Other functional responses!

```
n <- seq(0, 2, 0.1); a <- 0.5; b <- 1; c <- 3

d <- data.frame(N = n) %>%
  mutate("Type I" = a*N,
         "Type II" = N / (b + N),
         "Type III" = N^c / (b + N^c)) %>%
  pivot_longer(2:4)
```



Prey killed per predator
1.00
0.75
0.50
0.25
0.00
0.0
0.5
1.0
1.5
2.0
Prey density
Type I
Type II
Type III

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

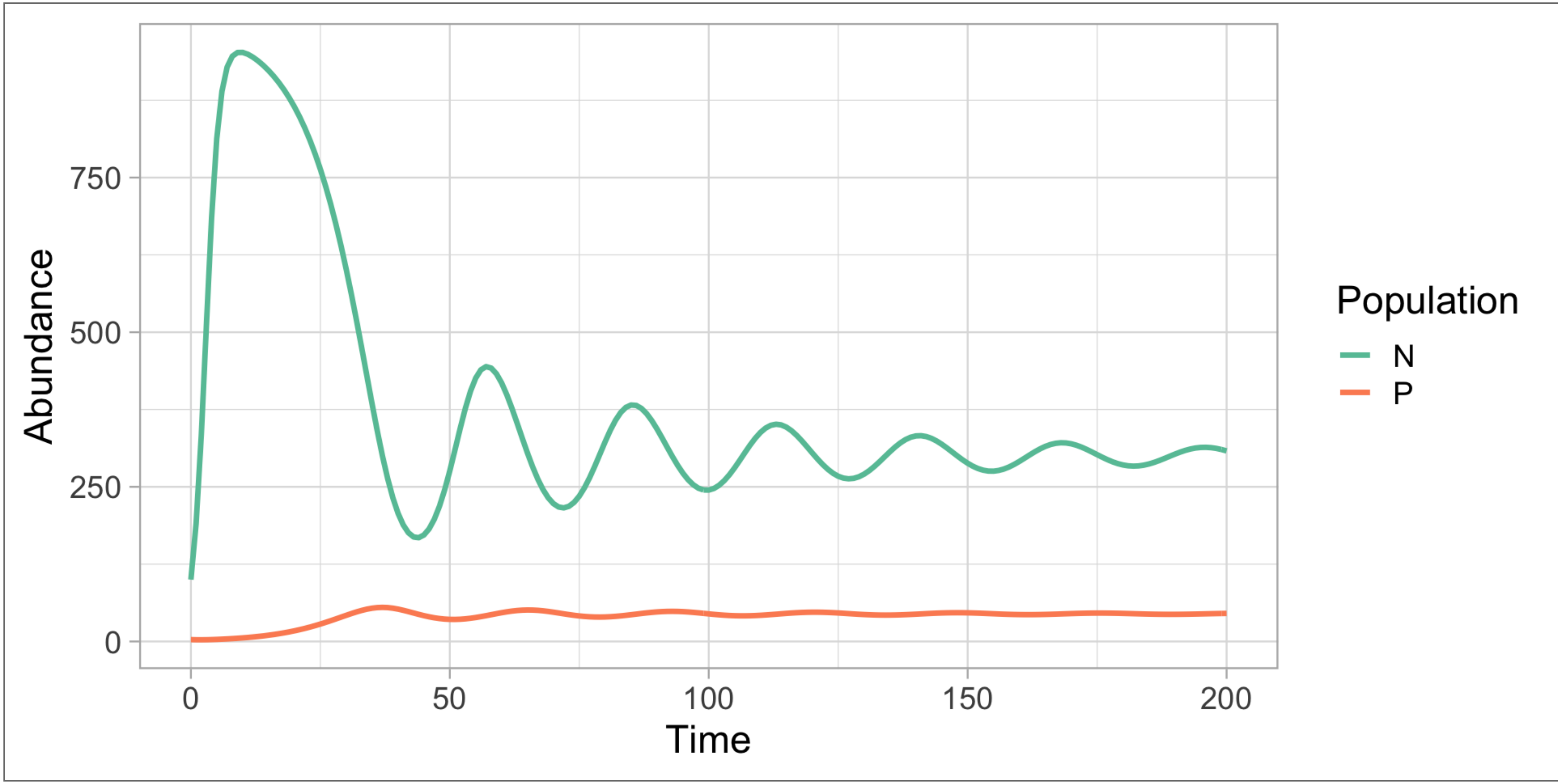
Rosenzweig and MacArthur

$$\frac{dN}{dt} = rN(1 - \alpha N) - \frac{\alpha N}{1 + \alpha h N} P$$
$$\frac{dP}{dt} = e\frac{\alpha N}{1 + \alpha h N} P - mP$$

Rosenzweig and MacArthur

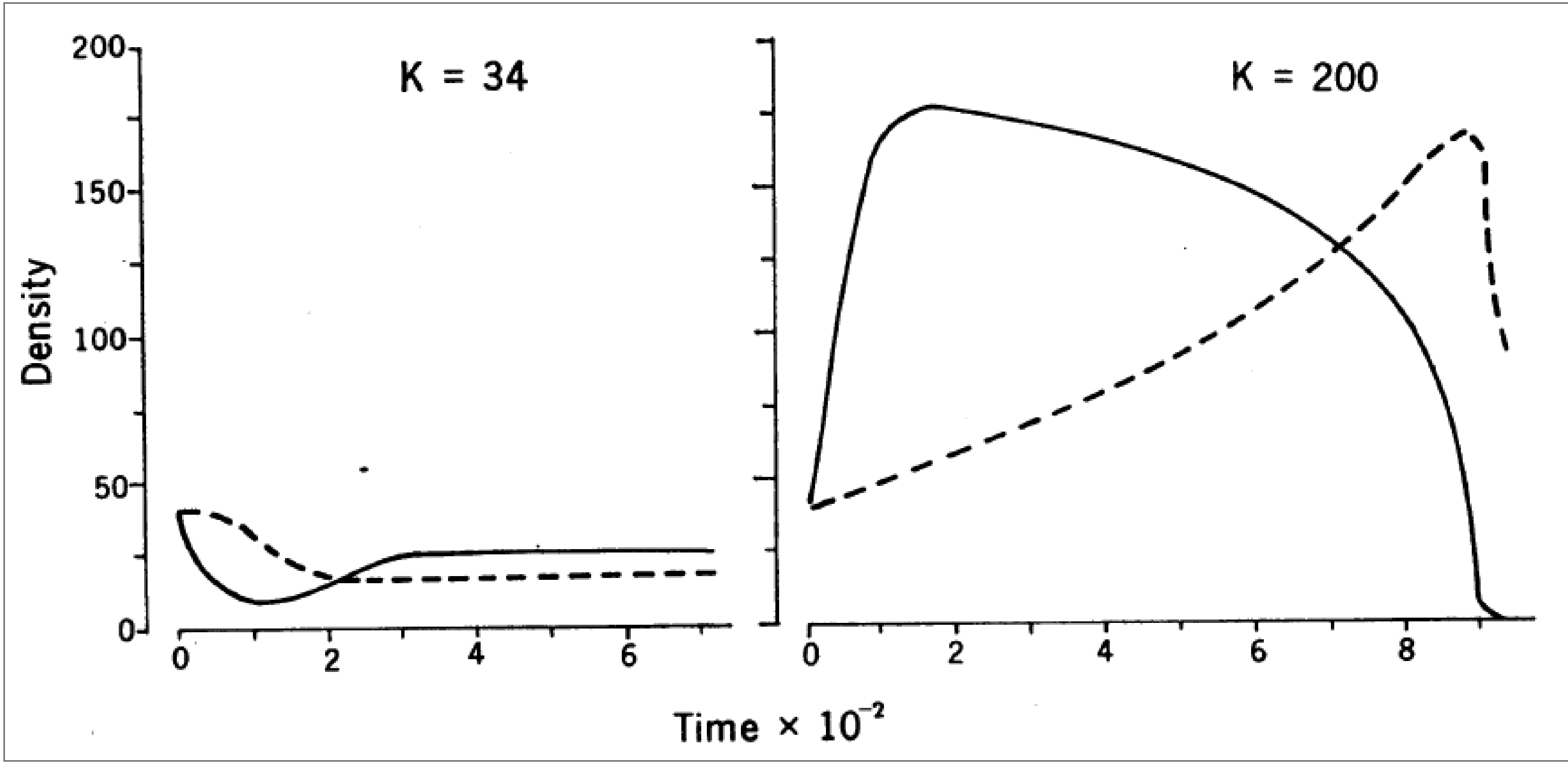
```
# https://hankstevens.github.io/Primer-of-Ecology/cr.html
cr_RM_pred <- function(time, y, p){
  N <- y[1]
  P <- y[2]
  with(as.list(p), {
    Ndot <- r*N*(1 - alpha*N) - a*N*P/(1 + a*h*N) # prey
    Pdot <- e*a*N*P/(1 + a*h*N) - m*P # predator
    return(list(c(Ndot, Pdot)))
  })
}

t <- 0:200
y0 <- c(N = 100, P = 3)

p <- list(r = 0.8, alpha = 0.001, a = 0.02, e = 0.04, m = .15, h =

outdf <- as.data.frame( ode(y0, t, cr_RM_pred,  p) ) %>%
  pivot_longer(-time, names_to = "Population", values_to = "Abundan
```

Rosenzweig and MacArthur



Rosenzweig and MacArthur

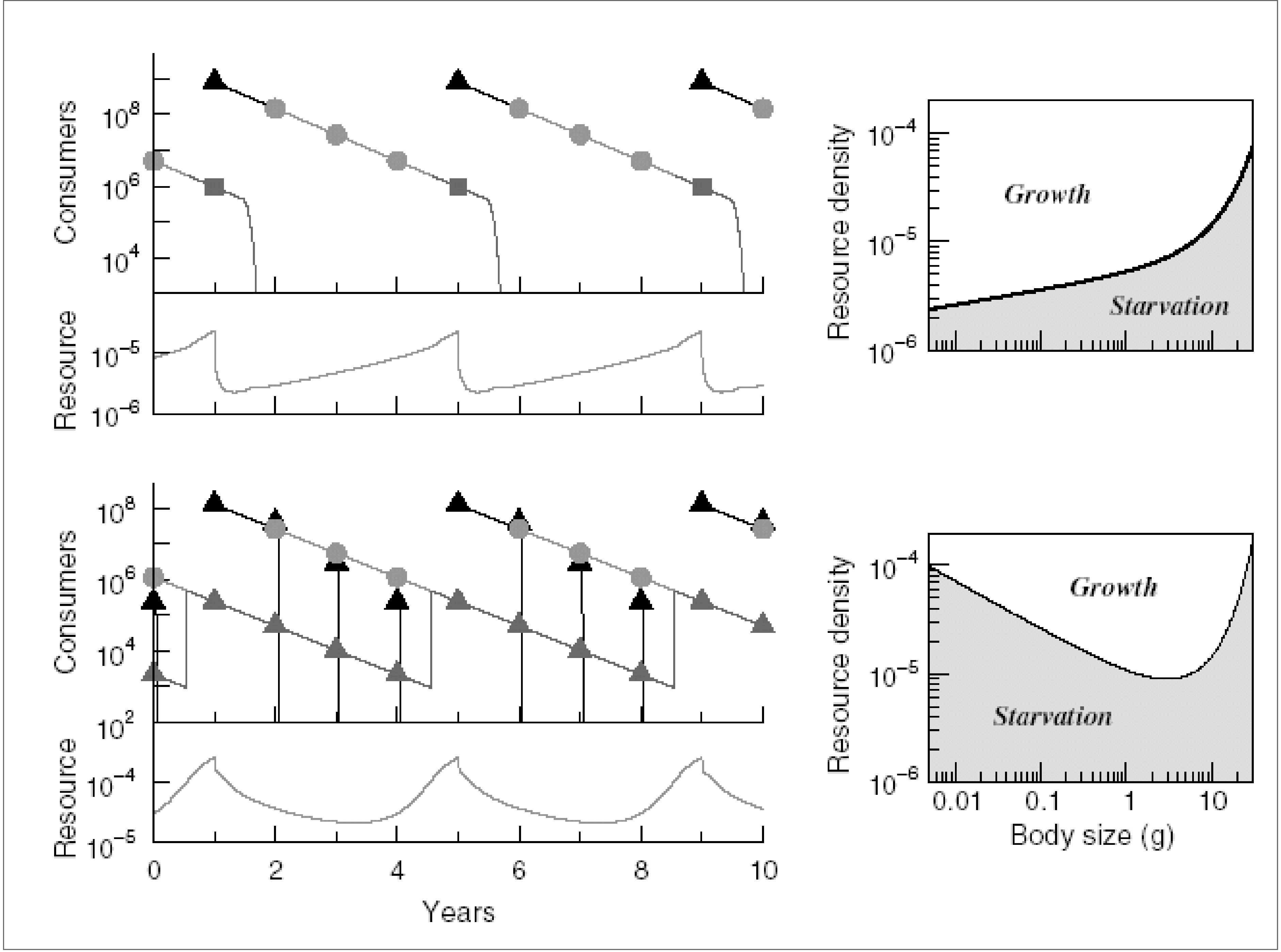
- Paradox of enrichment!



Other types of cycles...

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

Cohort-cycles



Consumers
Resource
Resource density
Growth
Starvation
Years
Body size (g)

Competition

- Interference
- Scramble / Exploitation

L-V competition model

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

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

L-V competition model

- Find the zero-growth isocline for species N_1

$$\frac{dN_1}{dt} = r_1 N_1 (\frac{K_1 - N_1 - \alpha_{12} N_2}{K_1})$$
$$0 = r_1 N_1 (\frac{K_1 - N_1 - \alpha_{12} N_2}{K_1})$$
$$0 = \frac{K_1 - N_1 - \alpha_{12} N_2}{K_1}$$
$$N_1 = K_1 - \alpha_{12} N_2$$

L-V competition model

- Find the zero-growth isocline for species N_2

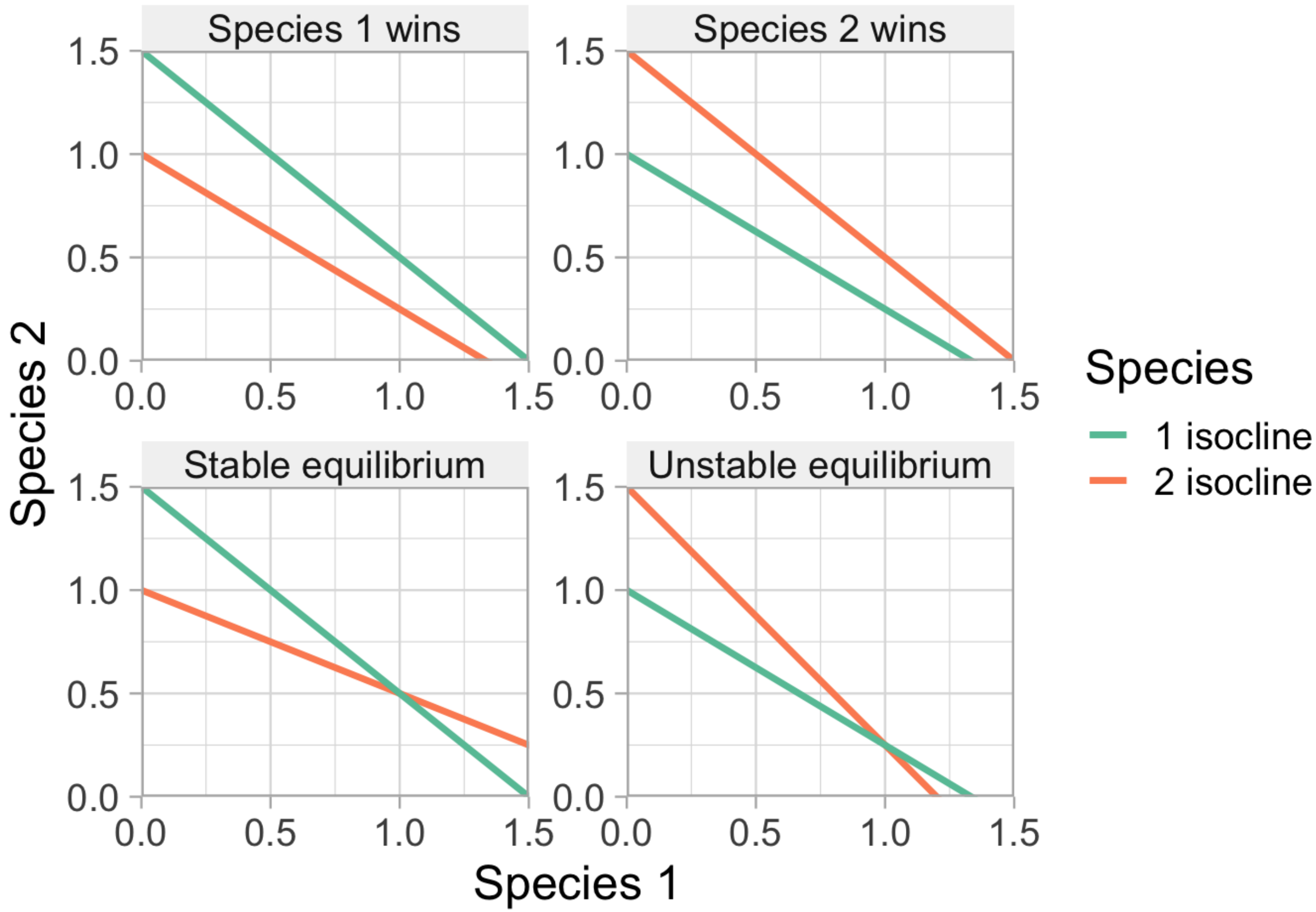
$$\frac{dN_2}{dt} = r_2 N_1 (\frac{K_2 - N_2 - \alpha_{21} N_1}{K_2})$$

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

L-V competition model

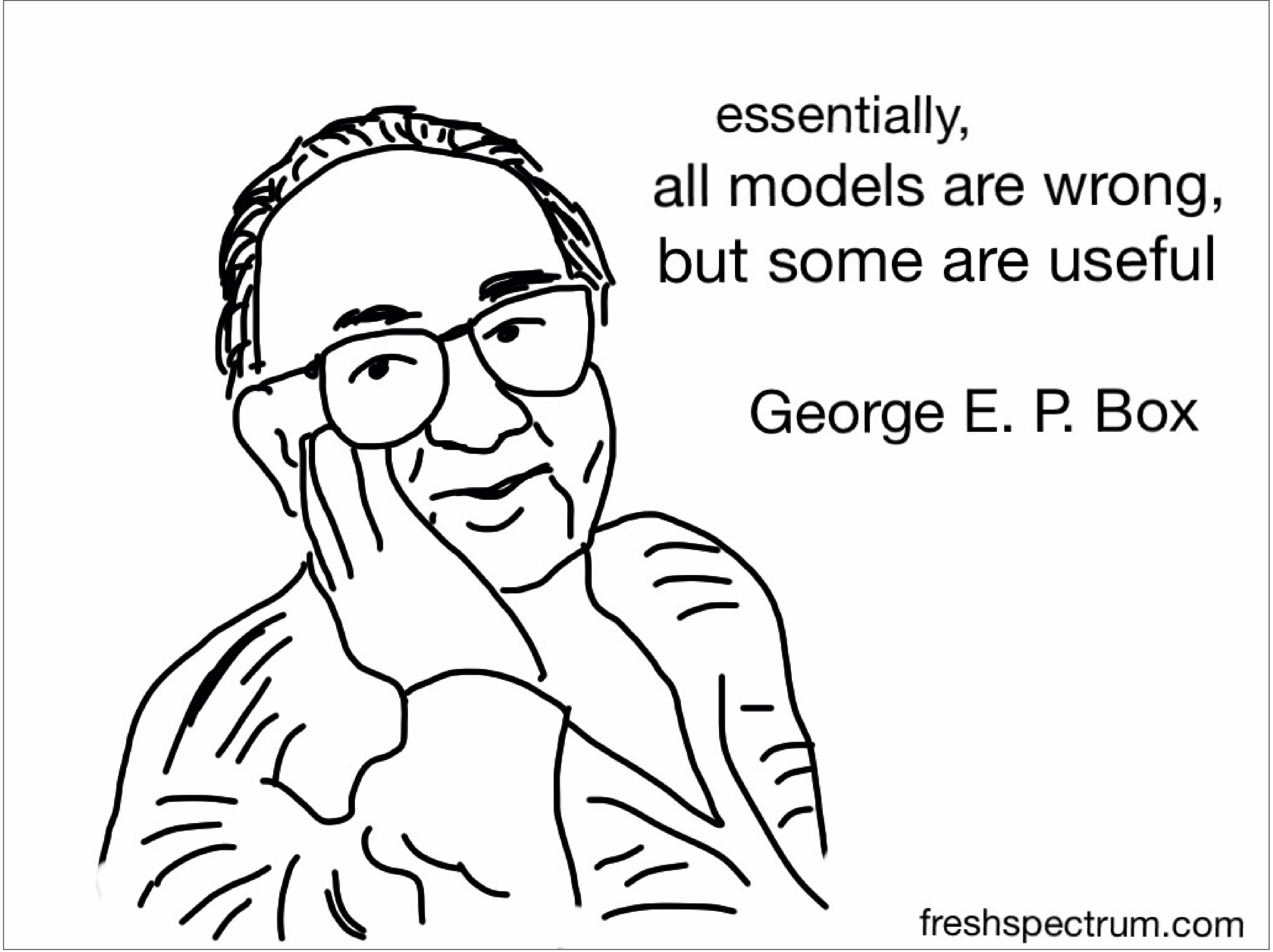
```r
N <- 0:20

# Species 1 wins
a_21 <- 0.75
a_12 <- 1
K_1 <- 1.5
K_2 <- 1

d1 <- data.frame(N = N) %>%
  mutate(N2_iso = K_2 - a_21*N,
         N1_iso = K_1 - a_12*N,
         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

1. Elton 1927

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

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

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

Food web models: strategic advice

Food web models: strategic advice

Food web models: strategic advice

Mathematical or statistical?

::: {.notes} Many of these models are based upon statistical techniques and are good at assessing the current state and making short-term predictions; however, as they do not model interactions between stocks, they lack predictive power on longer timescales. Additionally, there are size-based multi-species models that represent key biological processes and consider interactions between stocks such as predation and competition for resources. Due to the complexity of these models, they are difficult to fit to data, and so many size-based multi-species models depend upon single-species models where they exist, or ad hoc assumptions when they do not, for parameters such as annual fishing mortality. :::

Question time!

Error