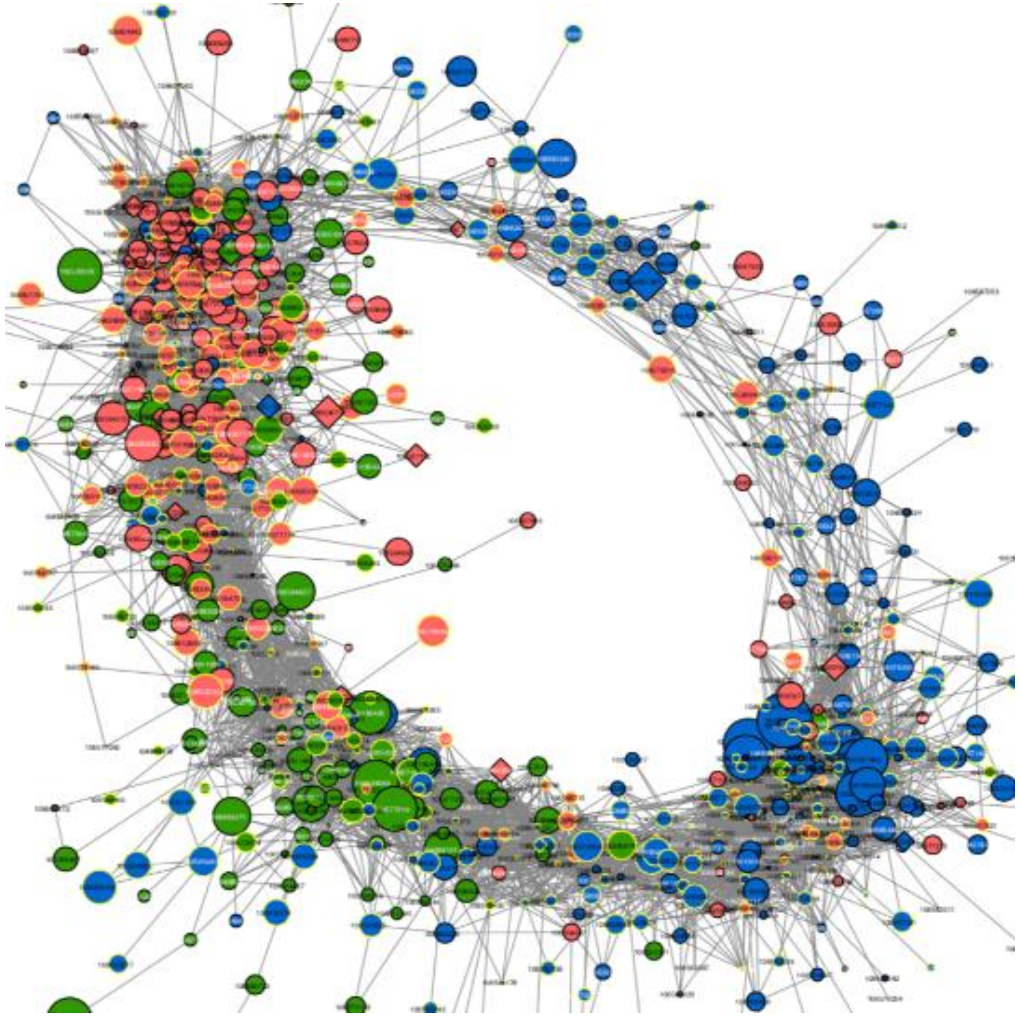
Path analysis & SEMs in ecology (WILD 595)



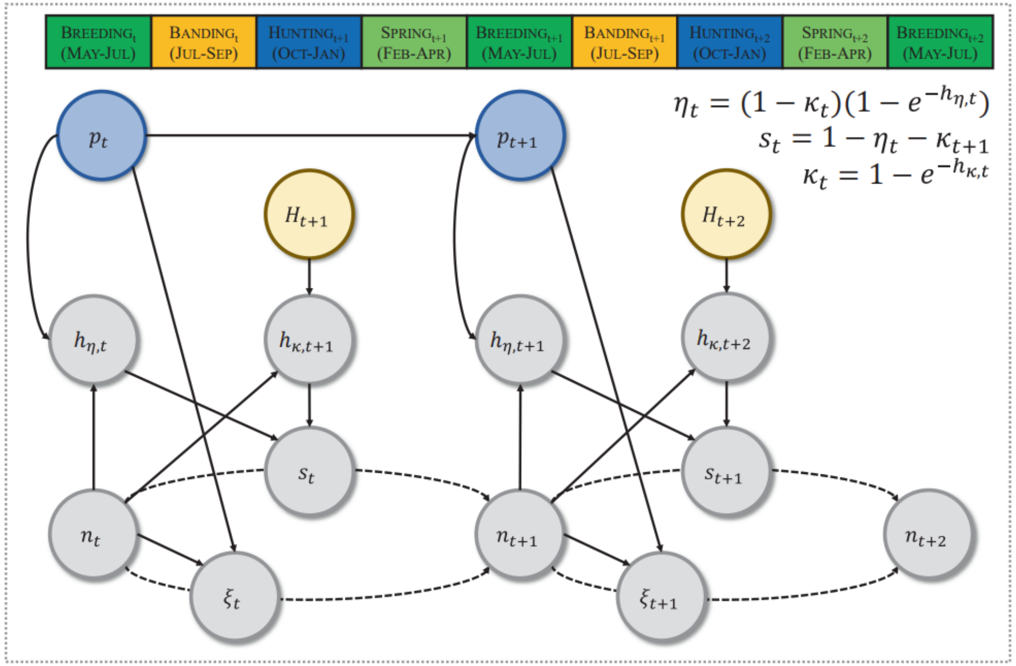
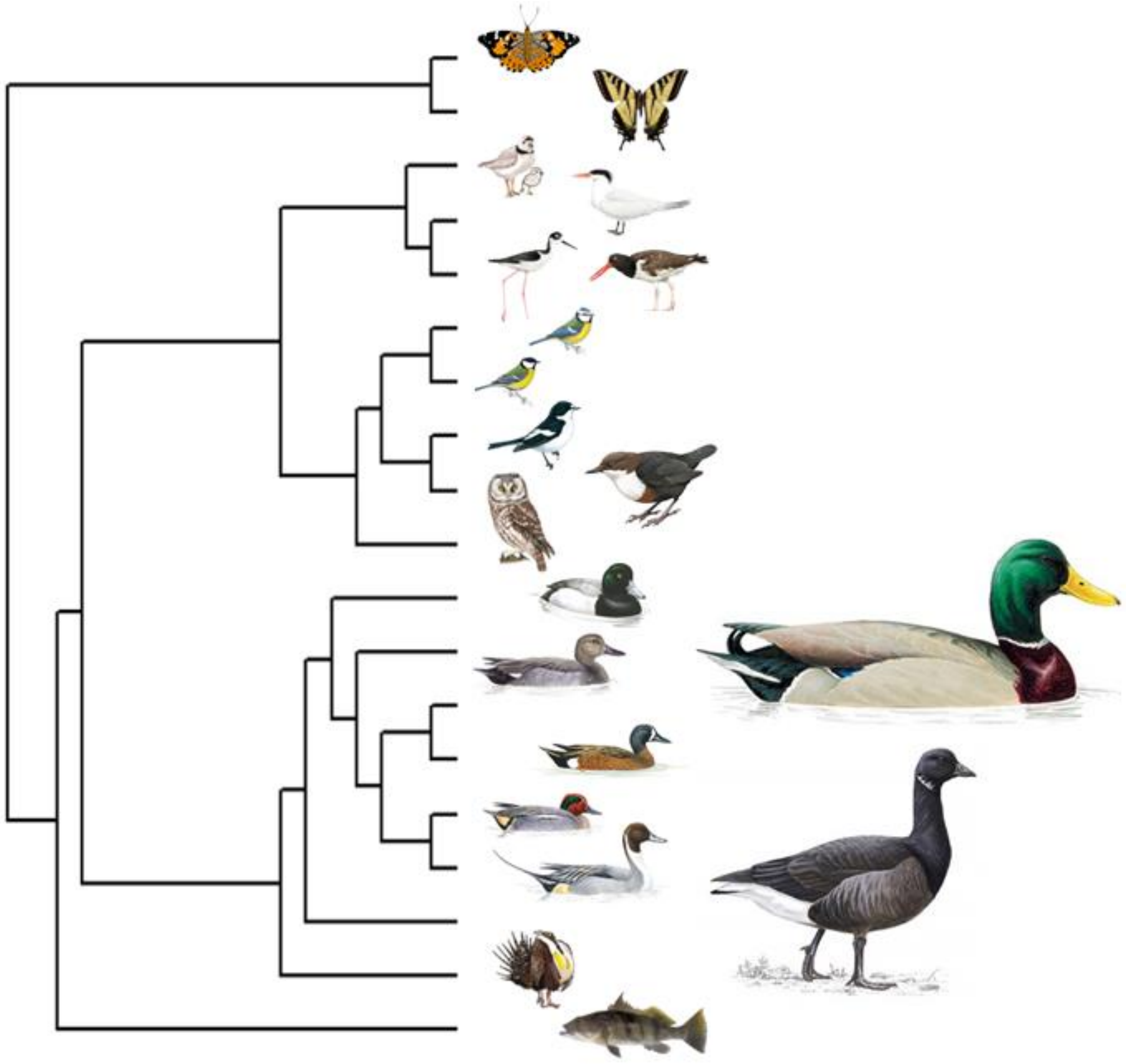


FIGURE 2 A directed acyclic graph demonstrating the relationships among abundance (**n**), ponds (**p**; blue), fecundity (ξ), hunting mortality hazard rate (h_κ), natural mortality hazard rate (h_η), survival (**s**) and the number of duck hunters (**H**; brown) for blue-winged teal breeding in the North American Prairie Pothole Region across the annual cycle (1973–3016). Solid arrows represent estimated directional relationships, and dashed arrows represent processes leading to changes in population abundance.

Hi!



Thomas Riecke
Assistant Professor
James K. Ringelman Chair in Waterfowl Conservation

thomas.riecke@umontana.edu

Who are you?

Accommodations

- **Let me know** (*as much as you need to/feel comfortable with*)

Other professional obligations

- **Let me know** (*as much as you need to/feel comfortable with*)

Anything else?

- **Let me know** (*as much as you need to/feel comfortable with*)

Grades

- **You'll almost certainly receive an excellent grade unless:**
  - ***You don't do a project***
  - ~~*You disrupt the teaching/learning process*~~
  - ~~*You don't come to class*~~

Project

- Perform and write up an analysis.
  - i.e., ‘**finish or at least draft a methods and results section for a thesis or dissertation chapter**.’

- **If you’re early in the program or don’t have any data yet**, I can help with simulating data that will be similar to future data, we can use an existing dataset that’s similar, or you can simply work on writing an excellent methods section for a proposal?

So why are we doing this?

Structural equation models are the best tool ever! – Lee Dyer

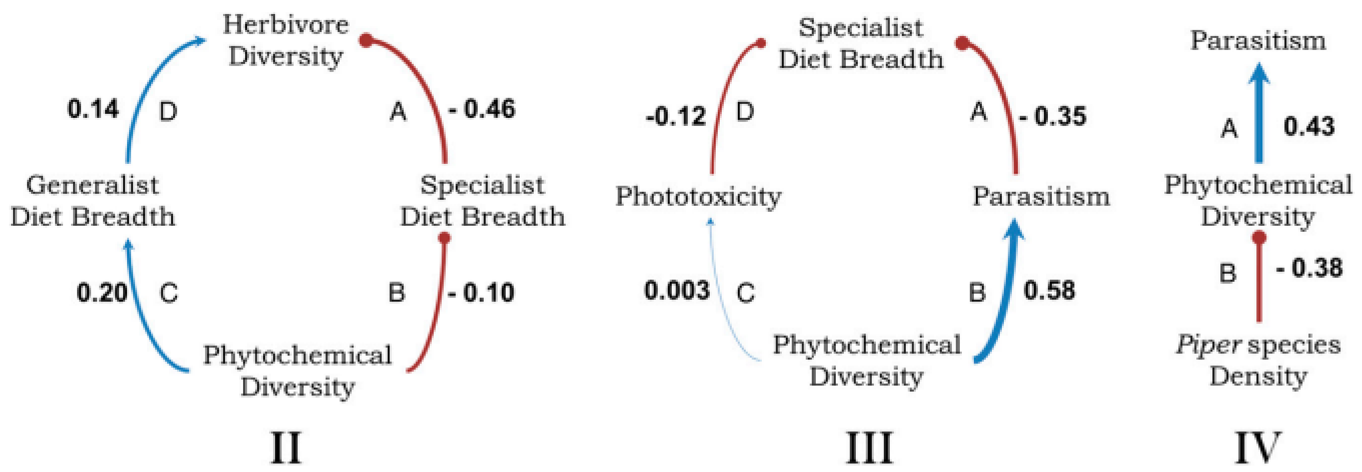
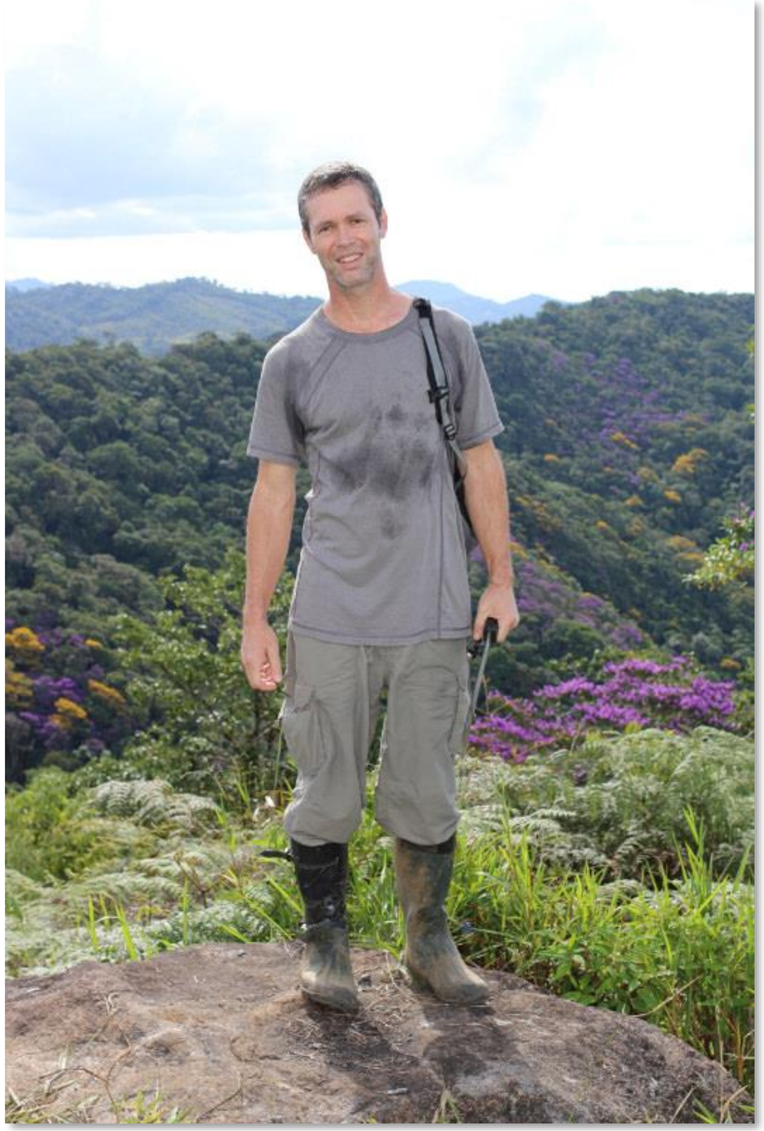


Fig. 3. Summary of the best-fitting path models based on predicted relationships between phytochemical diversity and herbivore diet breadth (model II) and parasitism rates (models III and IV) for *Piper* species. Each model used subsets of *Piper* host species for which all relevant data were available. Standardized path coefficients are noted. Positive relationships are indicated in blue with arrowheads indicating causality; negative relationships are indicated in red with bullet heads. Model II includes different diet breadths and quantifies associations between herbivore diversity, phytochemical diversity, and diet breadth of the herbivore community for 22 *Piper* species (model fit: $\chi^2 = 0.1047$, df = 2, $P = 0.95$). Greater phytochemical diversity drives greater levels of specialization and generalization, both of which contribute to higher herbivore diversity. For the subset of data that includes only *Piper* specialist caterpillars, model III quantifies associations between phytochemical diversity, phototoxicity, parasitism rates, and the number of *Piper* species that are hosts to the herbivore community for 13 *Piper* species (model fit: $\chi^2 = 0.1676$, df = 2, $P = 0.92$). In model IV, local *Piper* species density is included in a model of phytochemical diversity and specialist parasitism rates (20 species; model fit: $\chi^2 = 0.040$, df = 1, $P = 0.84$).



Richards et al. (**2015**) *PNAS*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Structural equation models are the best tool ever! – Lee Dyer

I was moderately skeptical

I began to use these approaches in my own research

Example(s): population dynamics (CMR, IPMs)

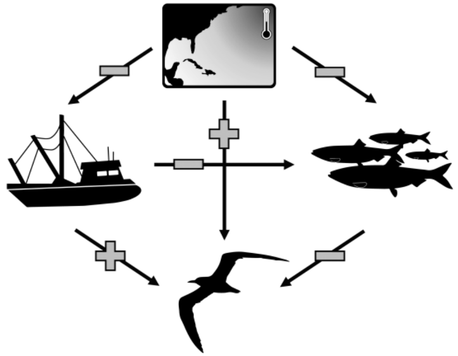


FIGURE 1 Simplified path diagram describing the hypothesized directionality (plus: Positive, bar: Negative association) regarding how environmental variables (i.e., sea-surface temperatures in the North Atlantic, fishery pressure, and fish production) influenced one another, as well as the indirect and direct pathways in which these sources of environmental variability influenced Royal tern mortality.

Received: 28 June 2022 | Revised: 26 September 2022 | Accepted: 5 October 2022
DOI: 10.1111/gcb.16482

Global Change Biology WILEY

RESEARCH ARTICLE

Climate change and commercial fishing practices codetermine survival of a long-lived seabird

Daniel Gibson[1,2] | Thomas V. Riecke[3] | Daniel H. Catlin[2] | Kelsi L. Hunt[2] | Chelsea E. Weithman[2] | David N. Koons[1] | Sarah M. Karpanty[2] | James D. Fraser[2]

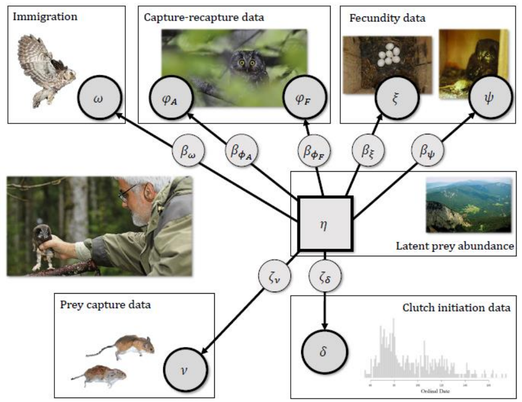


Figure 2. Directed acyclic graph demonstrating the modelled relationships between the mean number of *Apodemus* mouse and vole (Arvicolinae) remains discovered in nest boxes following breeding (ν), mean laying date (δ), latent breeding conditions (η; i.e., rodent abundance), and the demographic parameters clutch size (ξ), the probability that each egg fledges (ψ), breeding probability (γ), adult survival (ϕ_A), fledgling survival to adulthood (ϕ_F), and the expected number of immigrants (ω) for Tengmalm's owls breeding in the Jura Mountains in northwestern Switzerland and eastern France (1990-2020).

A hierarchical population model for the estimation of latent prey abundance and demographic rates of a nomadic predator

Thomas V. Riecke[1,2,*], Pierre-Alain Ravussin[3], Ludovic Longchamp[4], Daniel Trolliet[5], Dan Gibson[6] and Michael Schaub[1]

Gibson, Riecke, et al. **(2023)** *Global Change Biology*

Riecke et al. **(in revision)** *Ecological Modelling*

Example(s): understanding harvest effects

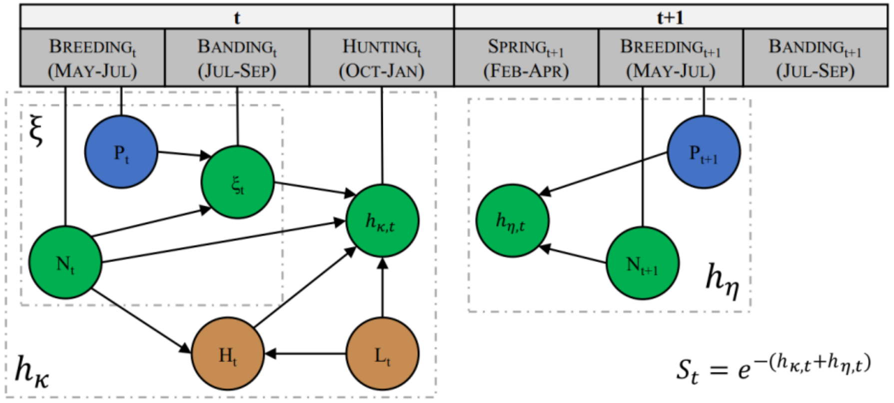


FIGURE 2 Directed acyclic graph demonstrating the hypothesized relationships among mallard breeding pair abundance (*N*), the number of ponds (*P*), harvest limits (*L*), the abundance of duck hunters (*H*), fecundity (ξ), harvest mortality hazard rate (h_κ), natural mortality hazard rate (h_η) and survival (*S*) for mallards marked and released in the Prairie Pothole Region of the United States and Canada, 1974–2016. Arrows represent covariate effects, grey dashed lines enclose separate generalized linear models and vertical solid lines denote the time period or interval when parameters were estimated, where survival (*S*) and natural mortality in year *t* are estimated from banding in year *t* to banding in year *t*+1. We estimated age-specific band recovery probabilities (*f*) as a function of age-specific harvest probability (κ), reporting rate (*r*) and crippling rate (*c*), $f = \kappa(1 - c)r_t$. We note that we hypothesized the same relationships among demographic components for both juvenile and adult females.

Received: 20 June 2021 | Accepted: 19 April 2022

DOI: 10.1111/1365-2656.13747

Journal of Animal Ecology

RESEARCH ARTICLE

A hierarchical model for jointly assessing ecological and anthropogenic impacts on animal demography

Thomas V. Riecke[1,2,3] | Benjamin S. Sedinger[4] | Todd W. Arnold[5] | Dan Gibson[6] | David N. Koons[6] | Madeleine G. Lohman[1,2] | Michael Schaub[3] | Perry J. Williams[2] | James S. Sedinger[2]

[1]Program in Ecology, Evolution, and Conservation Biology, University of Nevada, Reno, NV, USA; [2]Department of Natural Resources and Environmental Science, University of Nevada, Reno, NV, USA; [3]Swiss Ornithological Institute, Sempach, Switzerland; [4]College of Natural Resources, University of Wisconsin–Stevens Point, Stevens Point, WI, USA; [5]Department of Fisheries, Wildlife, and Conservation Biology, University of Minnesota, St. Paul, MN, USA and [6]Department of Fish, Wildlife, and Conservation Biology, Colorado State University, CO, USA

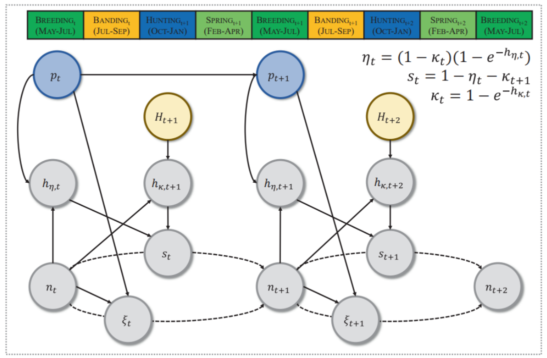


FIGURE 2 A directed acyclic graph demonstrating the relationships among abundance (***n***), ponds (***p***; blue), fecundity (ξ), hunting mortality hazard rate (h_κ), natural mortality hazard rate (h_η), survival (**s**) and the number of duck hunters (***H***; brown) for blue-winged teal breeding in the North American Prairie Pothole Region across the annual cycle (1973–3016). Solid arrows represent estimated directional relationships, and dashed arrows represent processes leading to changes in population abundance.

Received: 2 November 2021 | Accepted: 10 August 2022

DOI: 10.1111/1365-2656.13807

Journal of Animal Ecology

RESEARCH ARTICLE

Density-dependence produces spurious relationships among demographic parameters in a harvested species

Thomas V. Riecke[1,2,3] | Madeleine G. Lohman[1,2] | Benjamin S. Sedinger[1,2,4] | Todd W. Arnold[5] | Cliff L. Feldheim[6] | David N. Koons[7] | Frank C. Rohwer[8] | Michael Schaub[3] | Perry J. Williams[2] | James S. Sedinger[2]

[1]Graduate Program in Ecology, Evolution, and Conservation Biology, University of Nevada, Reno, Nevada, USA; [2]Department of Natural Resources and Environmental Science, University of Nevada, Reno, Nevada, USA; [3]Swiss Ornithological Institute, Sempach, Switzerland; [4]University of Wisconsin–Stevens Point, Stevens Point, Stevens Point, Wisconsin, USA; [5]Department of Fisheries, Wildlife, and Conservation Biology, University of Minnesota, St. Paul, Minnesota, USA; [6]California Trout, San Francisco, California, USA; [7]Fish, Wildlife, and Conservation Biology & Graduate Degree Program in Ecology, Colorado State University, Ft. Collins, Colorado, USA and [8]Delta Waterfowl Foundation, Bismarck, North Dakota, USA

Riecke et al. **(2022a)** *Journal of Animal Ecology*

Riecke et al. **(2022b)** *Journal of Animal Ecology*

Example(s): sequential fitness components

Individual quality and environmental factors interact to shape reproduction and survival in a resident bird of prey

Roman Bühler[1,2], Thomas V. Riecke[1,3], Kim Schalcher[2], Alexandre Roulin[2] and Bettina Almasi[1]

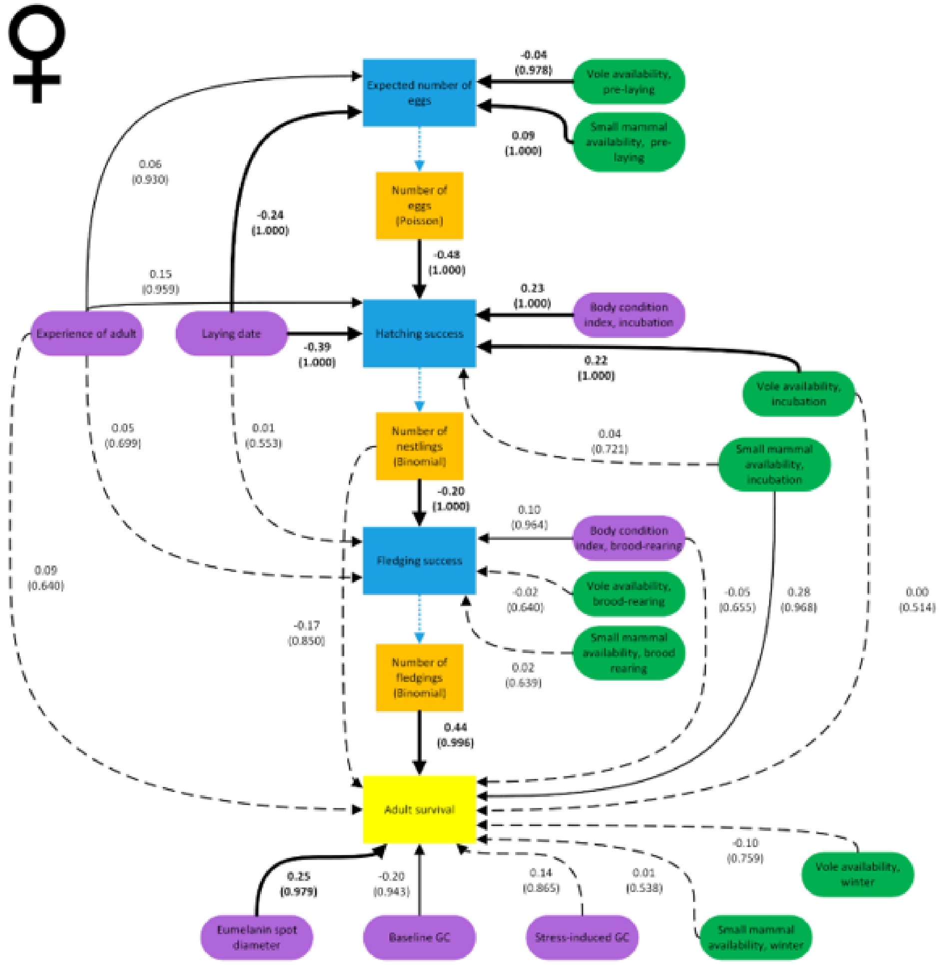


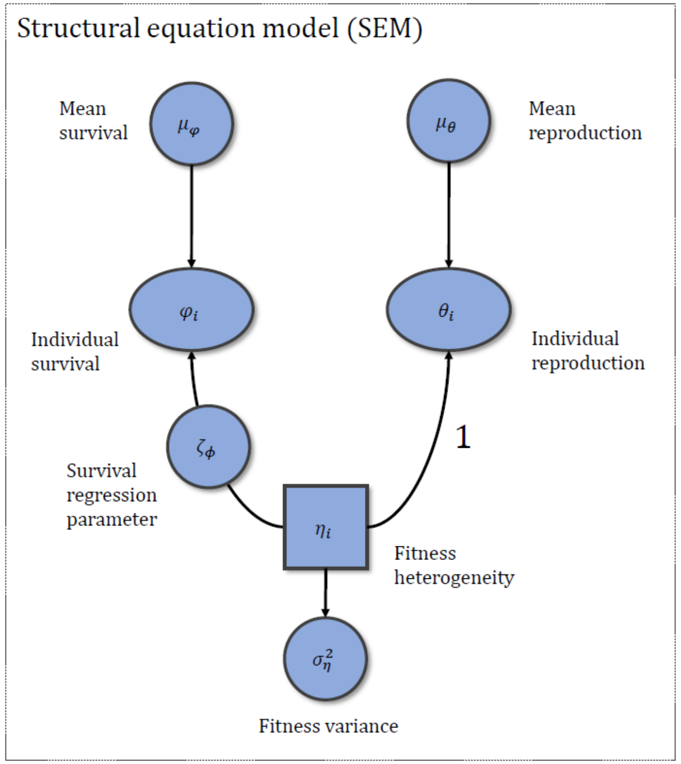
Figure 4: A directed acyclic graph demonstrating the relationships of intrinsic (red) and extrinsic (green) covariates on female reproductive success (blue) and survival (yellow). Estimates and f-values (in brackets) are derived from the models shown in supplementary material S9 and are based on 556 individuals over 5 years. Bold arrows indicating f values >0.975, solid lines f values between 0.9 and 0.974 and dashed lines f values <0.9.

Bühler, Riecke, et al. **(2024)** *Royal Society Open Science*

Example: latent individual heterogeneity & life-history trade-offs

Estimating latent fitness heterogeneity

Thomas V. Riecke[1,2,3], Dan Gibson[4], Rémi Fay[5], Sarah Cubaynes[6], Madeleine G. Lohman[7,8] and Michael Schaub[1]



Estimating latent heterogeneity in individual fitness using structural equation models

Thomas V. Riecke[1,2,3], Rémi Fay[4], Johann Hegelbach[5], Pierre-Alain Ravussin[6], Daniel Arrigo[7] and Michael Schaub[1]

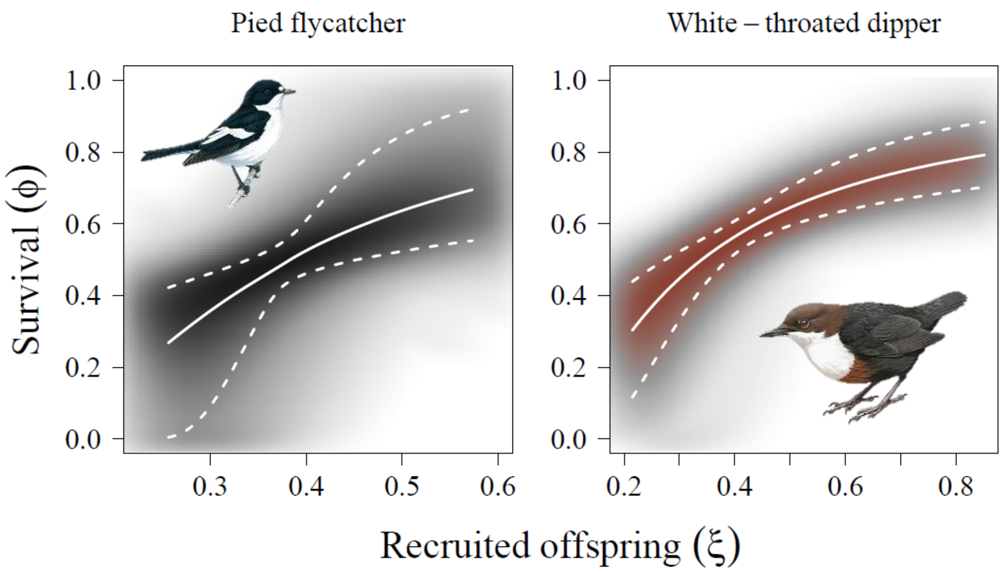


Figure 1. Medians (solid lines) and 95% confidence intervals (dashed lines) for joint estimates of survival (ϕ) and mean recruits per breeding season (ξ) of one-year-old European pied flycatcher (left; *Ficedula hypoleuca*) and white-throated dipper (right; *Cinclus cinclus*) females breeding in Switzerland. The density of the shading corresponds to the density of the posterior distribution.

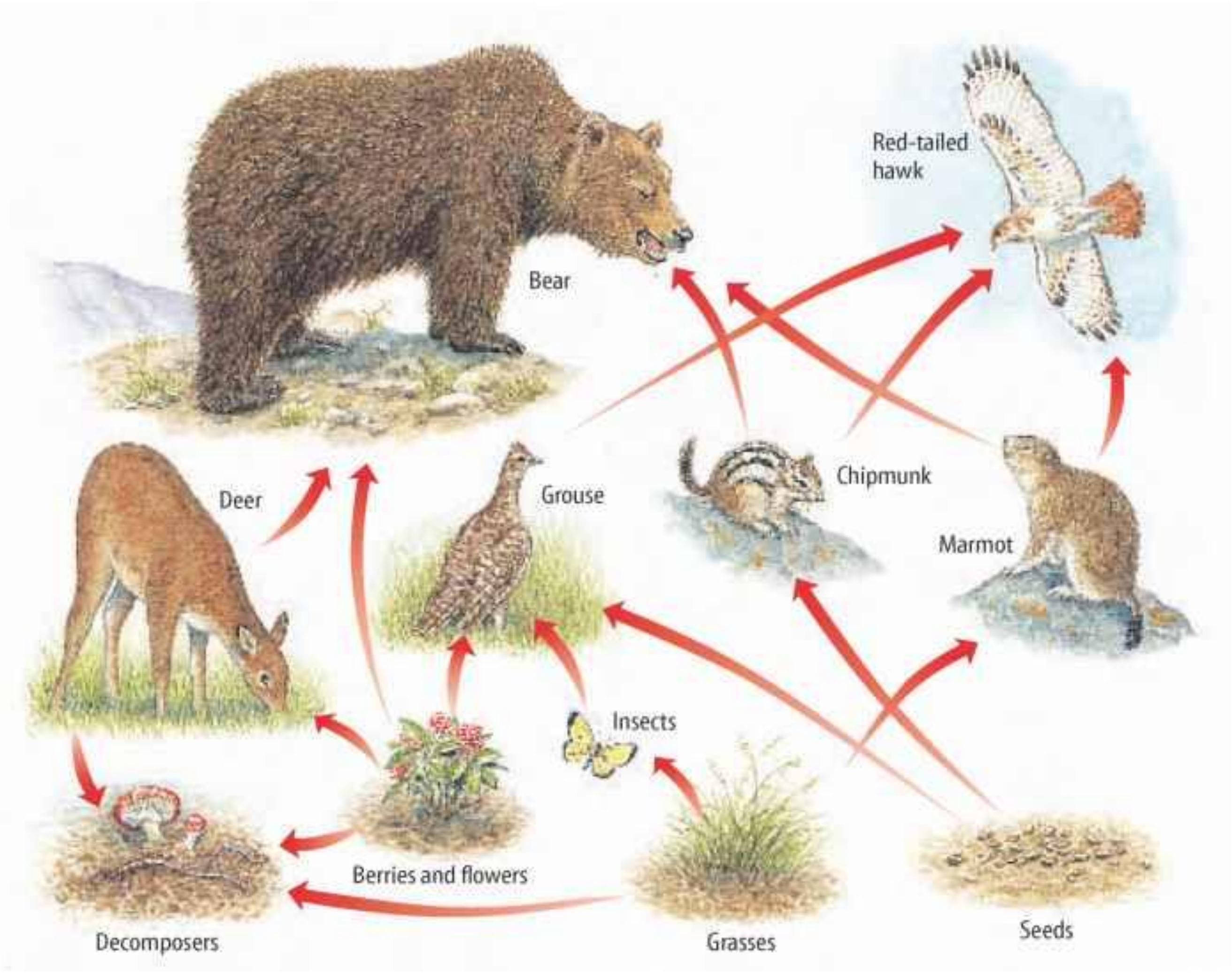
Riecke et al. **(review)** *Methods in Ecol & Evol*

Riecke et al. **(in rejection)** *Ecology*

These tools have transformed how I do research.

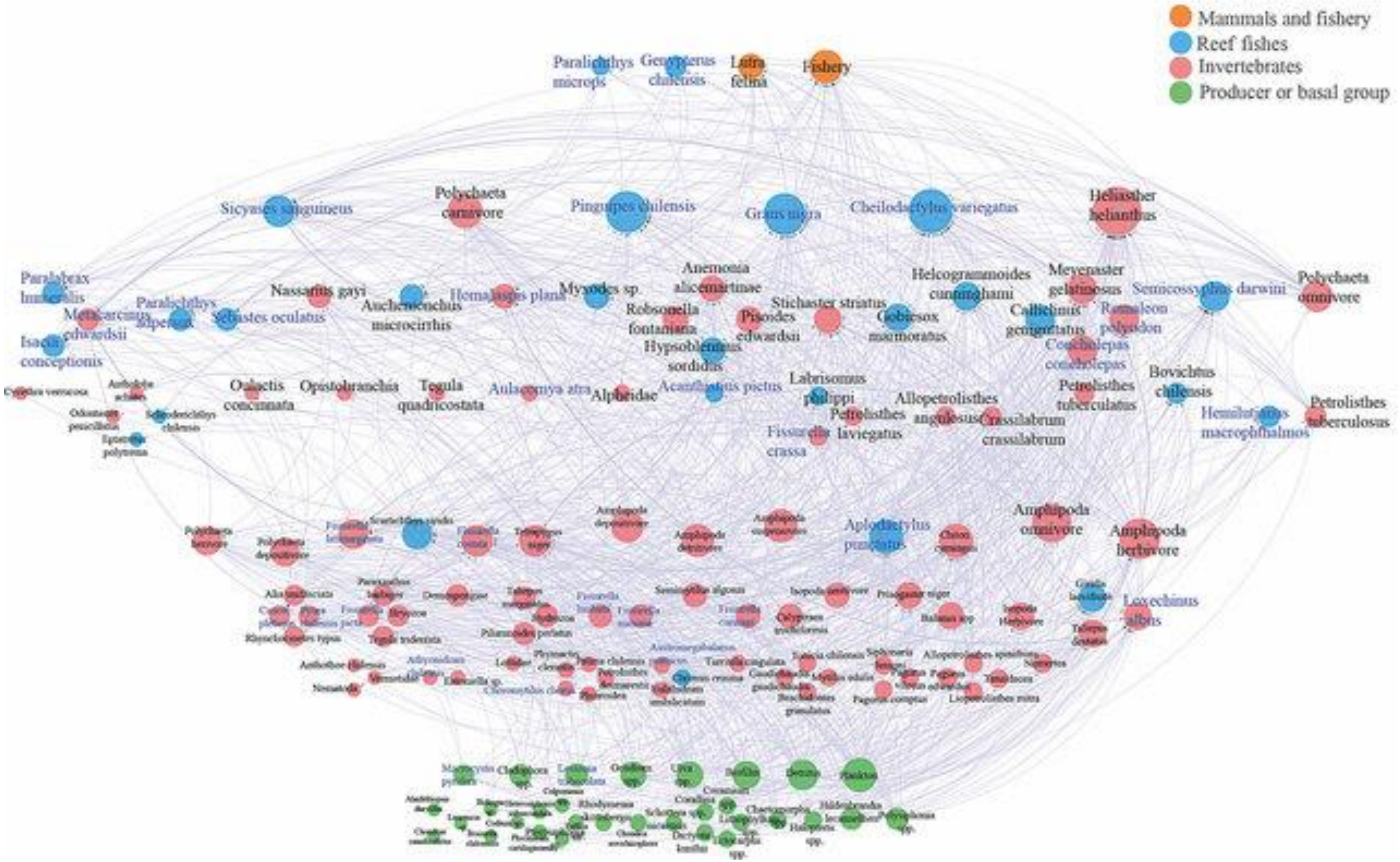
I still have a tremendous amount to learn (it’s been 3 years)!

Ecological systems are complex networks (e.g., food webs)



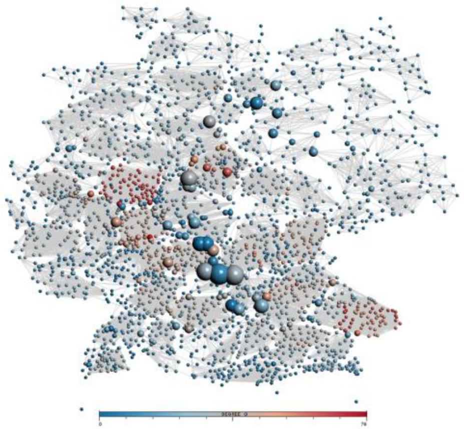
Your elementary school biology textbook (probably)

Ecological systems are complex networks (e.g., food webs)



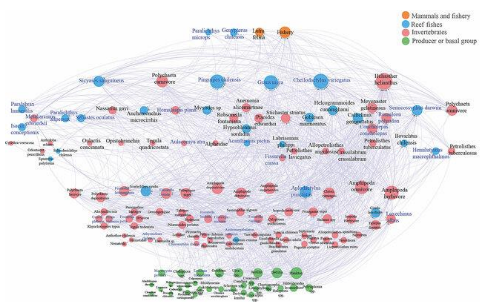
Perez-Matus et al. (2017) Marine Ecology Progress Series

Ecological systems are <u>unbelievably</u> complex networks…



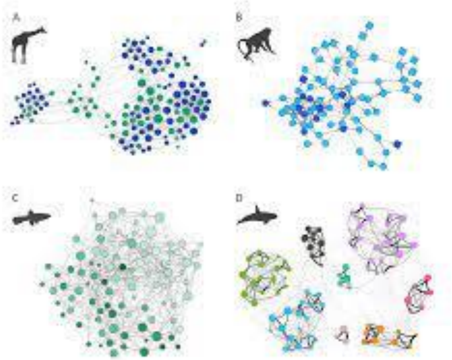
Climate network
Abiotic systems

Tominski et al. (2017)
Information Visualization IV



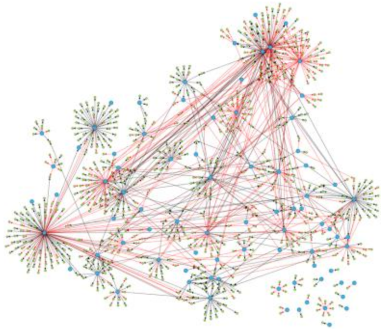
Food Network
Among populations

Perez-Matus et al. (2017)
Marine Ecology Progress Series



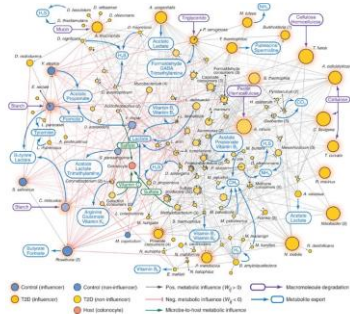
Social Network
Within populations

Brask et al. (2005)
arXiv



Gene Network
Within individuals

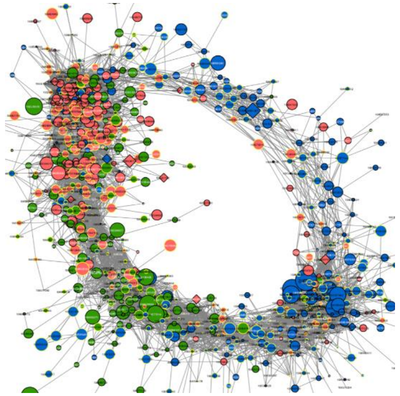
Ma et al. (201)
PLOS ONE



Microbial Network
Within individuals

Sung et al. (2017)
Nature Communications

Ecological ‘reality’ is a complex product of abiotic conditions, community & social dynamics, genetics, & microbial communities



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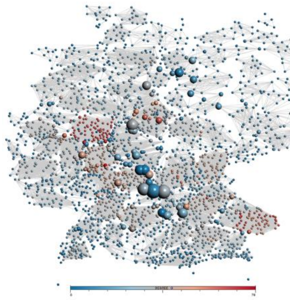
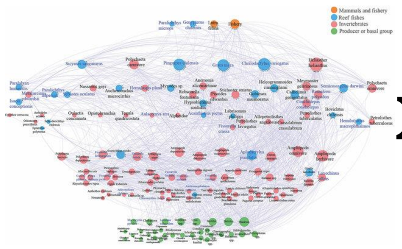


x



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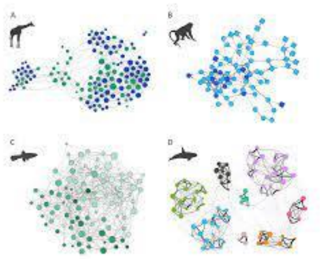

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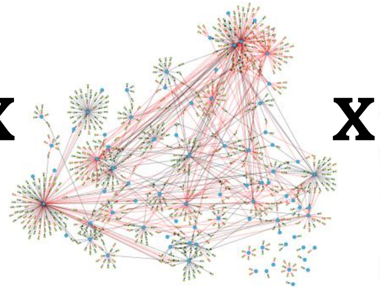

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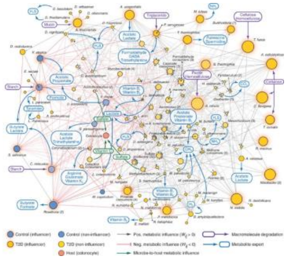
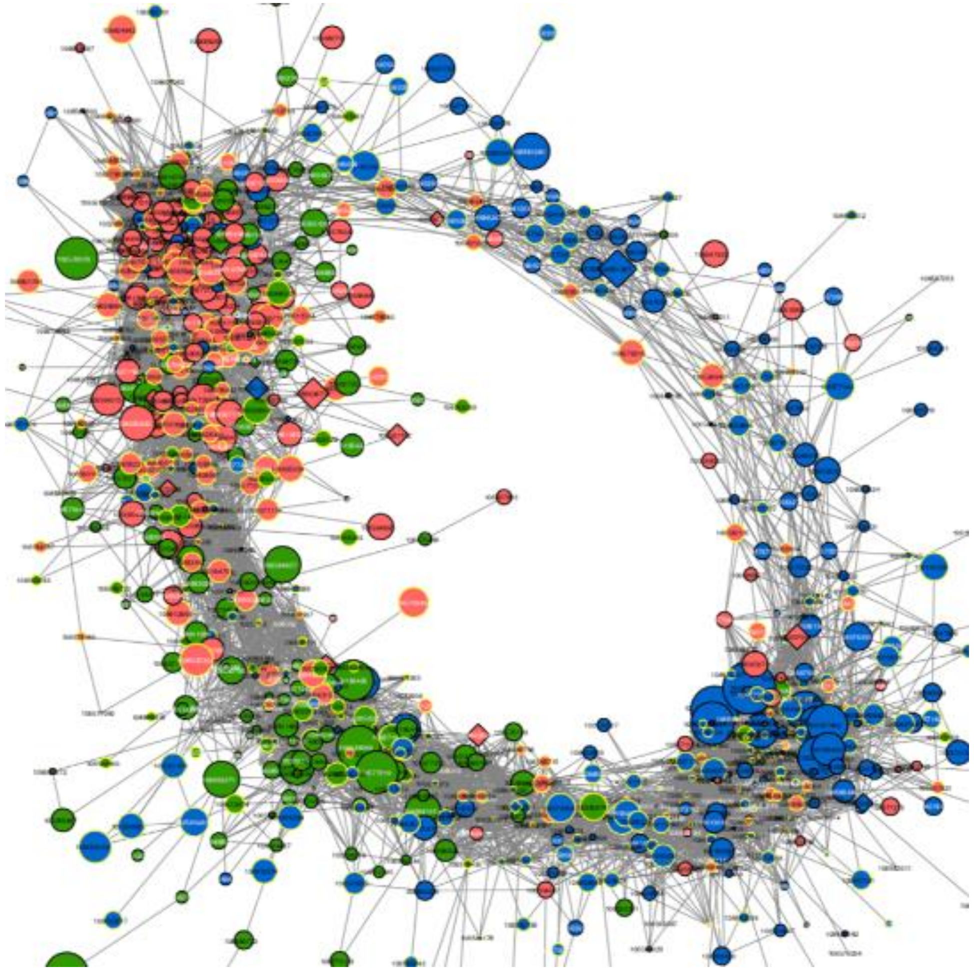
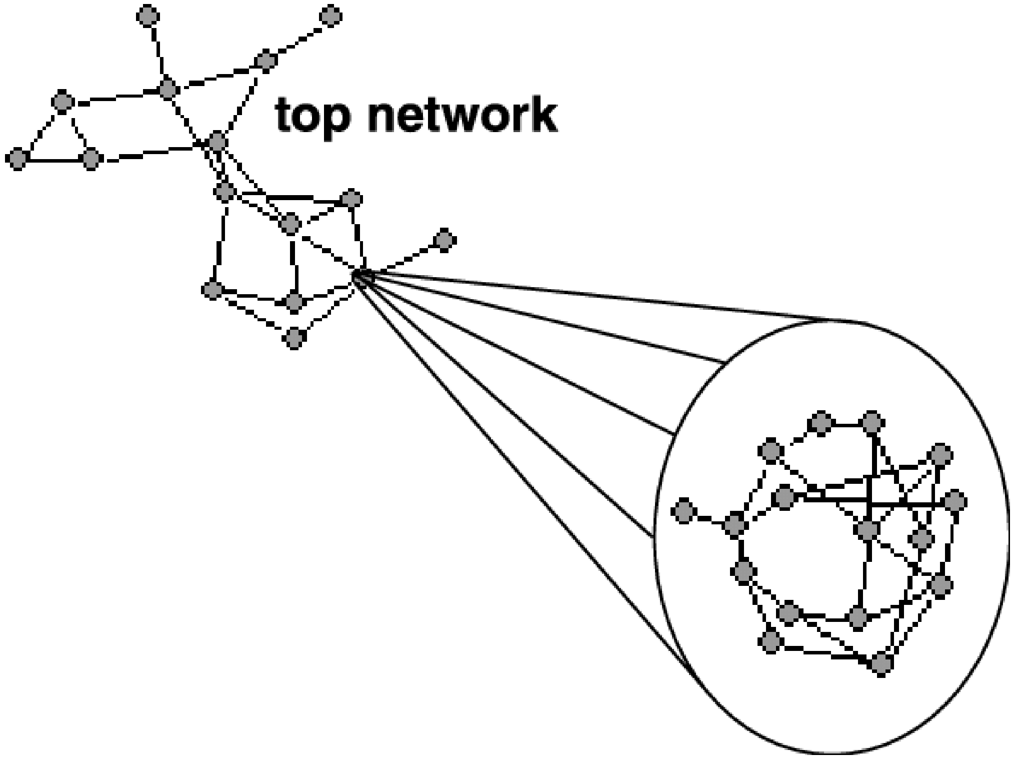


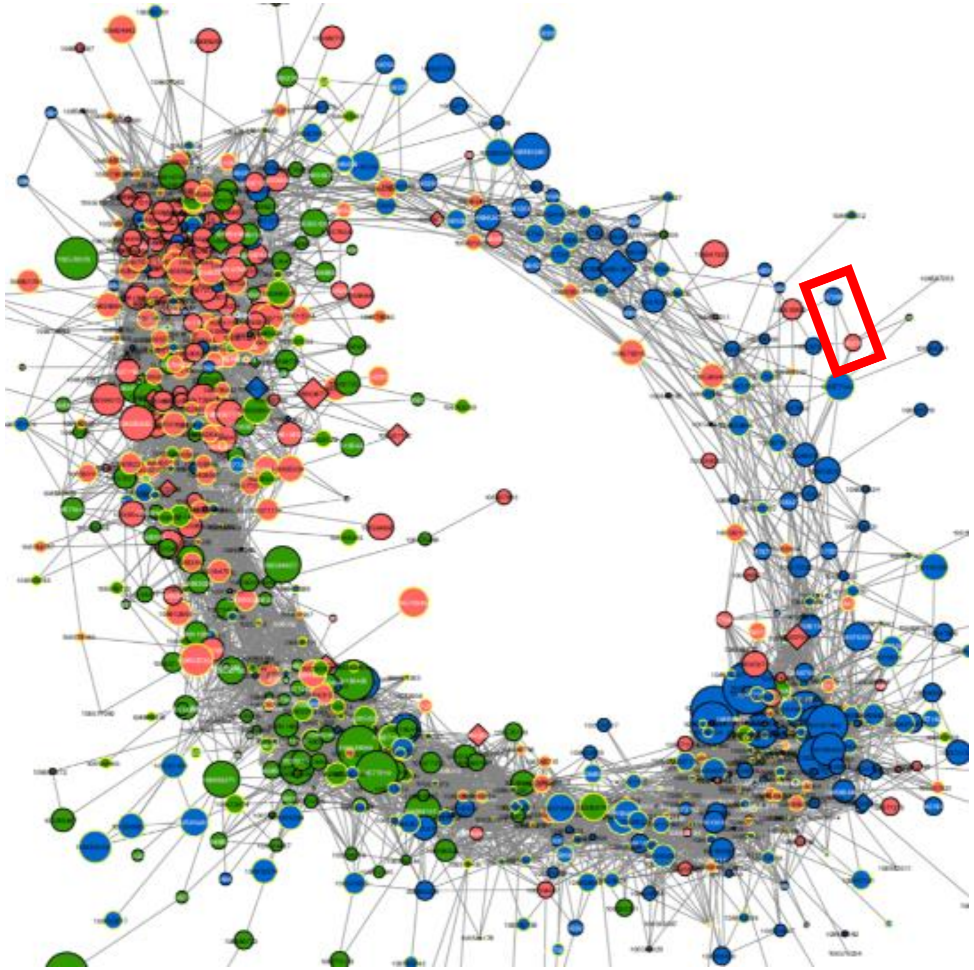
‘Reality’

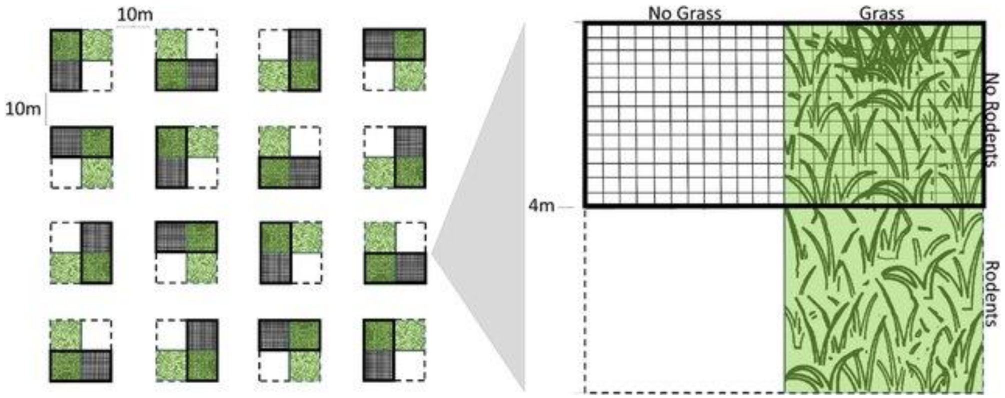
Ecological reality is <u>beyond our comprehension</u>





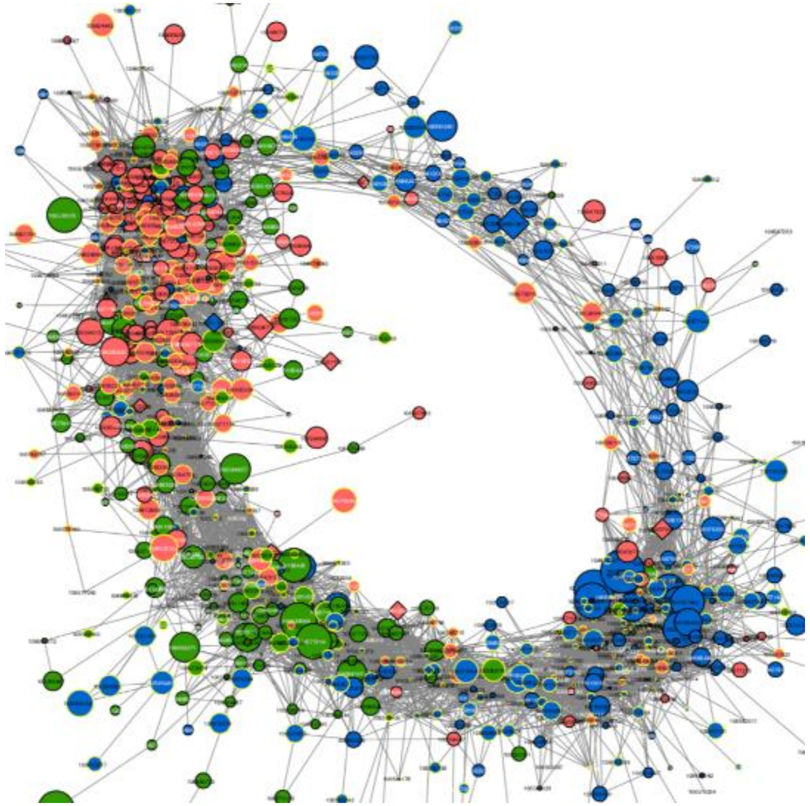
Science responds to this complexity with experiments





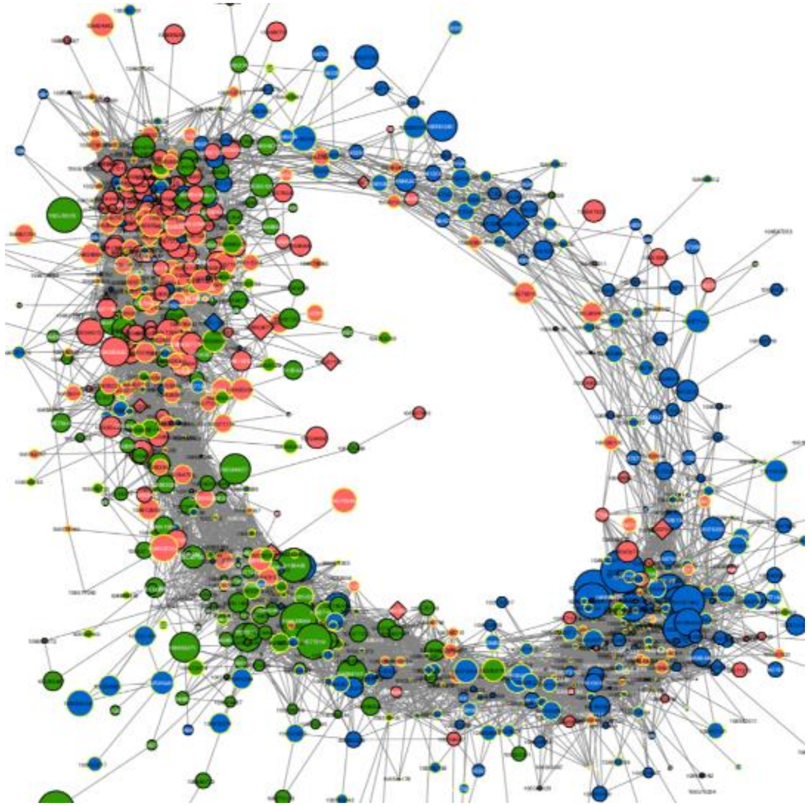
Experiments are <u>beautiful</u>!

We can’t always do experiments (for myriad reasons)



Similar problems in other fields (e.g., epidemiology, social sciences)

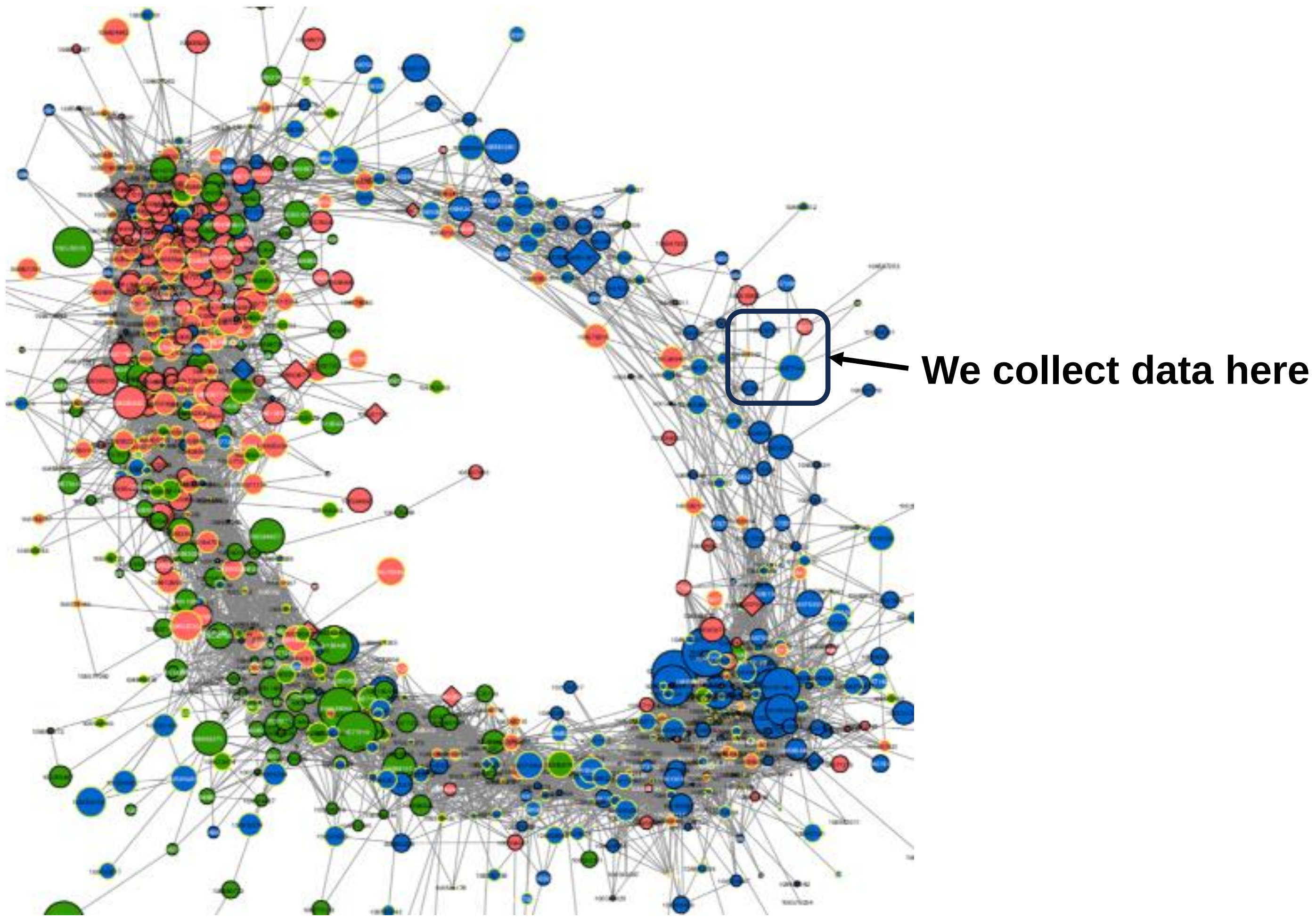
We can never do experiments in the past!

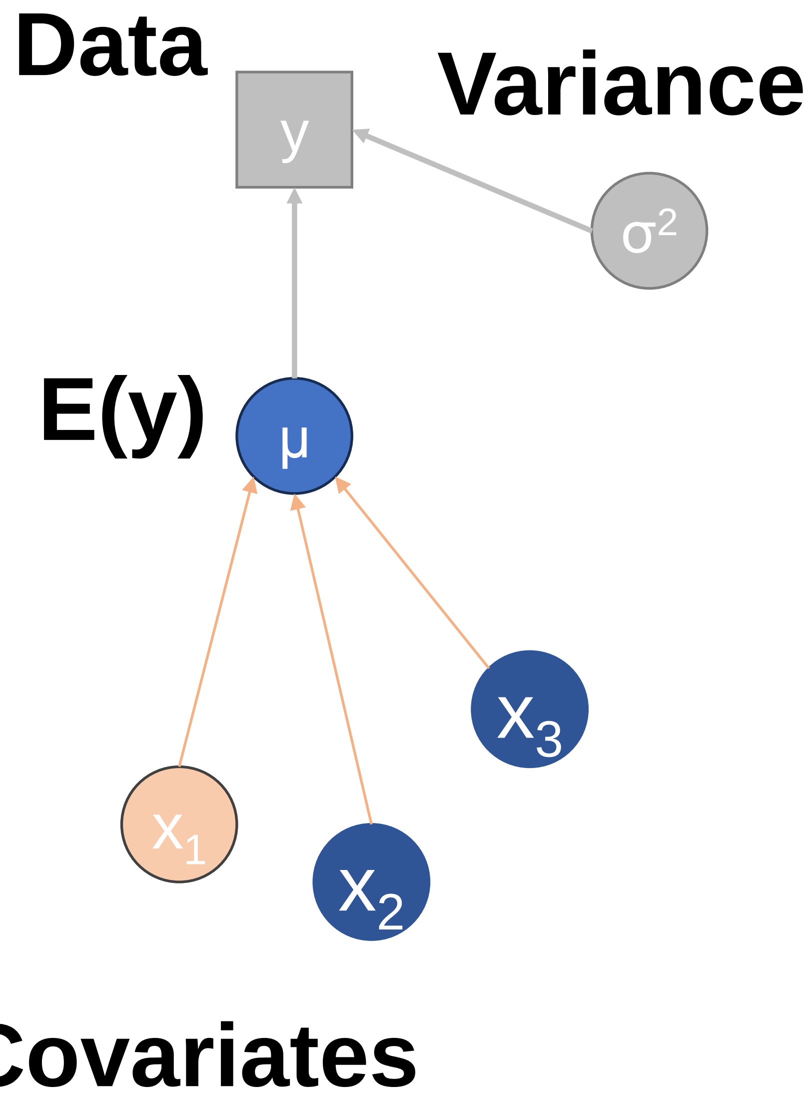


Similar problems in other fields (e.g., epidemiology, social sciences)

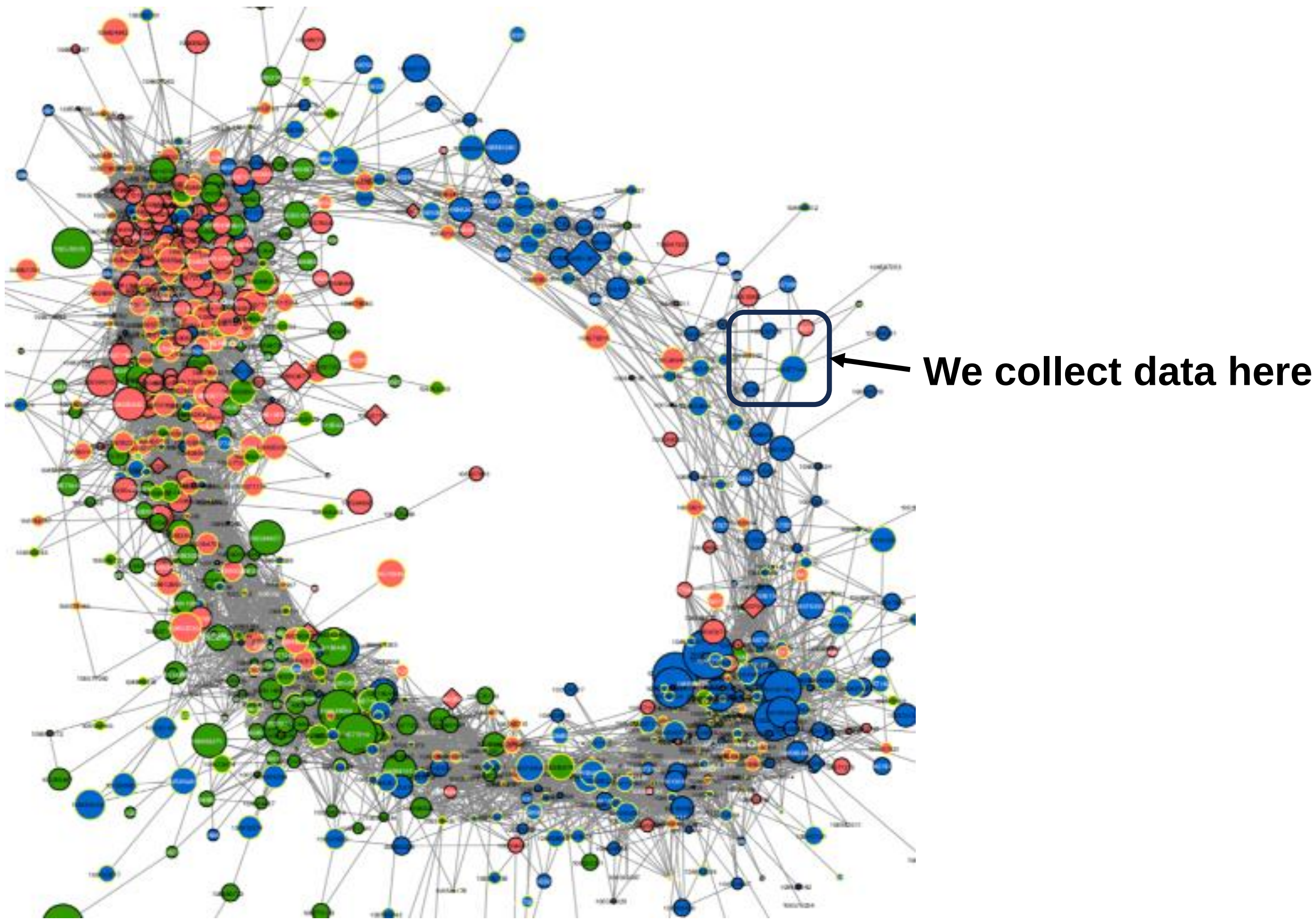
So what do we do?!

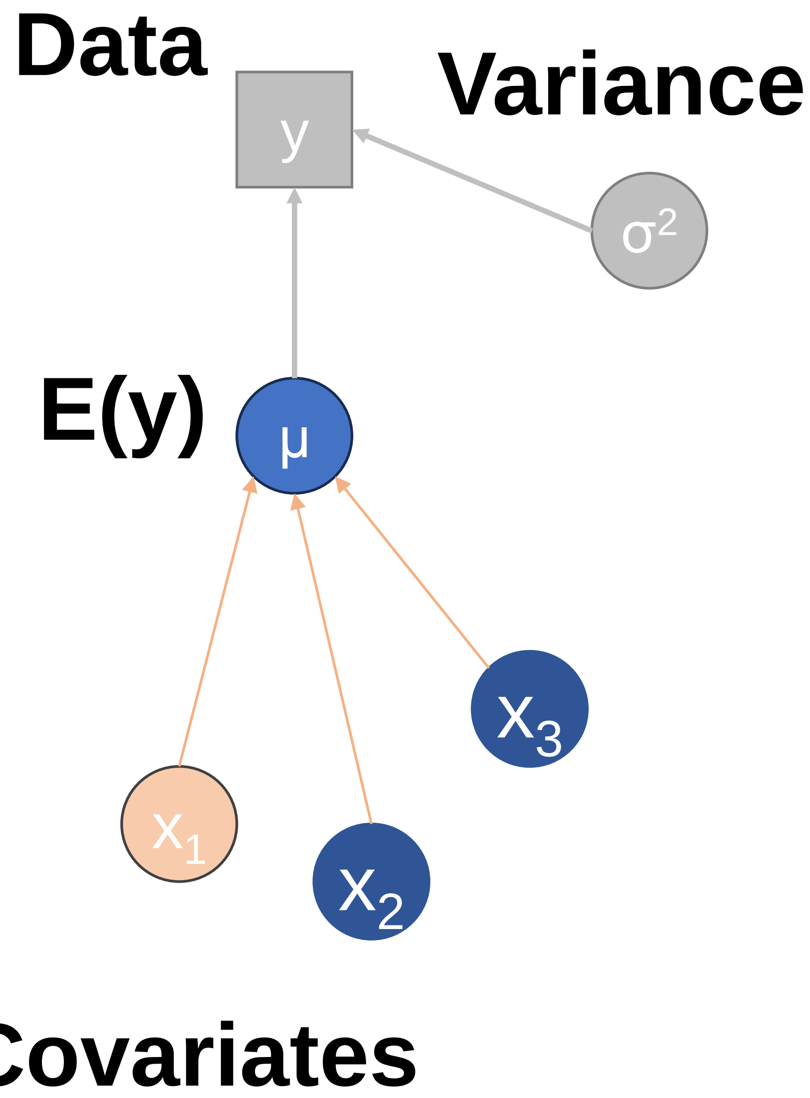
GLMs dominate observational ecological analyses



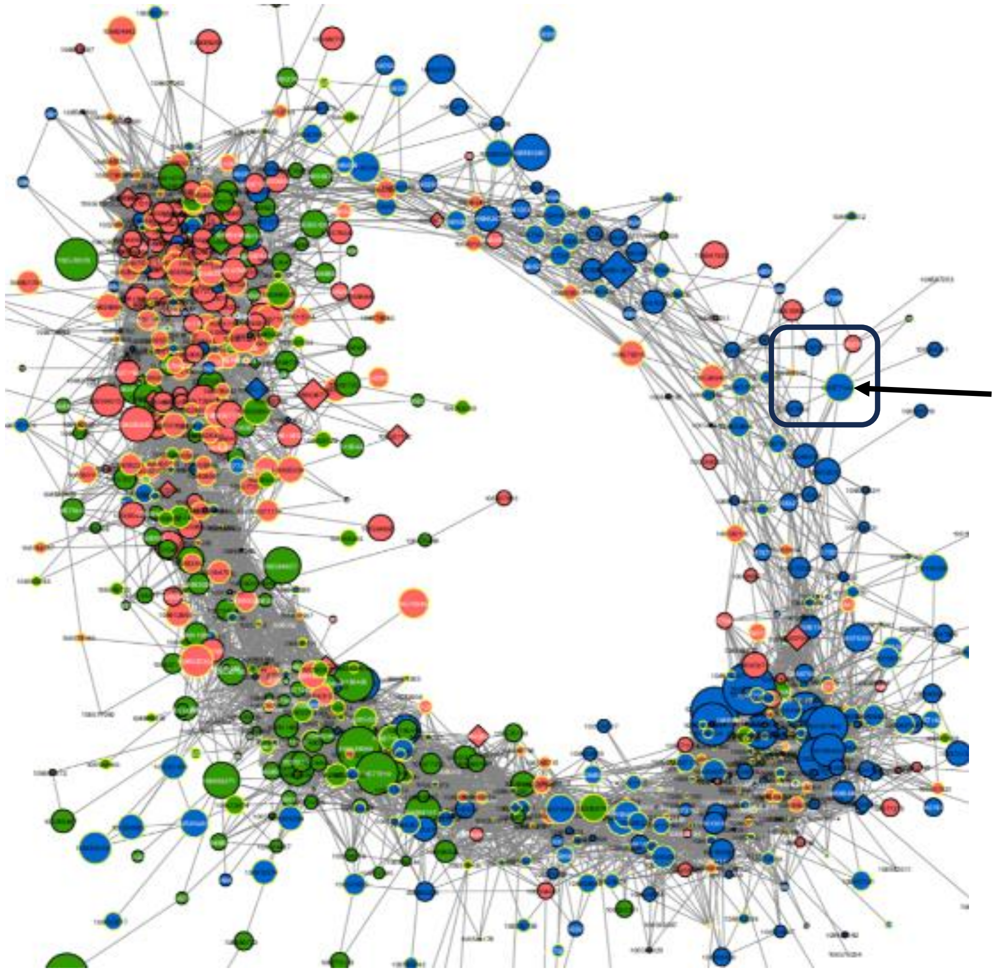


GLMs focus on a single response as a function of covariates





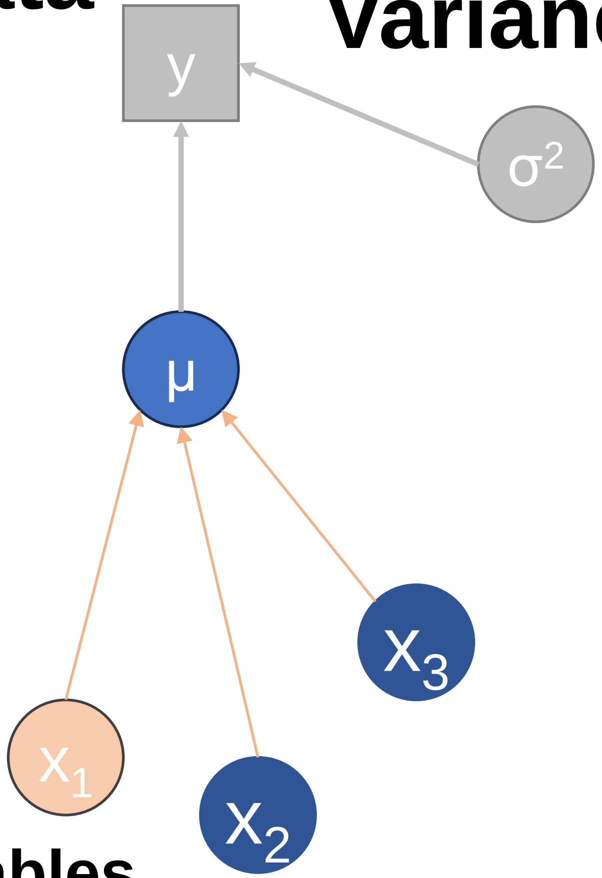
GLMs focus on a single response (i.e., dependent variable)…



Dependent variable

Data

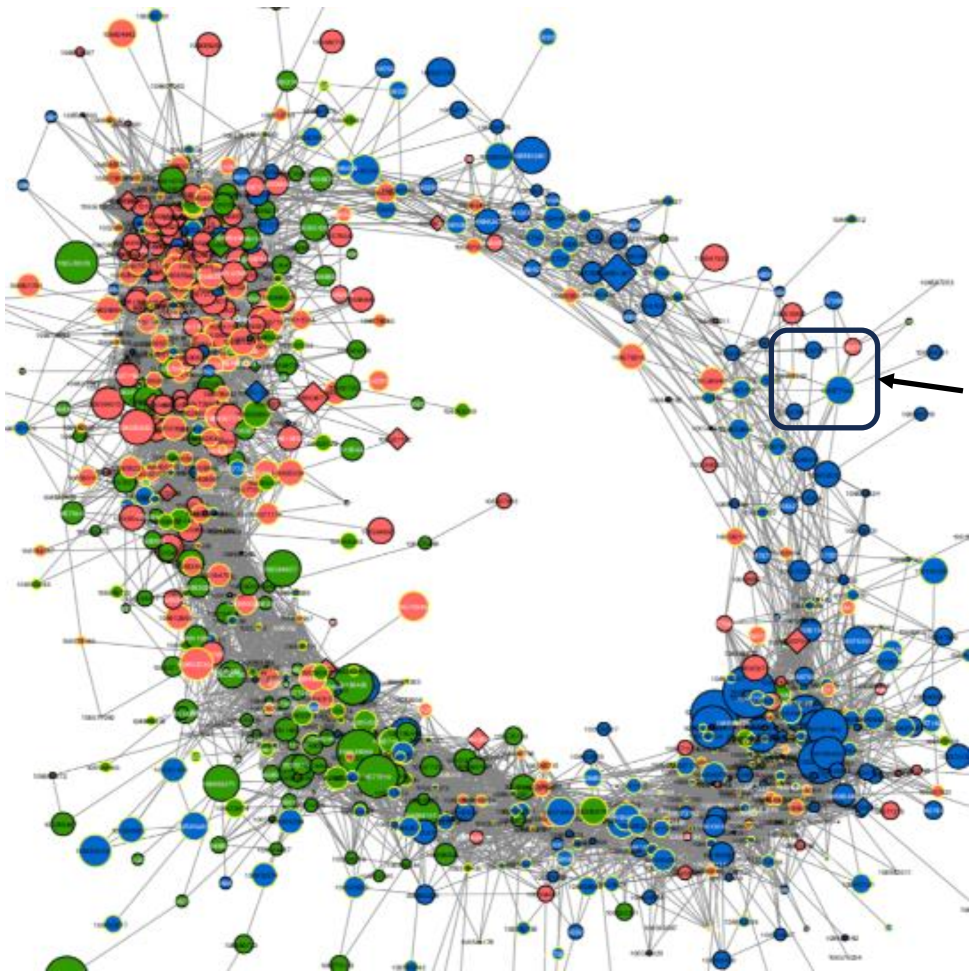
Variance



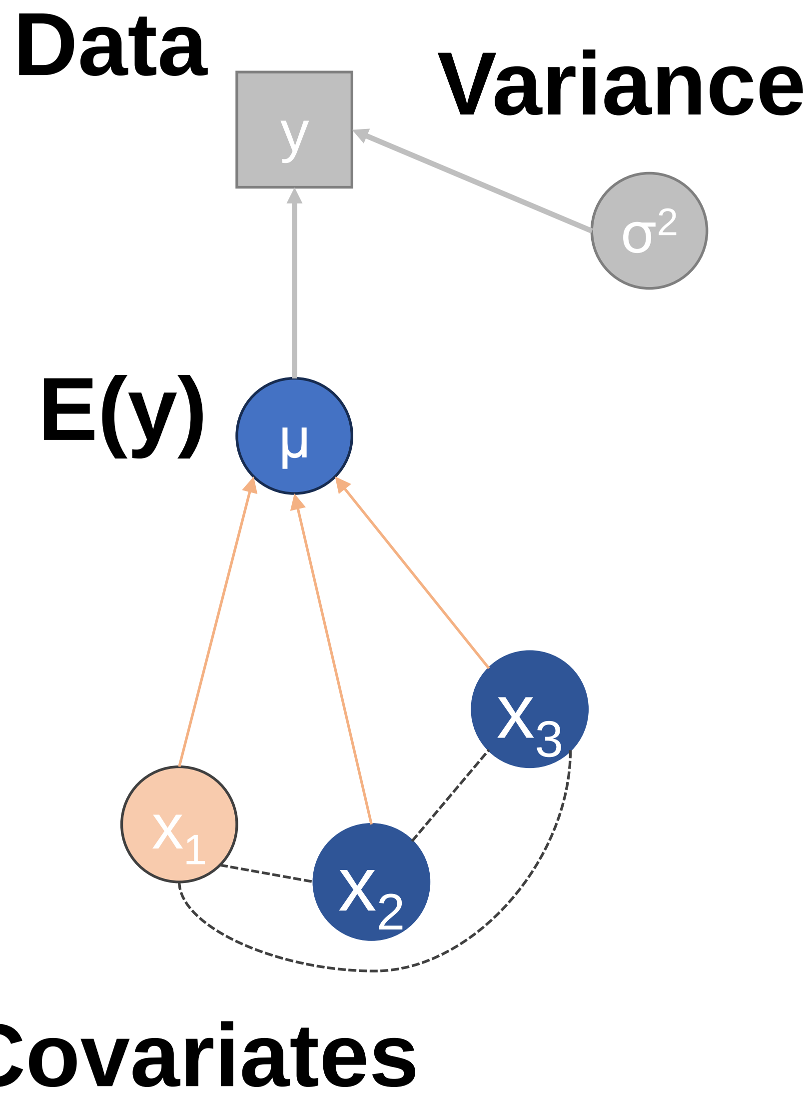
Independent variables

as a function of covariates (i.e., independent variables)

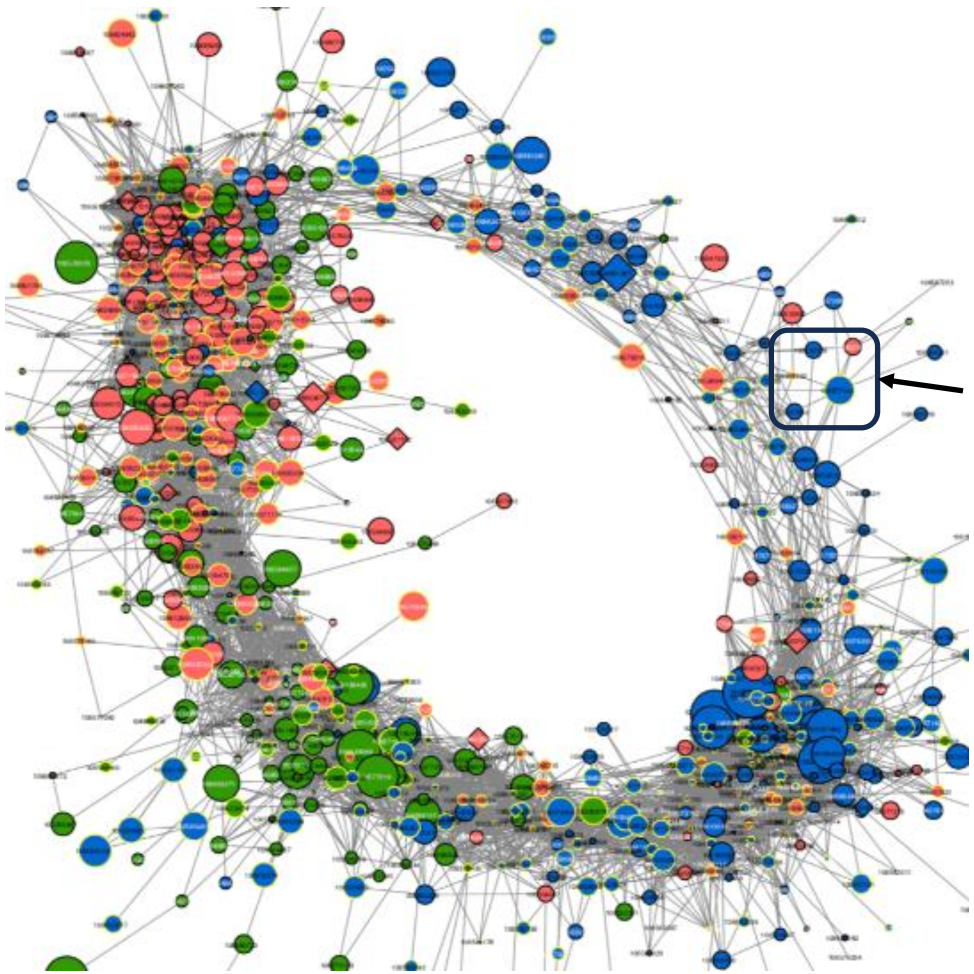
Covariates are often connected, or <u>collinear</u> (<u>NOT</u> ‘independent’)



We collect data here



Multicollinearity is a major ‘problem’ in ecological analysis



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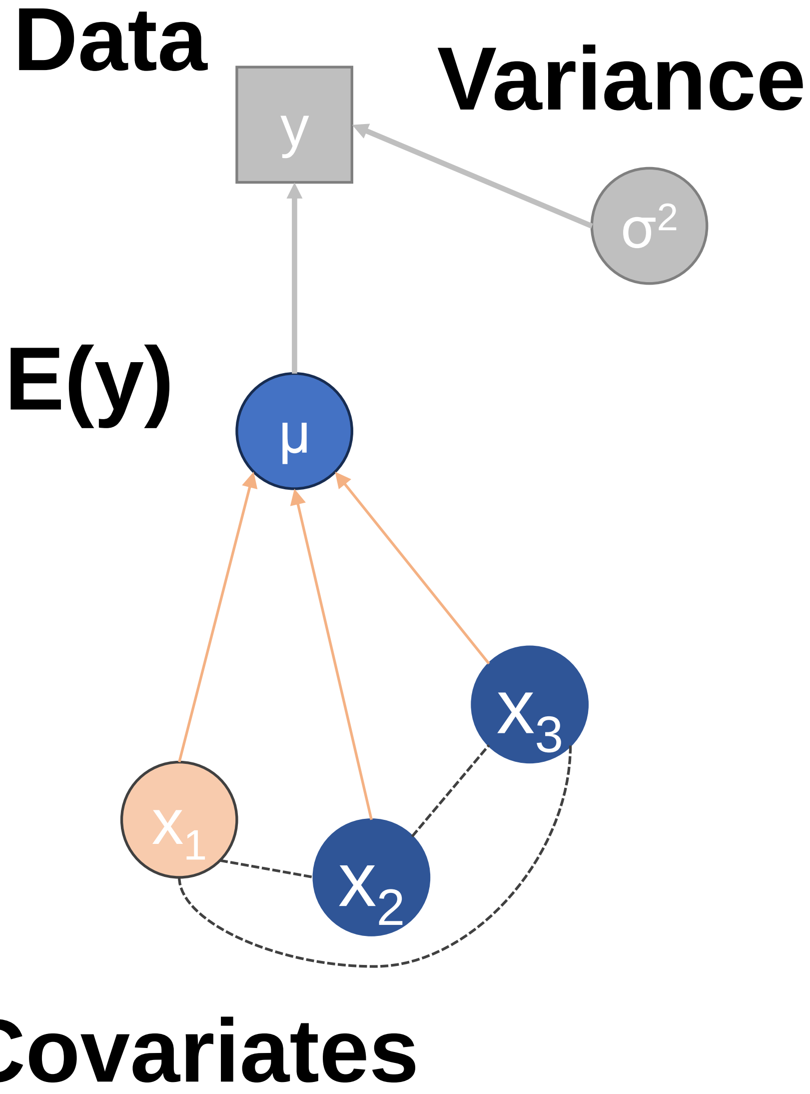
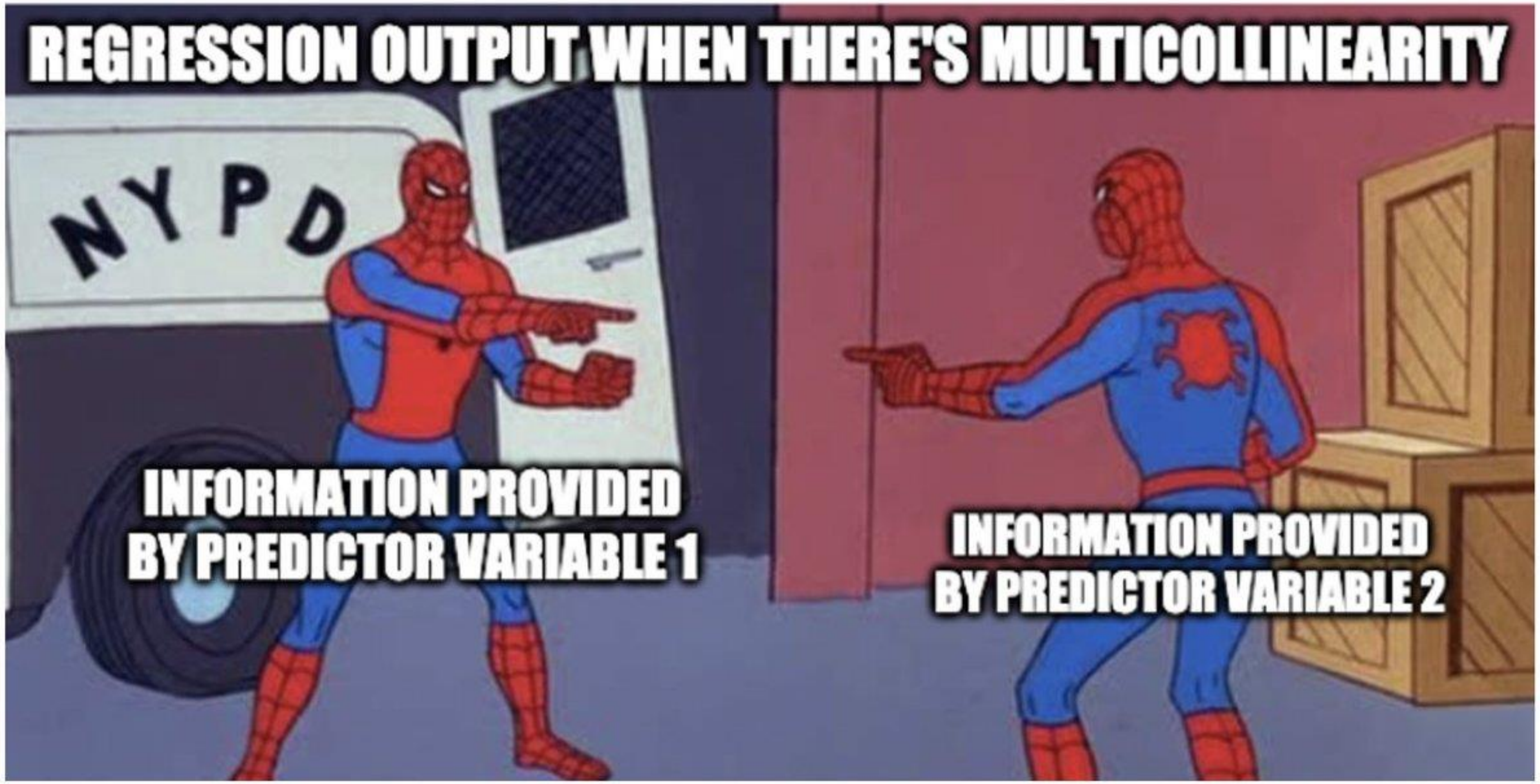


How many of you have had to exclude collinear ($r > 0.7$) covariates?

Why did you do that?

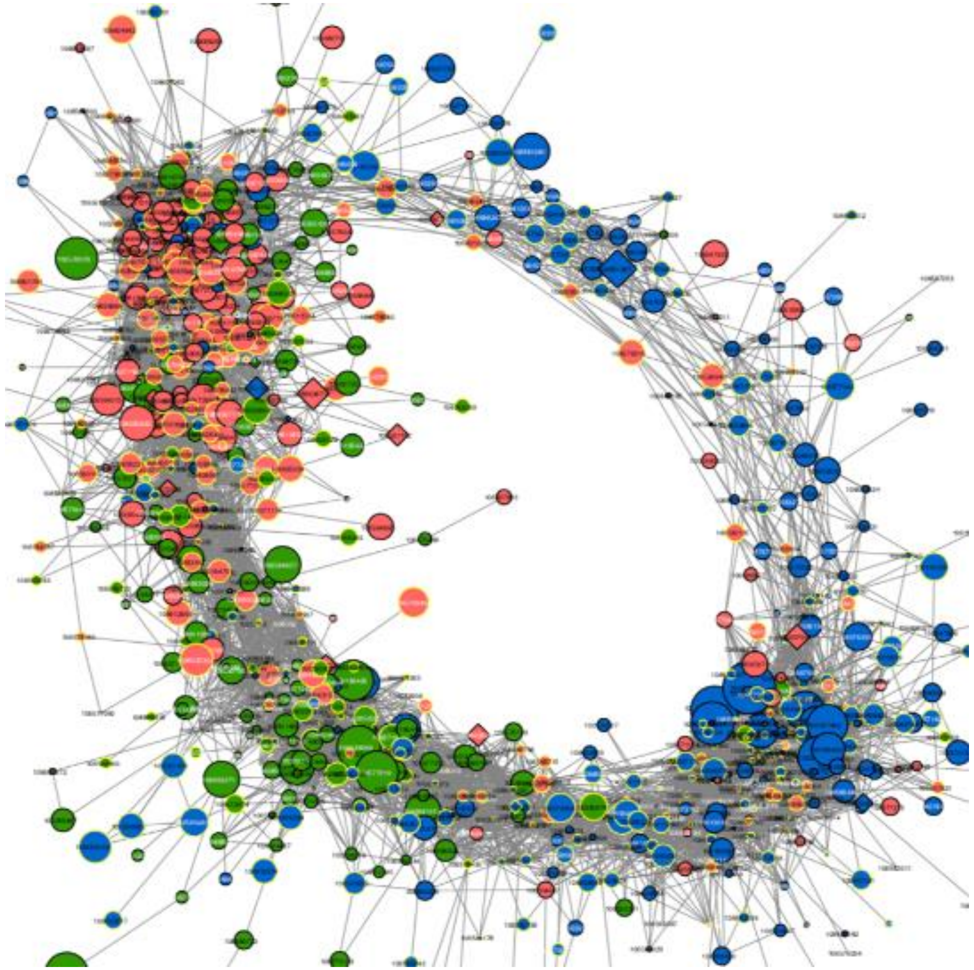


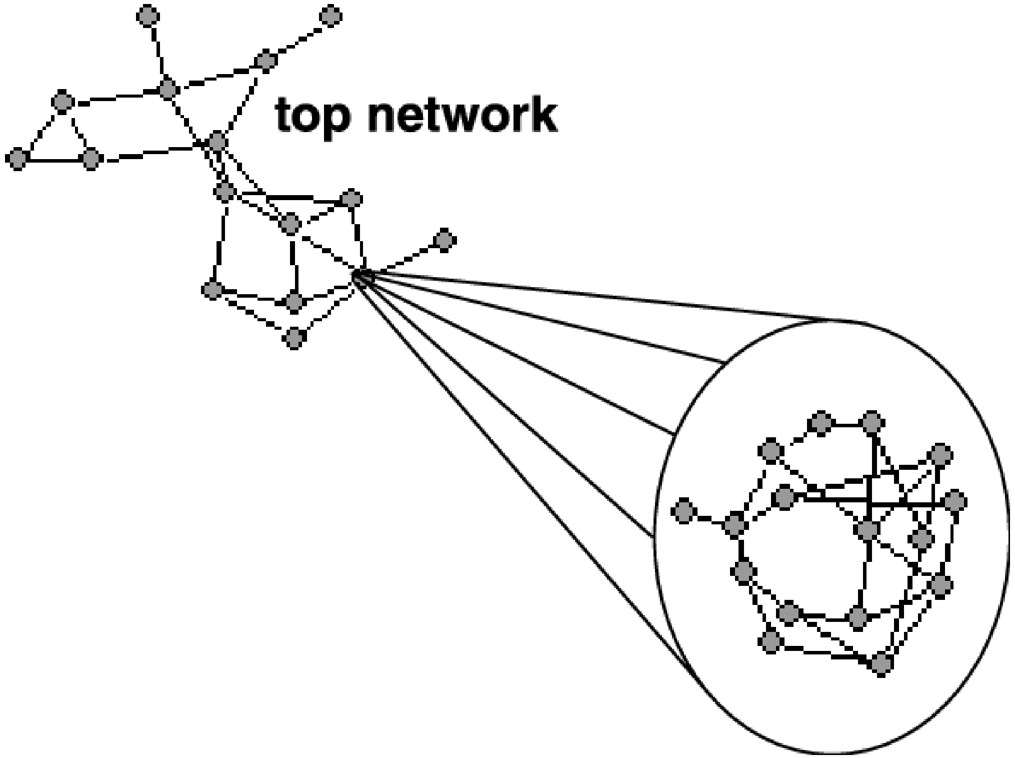
How did you exclude covariates?

- *a priori*
- test which fit ‘best’ (i.e., ‘iterative’ model selection?)
- haphazardly?
- r = 0.694... it’s fine!

How many of you felt ‘good’ about throwing away data?

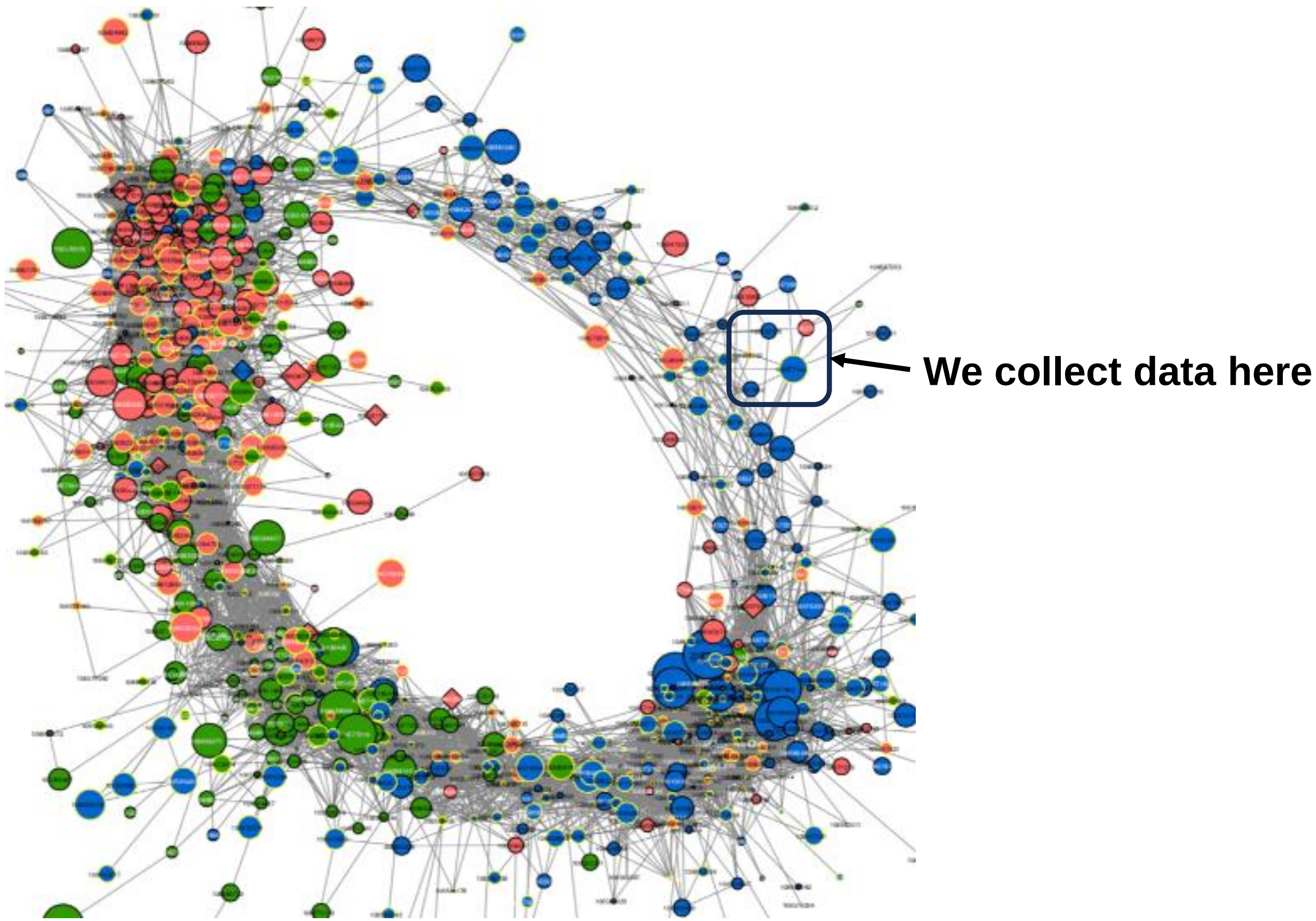
So what do we do?

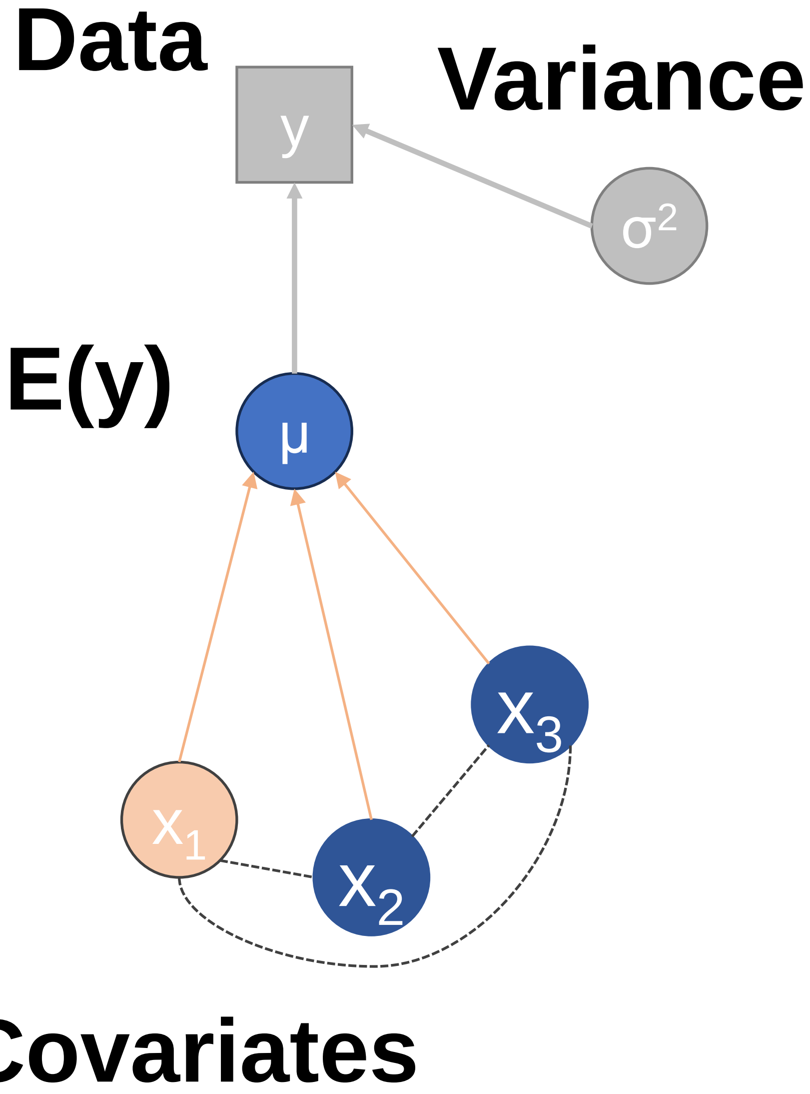




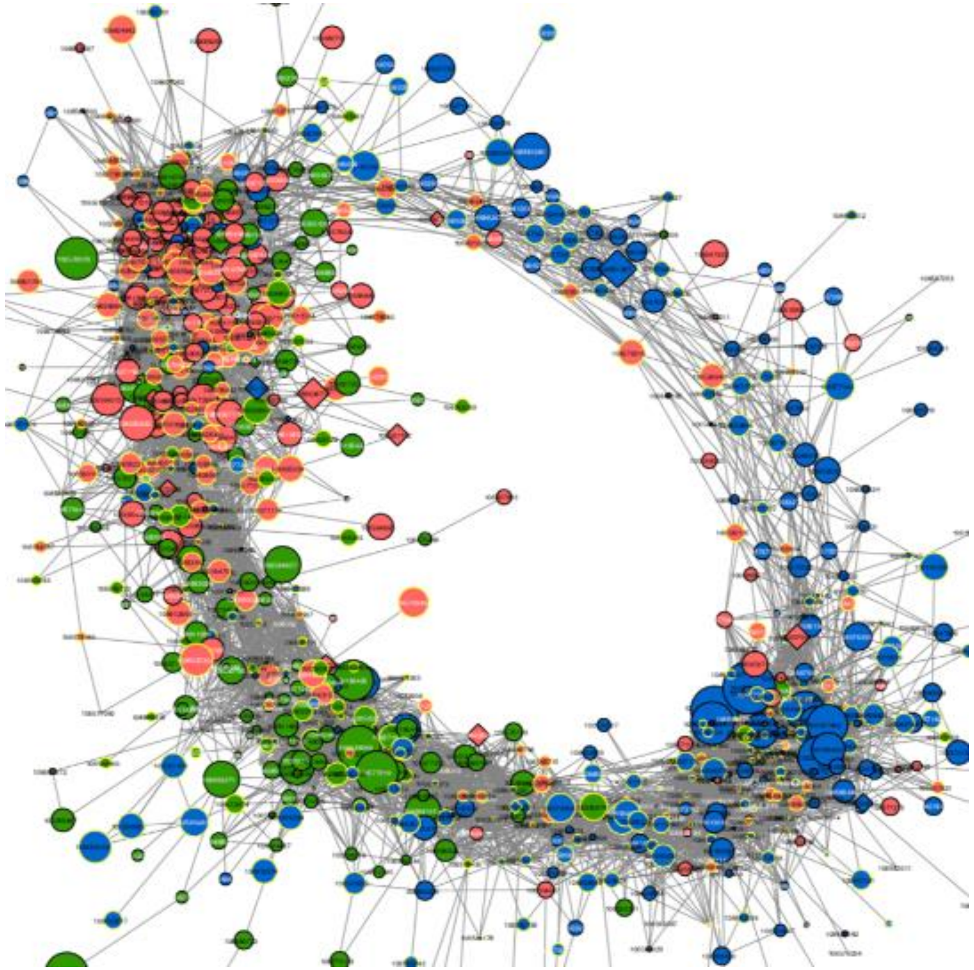
Why were they collinear?

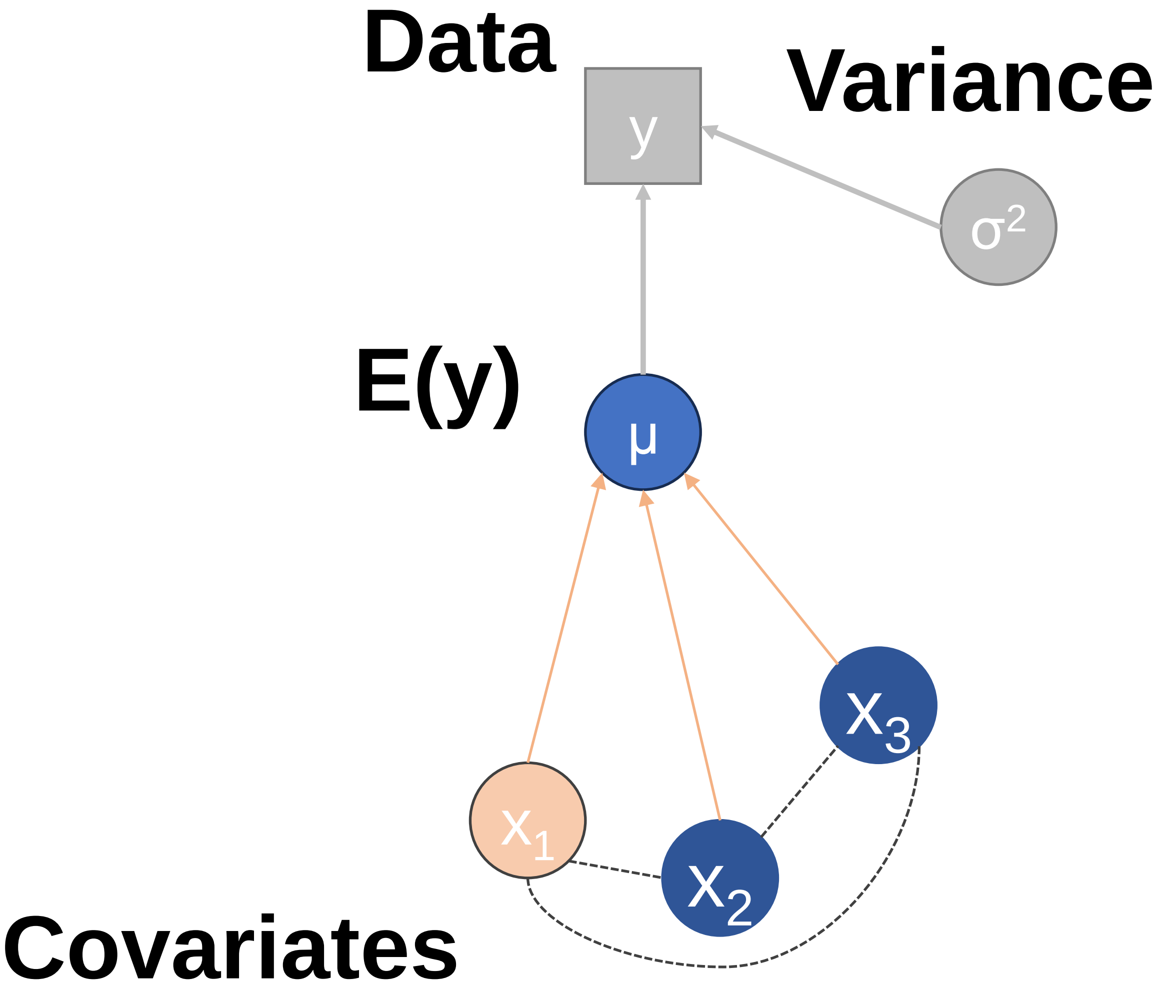
Why were they collinear? The motivating problem!





All models are wrong, but some are useful – GC Box





No models are right, and most are useless **– TW Arnold**

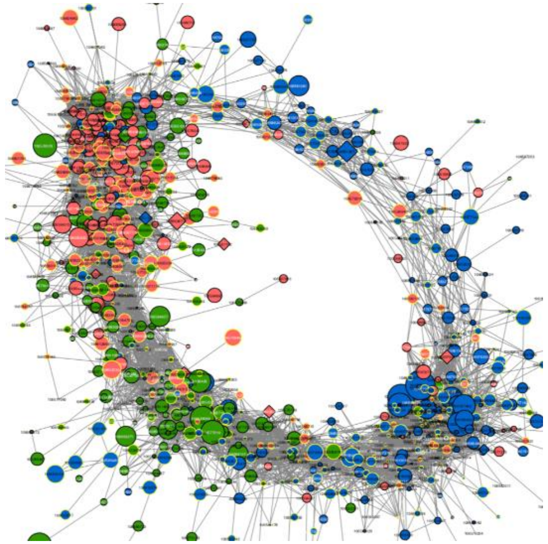
Why were they collinear?

1) One affects the other

2) They’re both a result of an underlying latent process

3) ~~‘random’?~~

The key <u>idea</u> for this class…



Can we model that* instead of pleading ‘multicollinearity’?

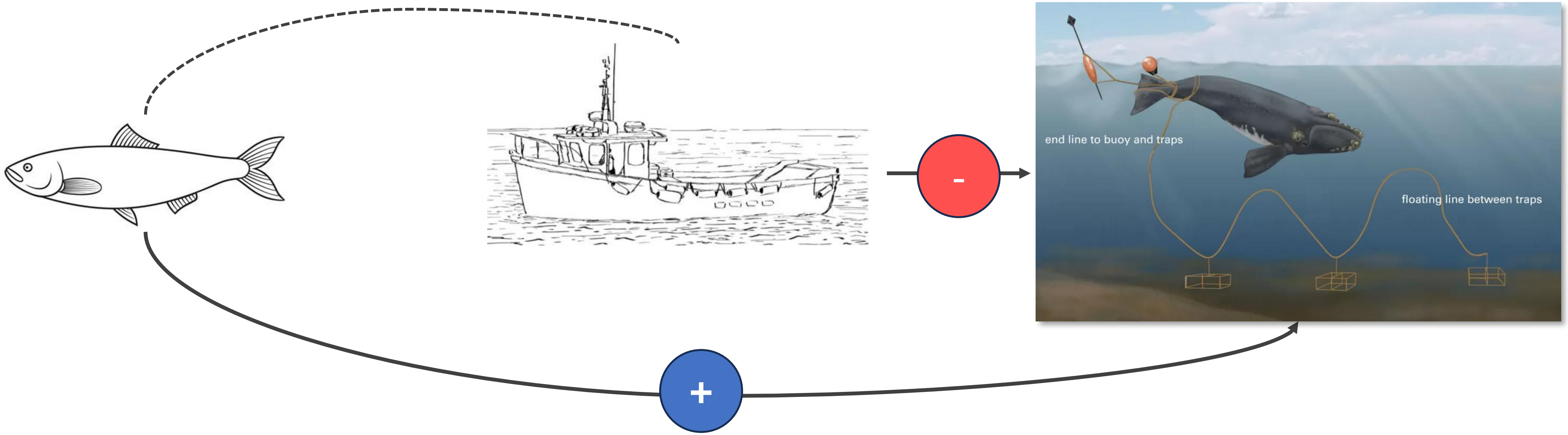
**No. Not in it’s entirety, reality is far too complicated for us to begin to comprehend*

We can do better...

The ‘<u>intellectual leap</u>’ is to be able to think about more than one response variable at a time

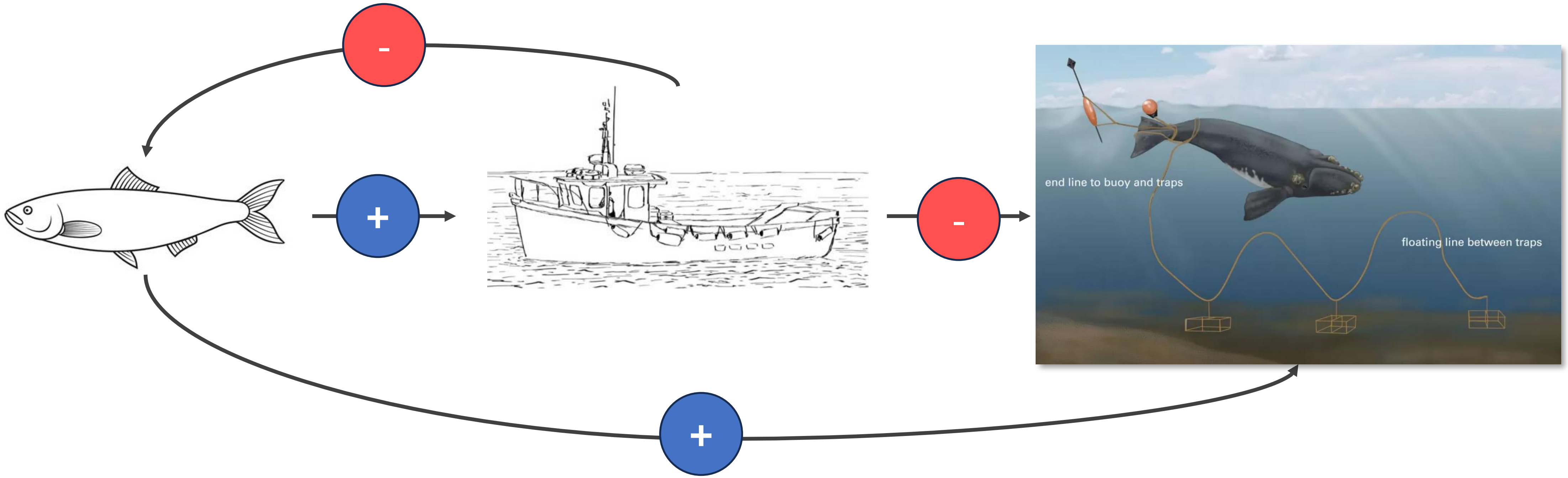
i.e., more than one variable will ‘depend’ on other variables...

GLM problem



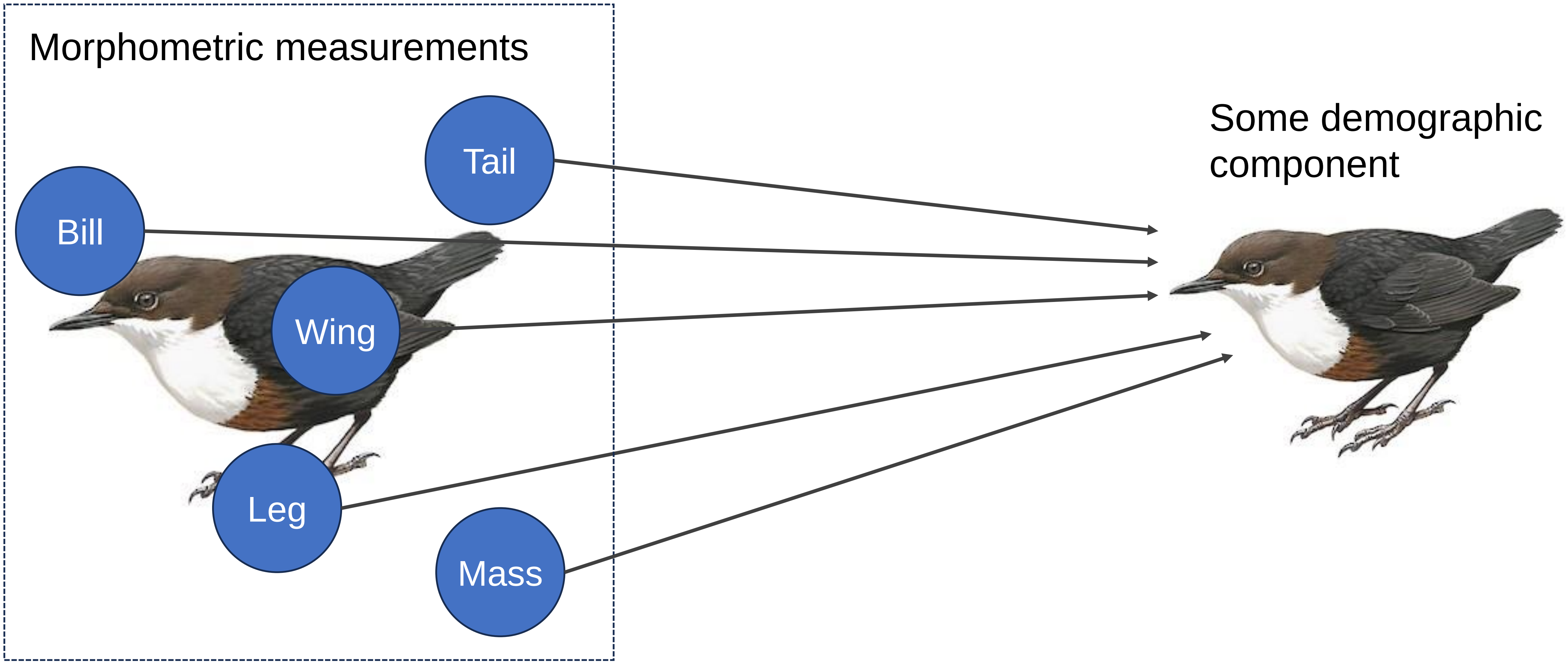
Fish and fishing are collinear because they affect each other

‘Path analysis’ solution



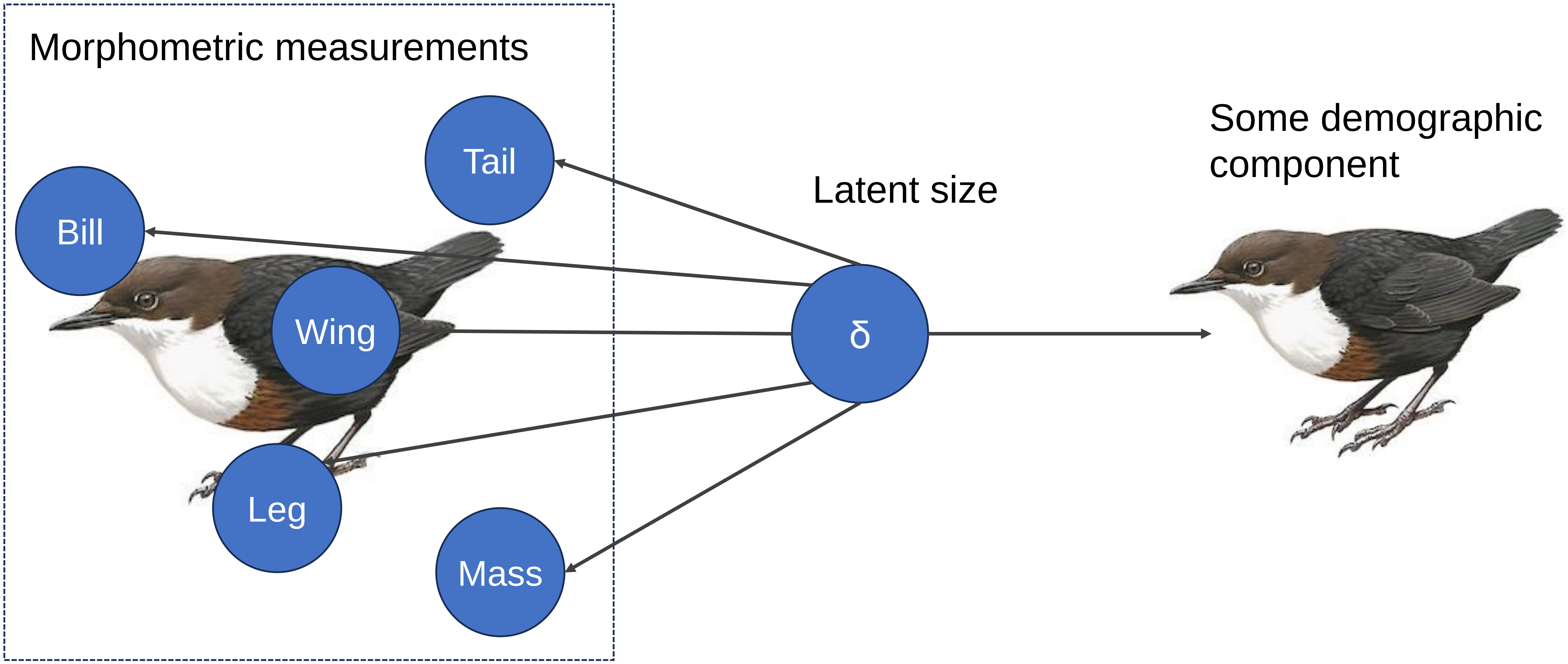
We can explicitly model those relationships

Structural equation model (when covariates arise from a latent process)



These are all measurement of different aspects of ‘size’

Structural equation model (when covariates arise from a latent process)



These are all measurement of different aspects of ‘size’

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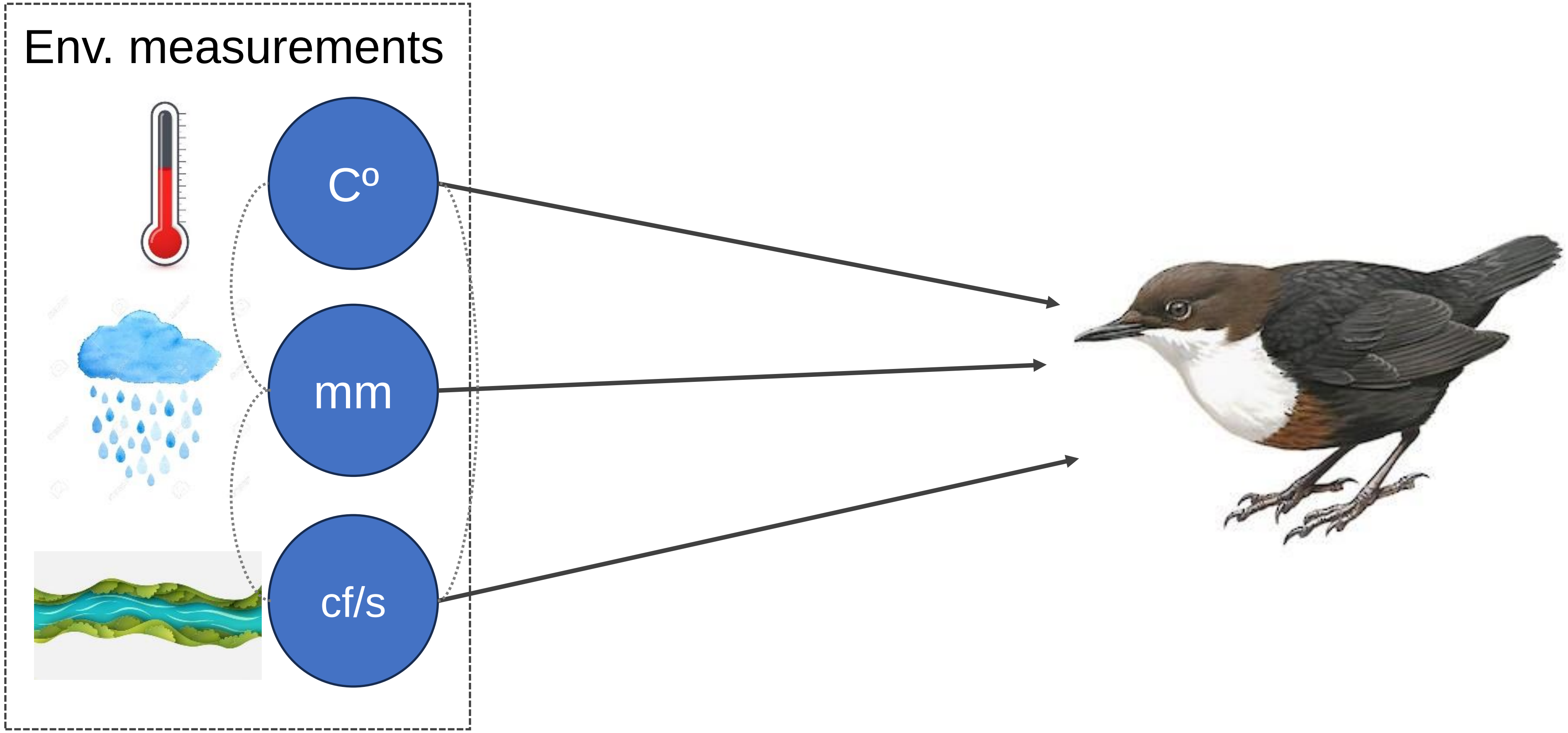
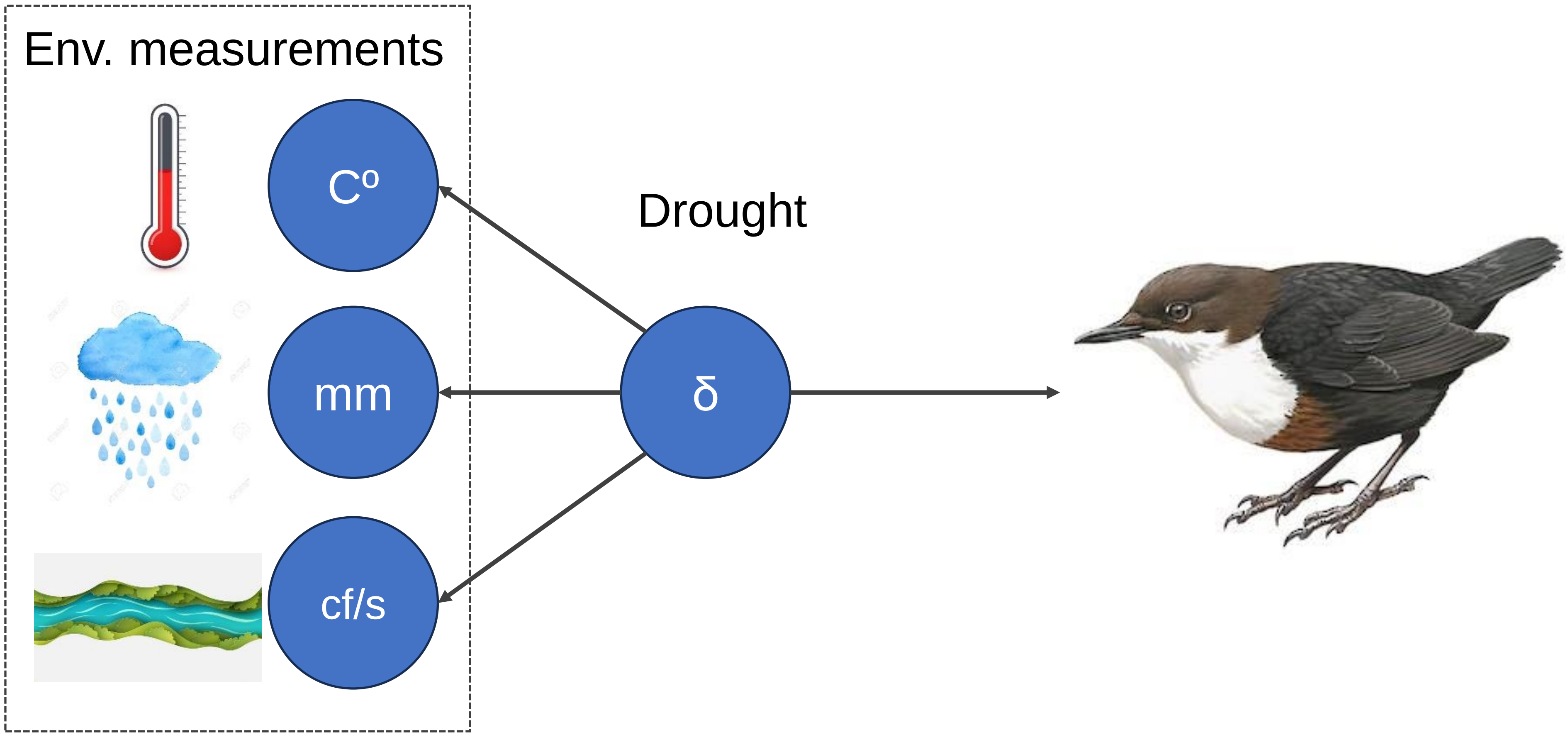


Flow rate, precipitation, and temperature as measurements of hot/dry v. cool/wet

Structural equation model (when covariates arise from a latent process)



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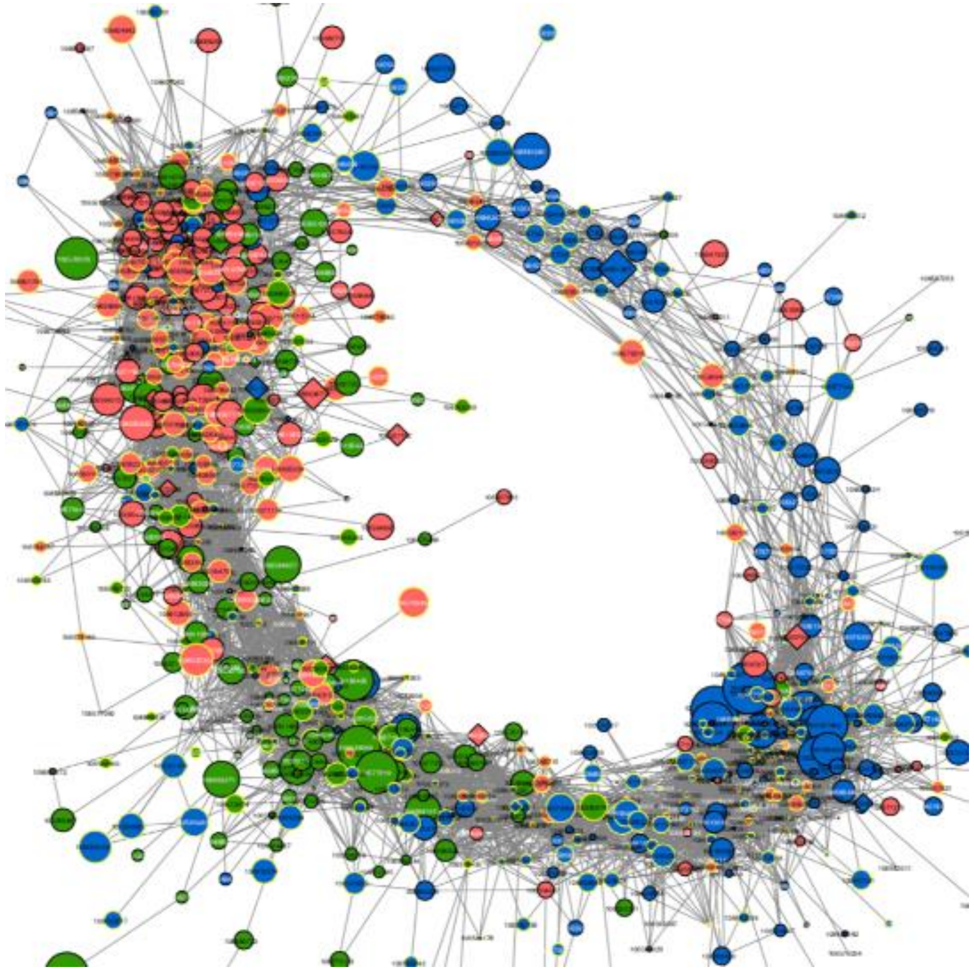

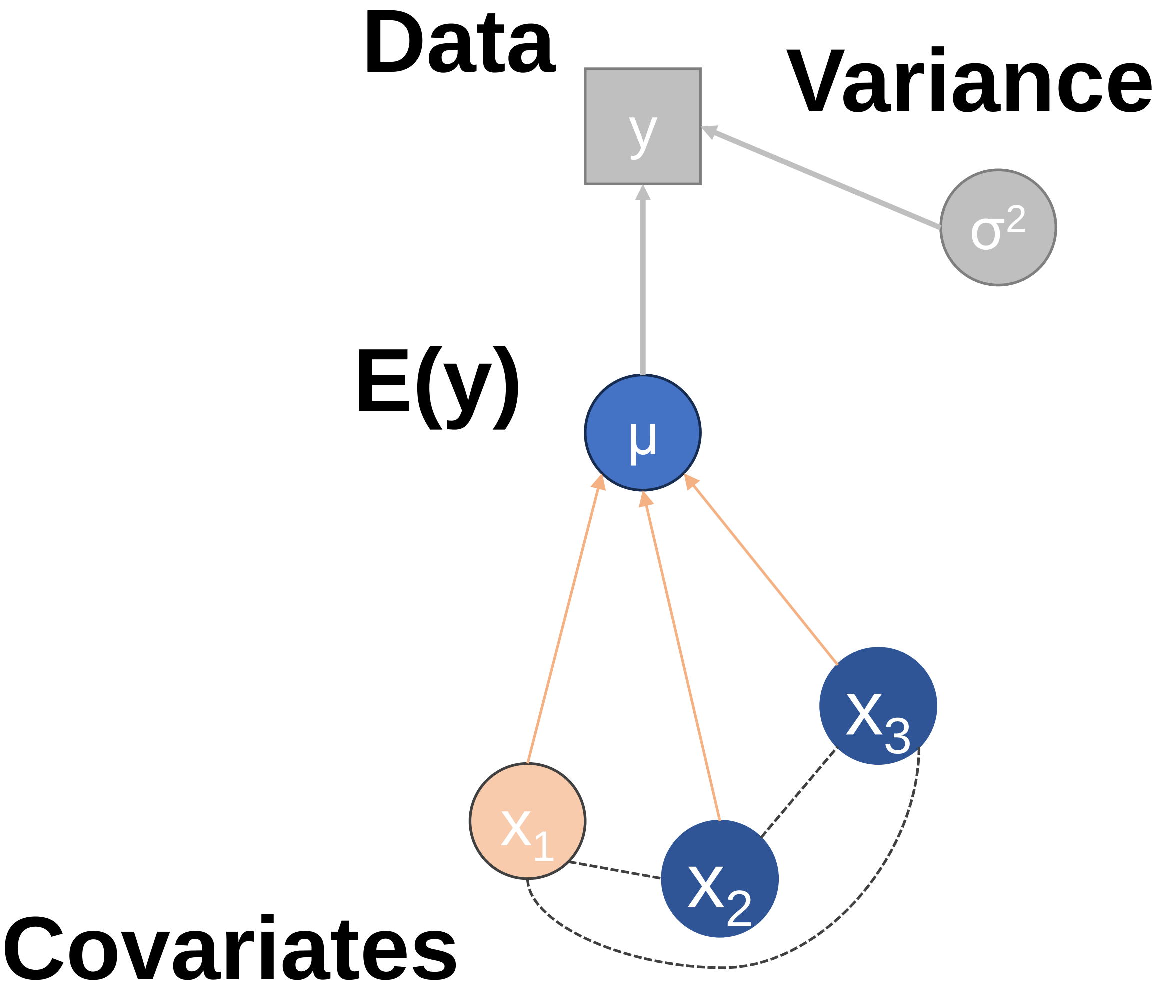

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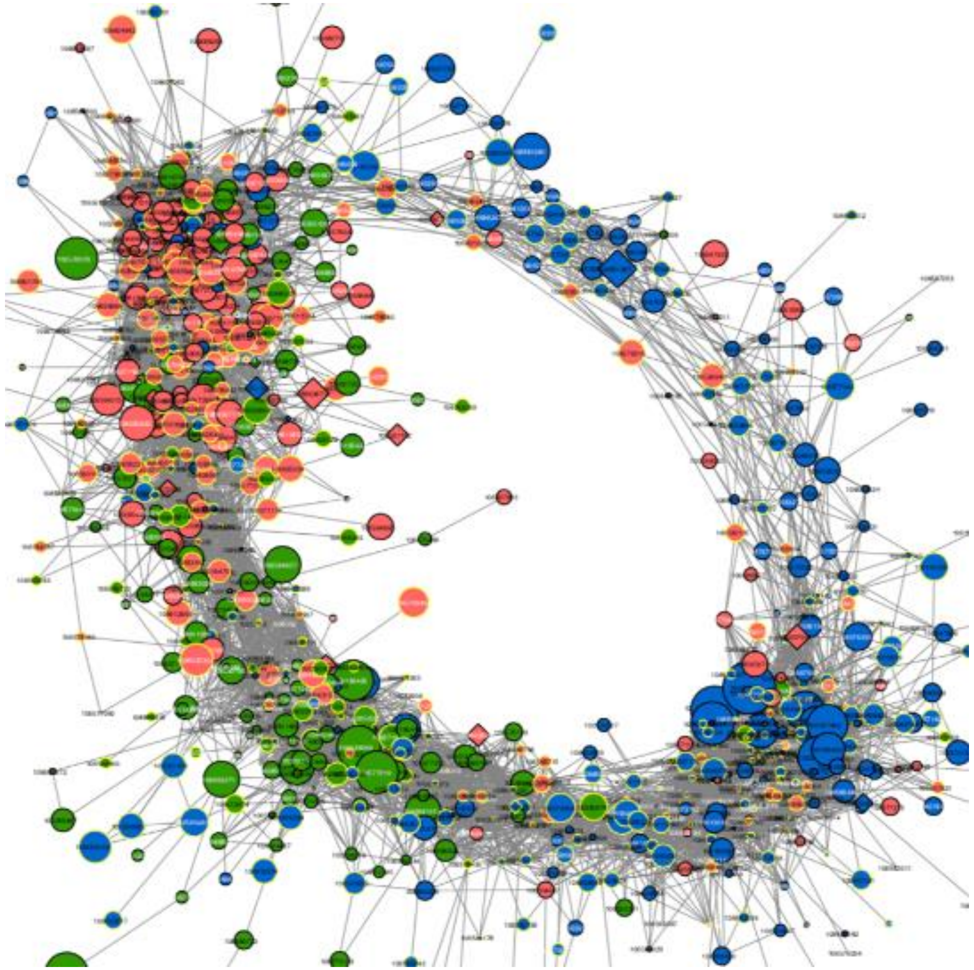

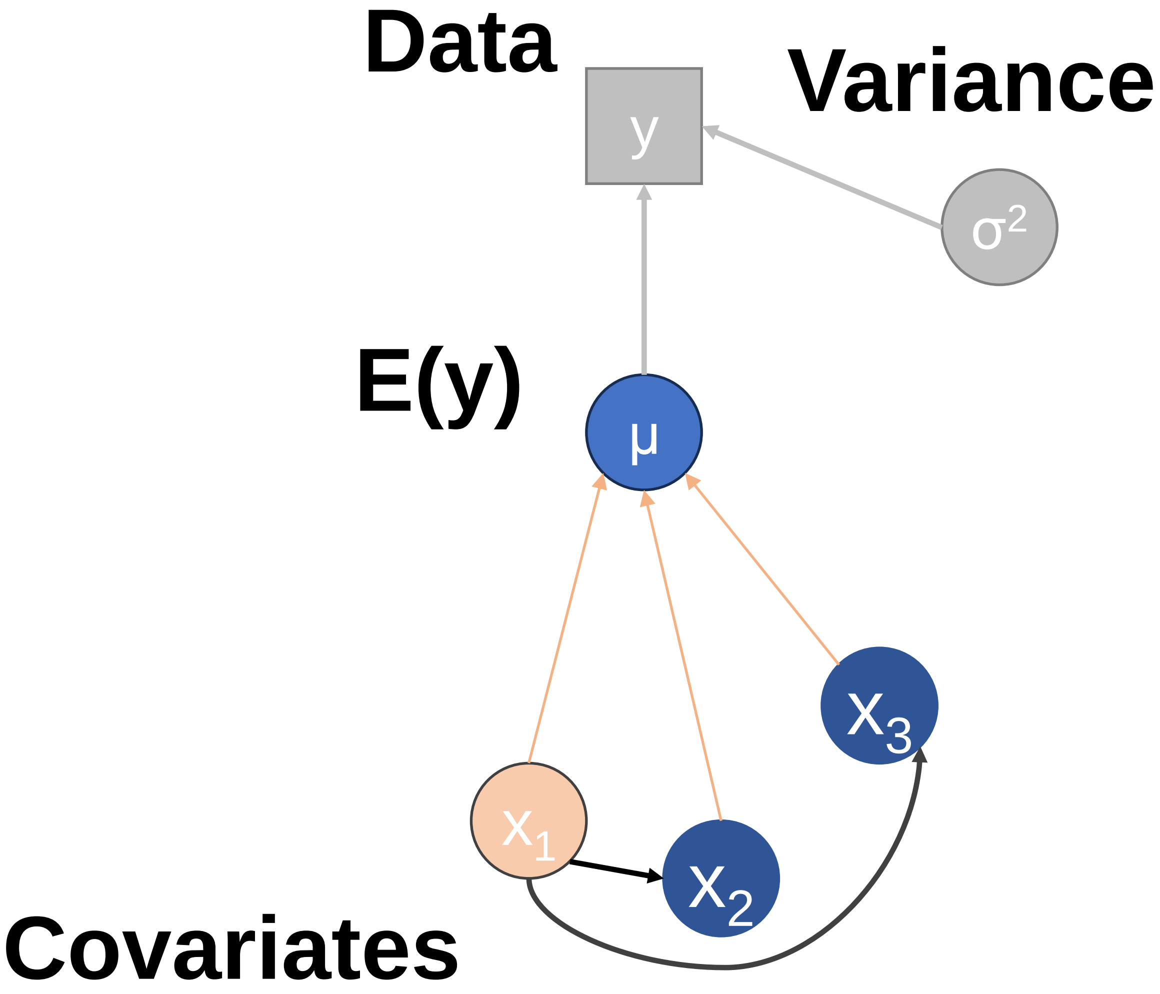

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These can get pretty complicated pretty quickly…

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Journal of Animal Ecology

RESEARCH ARTICLE

Density-dependence produces spurious relationships among demographic parameters in a harvested species

Thomas V. Riecke[1,2,3] | Madeleine G. Lohman[1,2] | Benjamin S. Sedinger[1,2,4] | Todd W. Arnold[5] | Cliff L. Feldheim[6] | David N. Koons[7] | Frank C. Rohwer[8] | Michael Schaub[3] | Perry J. Williams[2] | James S. Sedinger[2]

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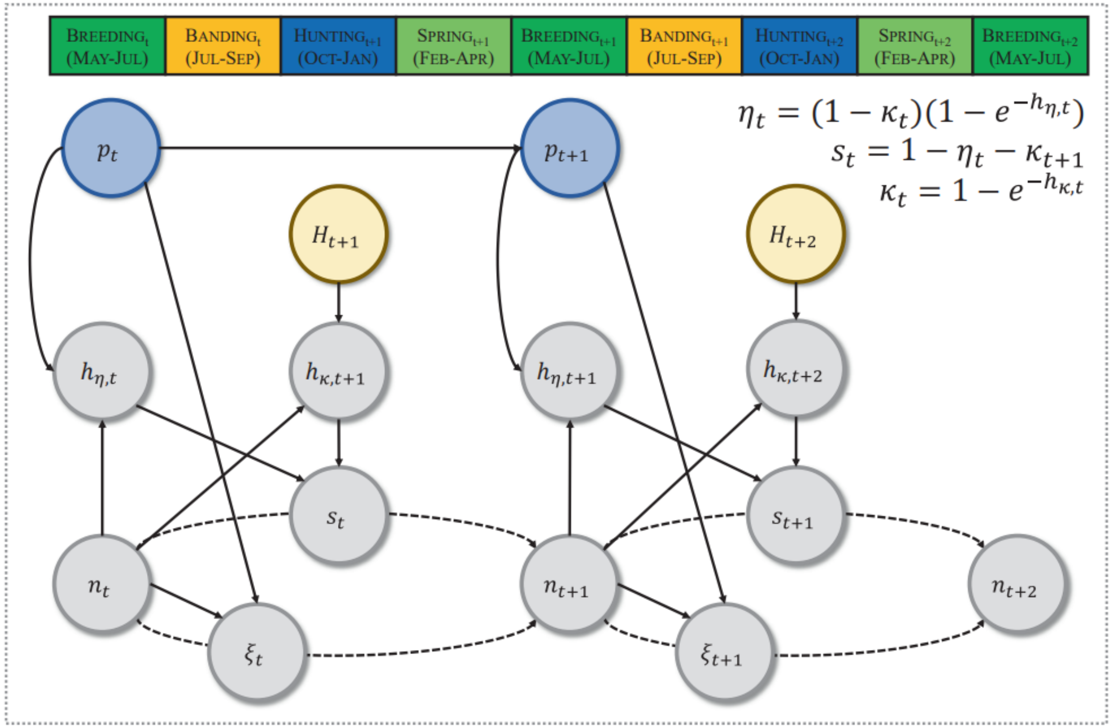

FIGURE 2 A directed acyclic graph demonstrating the relationships among abundance (**n**), ponds (**p**; blue), fecundity (ξ), hunting mortality hazard rate (**h_κ**), natural mortality hazard rate (**h_η**), survival (**s**) and the number of duck hunters (**H**; brown) for blue-winged teal breeding in the North American Prairie Pothole Region across the annual cycle (1973–3016). Solid arrows represent estimated directional relationships, and dashed arrows represent processes leading to changes in population abundance.

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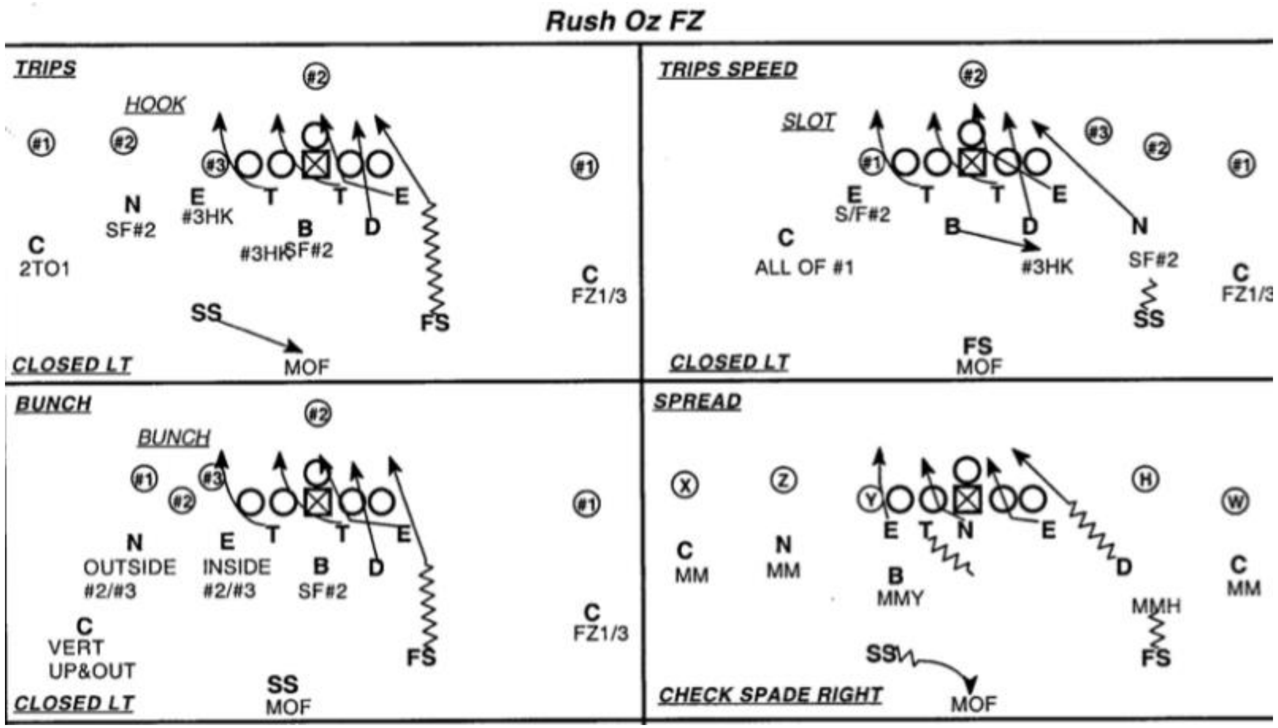

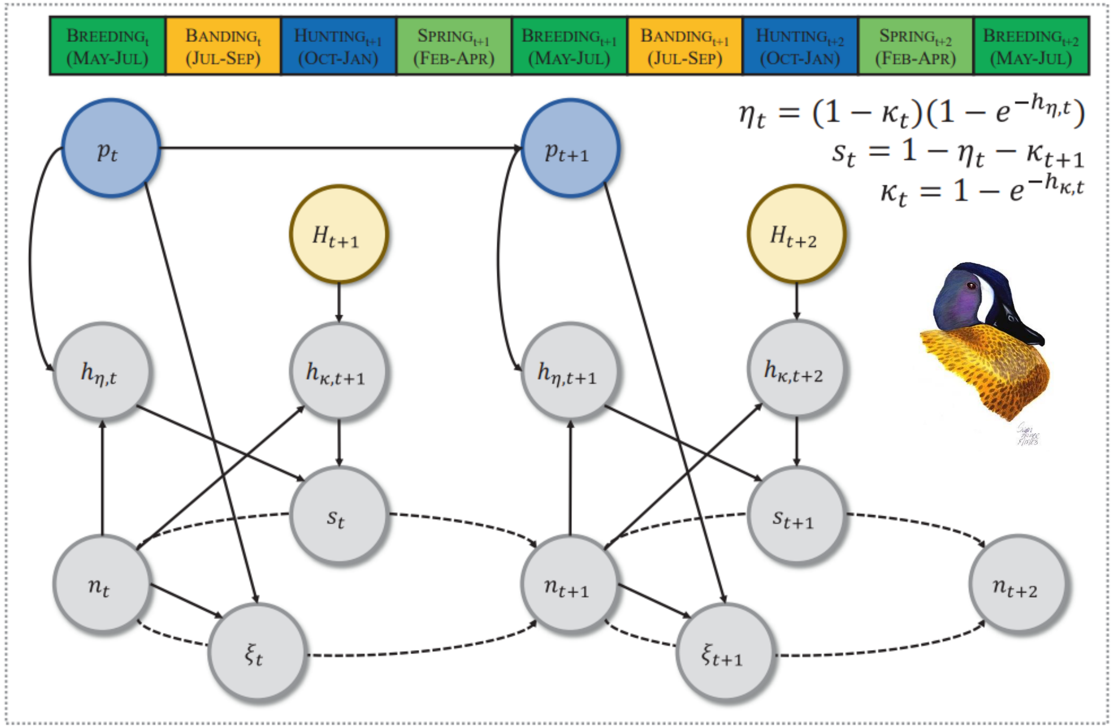

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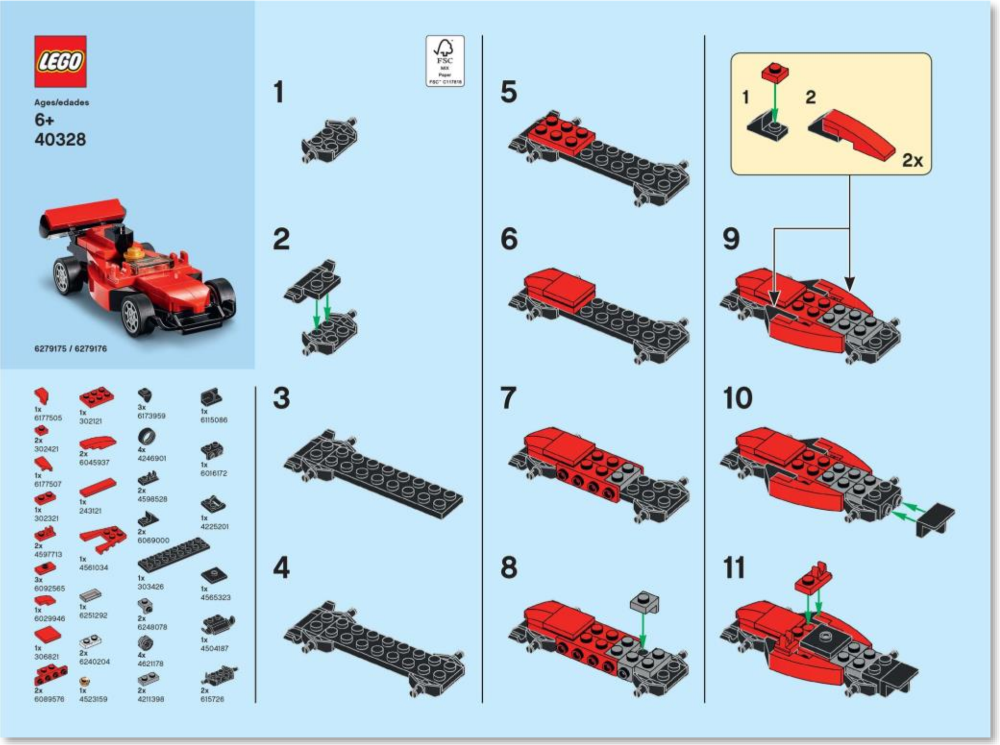

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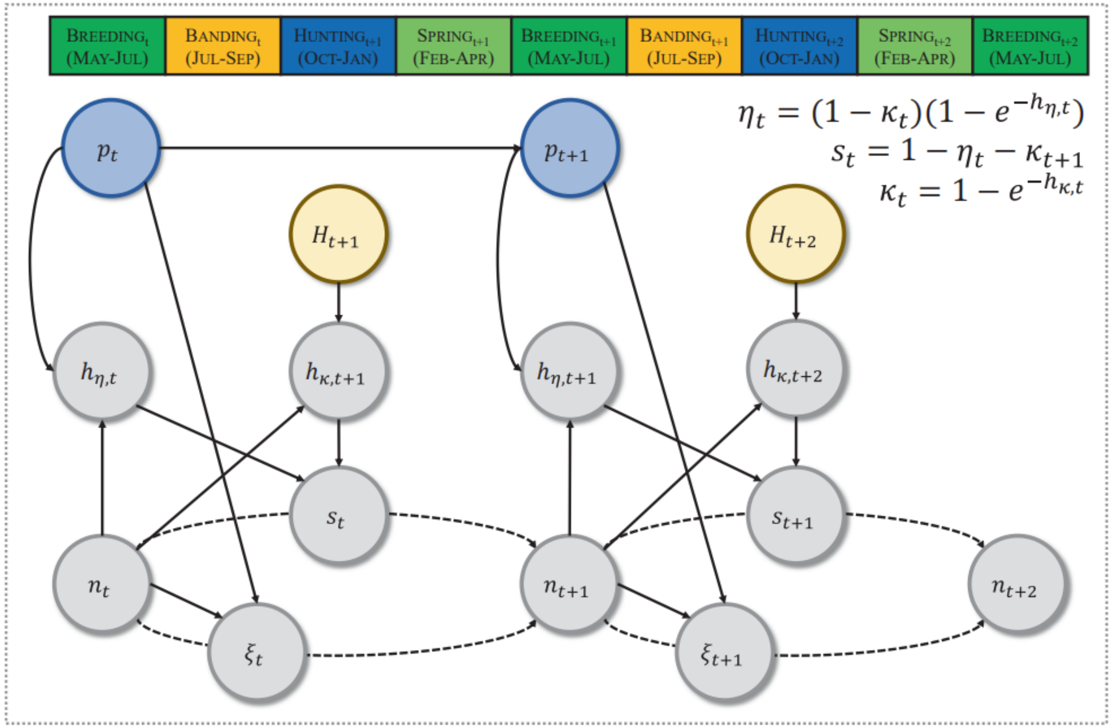

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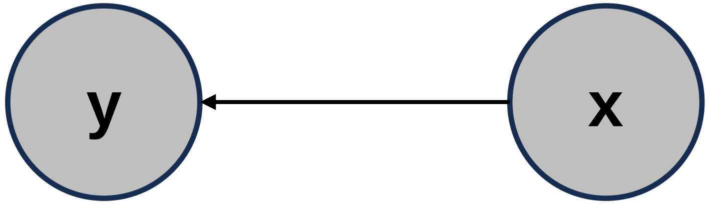
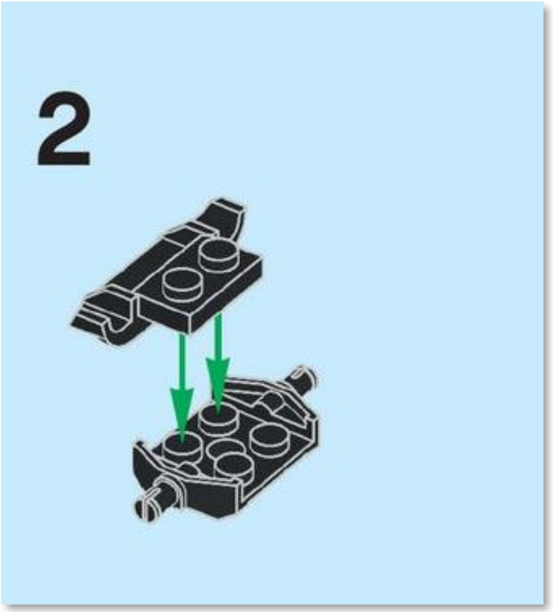
We can overcome this complexity

1. Develop a fundamental understanding of linear models

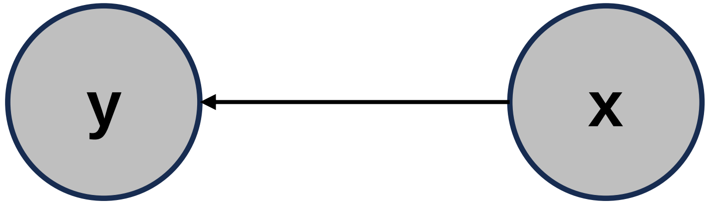


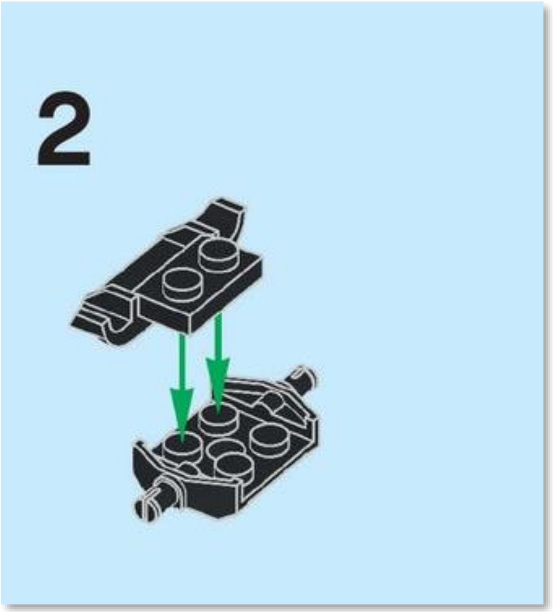


$$y_i \sim \text{normal}(\beta_0 + \beta_1 x_i, \sigma^2)$$

We can overcome this complexity

1. Develop a fundamental understanding of (generalized) linear models



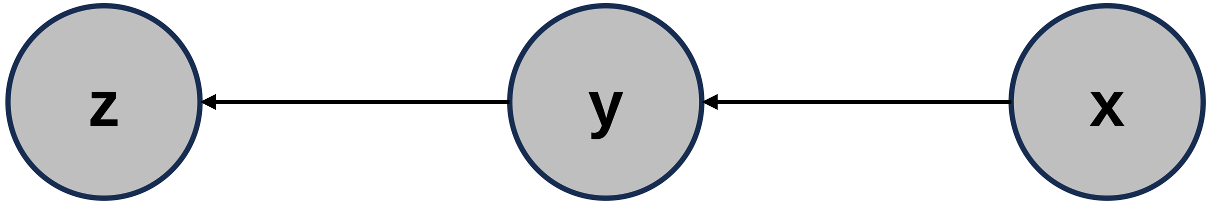


$$y_i \sim \text{lognormal}(\beta_0 + \beta_1 x_i, \sigma^2)$$

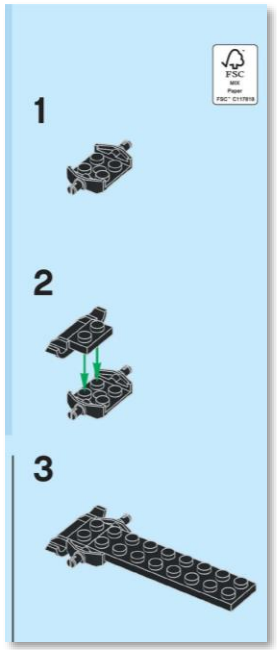
We can overcome this complexity

1. Develop a fundamental understanding of (generalized) linear models

2. Understand that linear models can be applied in ‘layers’ or hierarchies with multiple response variables and multiple measurements of response variables



$$y_i \sim \text{normal}(\beta_0 + \beta_1 x_i, \sigma_y^2)$$
$$z_i \sim \text{normal}(\alpha_0 + \alpha_1 y_i, \sigma_z^2)$$

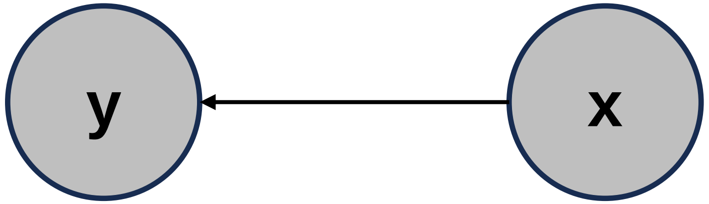


We can overcome this complexity

1. Develop a fundamental understanding of linear models

2. Understand that linear models can be applied in ‘layers’ or hierarchies with multiple response variables and multiple measurements of response variables

3. Understand that’s what structural equation models and path analyses are...



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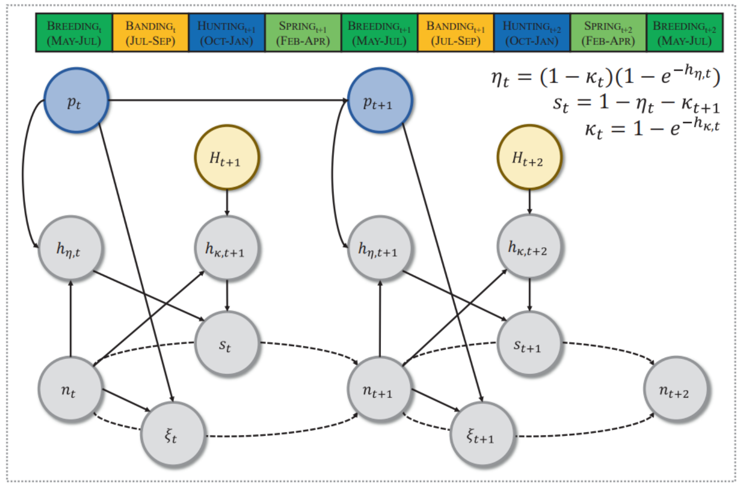

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Goals of this class

1. Develop a fundamental understanding of linear models

2. Understand that linear models can be applied in ‘layers’ or hierarchies with multiple response variables and multiple measurements of response variables

3. Understand that’s what structural equation models and path analyses are, and apply these concepts to your own data (if you want?)

How are we going to get there?

- **PART I. Introduction and linear models**
  - **Week 1:** *Why SEM? Why Bayesian?*
  - **Week 3:** *Linear models*
  - **Week 4:** *Generalized linear models*

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- **PART II. Structural equation models**
  - **Week 5:** *Direct and indirect effects*
  - **Week 6:** *Latent variables*
  - **Week 7:** *Composite covariates and cross-lags*

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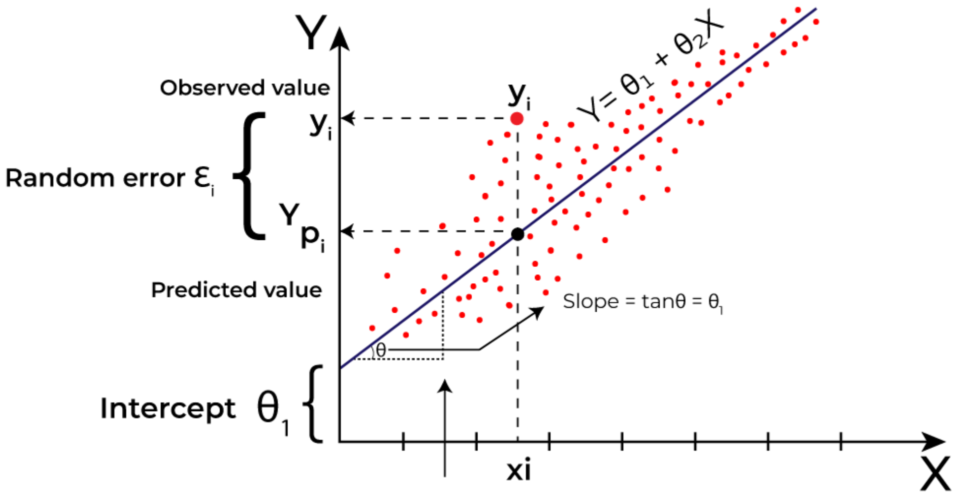
- **PART II. Structural equation models**
  - **Week 5:** *Direct and indirect effects*
  - **Week 6:** *Latent variables*
  - **Week 7:** *Composite covariates and cross-lags*
- **PART III. Case studies to reinforce concepts**
  - **Week 8:** *Resource selection and reproductive success*
  - **Week 9:** *Occupancy and body condition*
  - **Week 10:** *Cross-lags: life-history trade-offs*
  - **Week 11:** *Cross-lags: density-dependence and harvest*

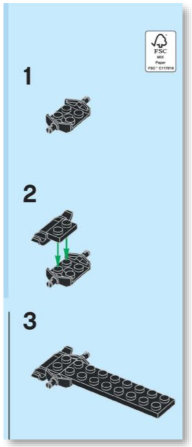
Things you need to do by next week

- **Install programs**
  - *JAGS*
  - *The latest version of R*
  - *The latest version of RStudio*
- **Install packages**
  - *jagsUI*
  - *rstan*
  - *rtools*
  - *vioplot*
- **Run test scripts from course GitHub**

A note on ‘attitude’

- Parts of this class are going to be extremely complicated. That’s a good thing.

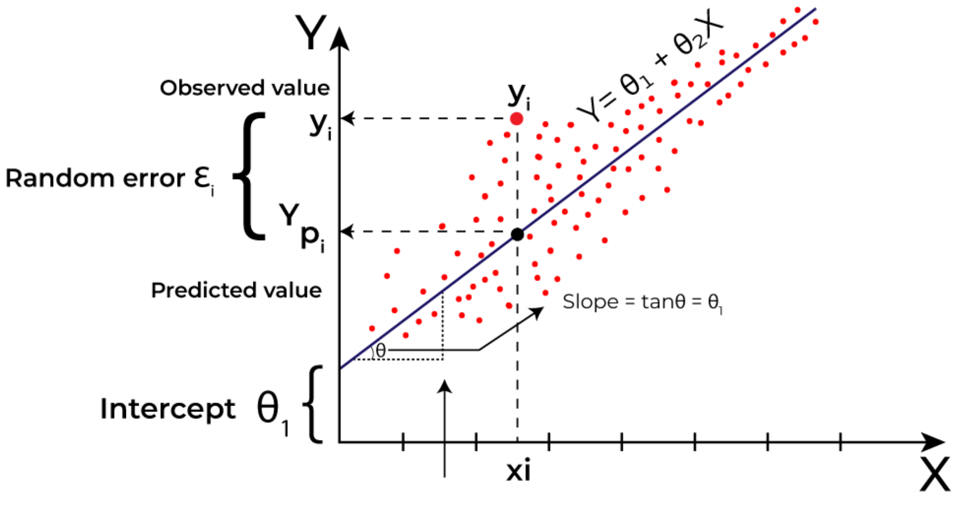


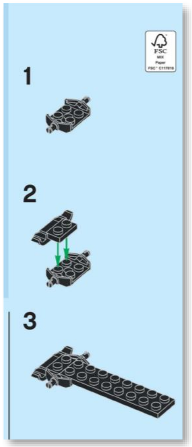


A note on ‘attitude’

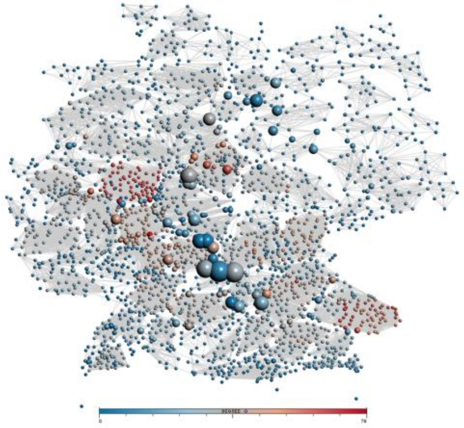
- Parts of this class are going to be extremely complicated. That’s a good thing.

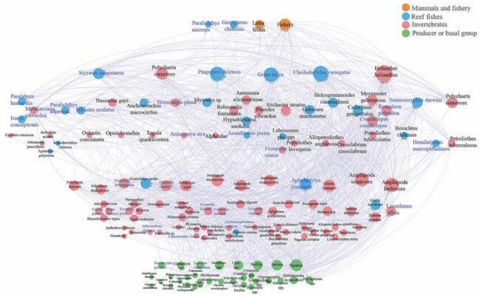
- <u>**Three goals for learning**</u>
  1. Don’t give up. These are all ‘expanded’ or more complicated <u>linear models.</u>
  2. Set <u>realistic goals</u>, and celebrate small achievements/progress!
  3. Ask questions.

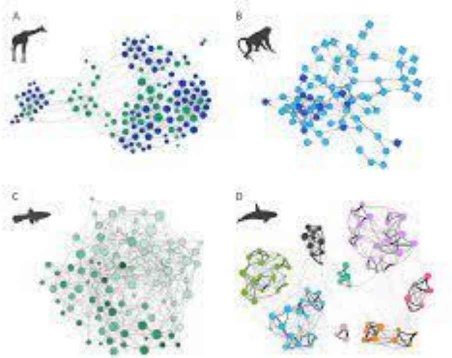


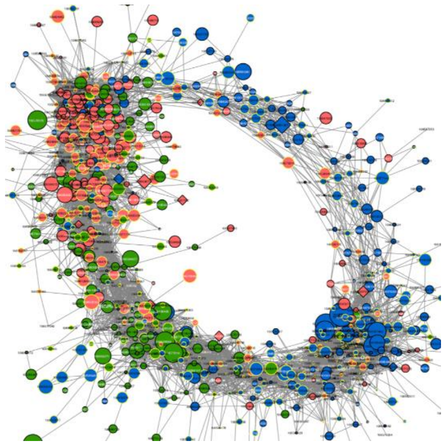


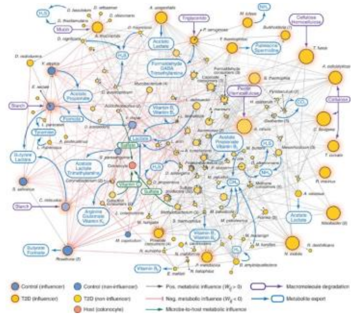
We’re never going to model reality











Climate network
Abiotic systems

Food Network
Among populations

Social Network
Within populations

Gene Network
Within individuals

Microbial Network
Within individuals

No models are right, and most are useless – TW Arnold

SEMs let us get closer (maybe a little more useful?)

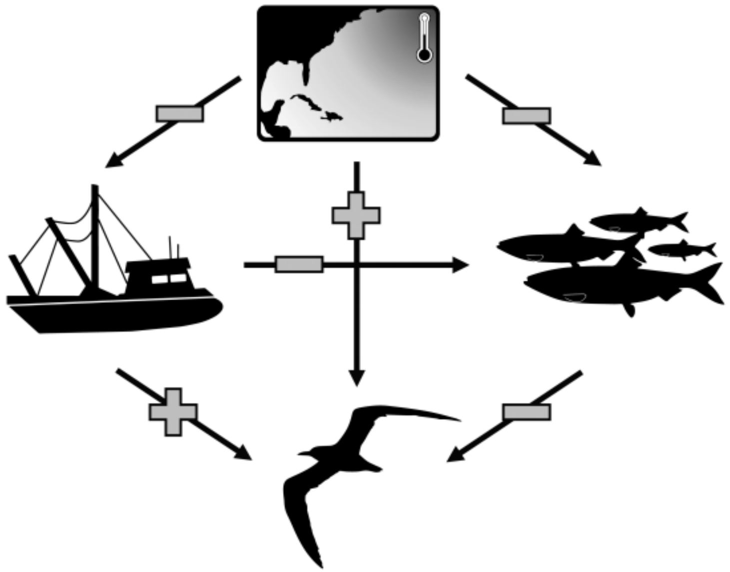
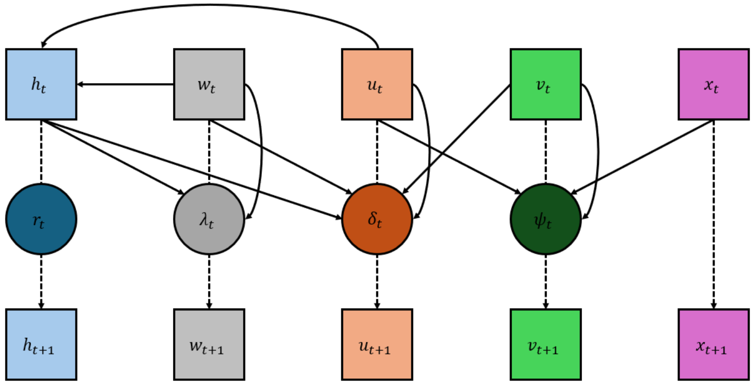


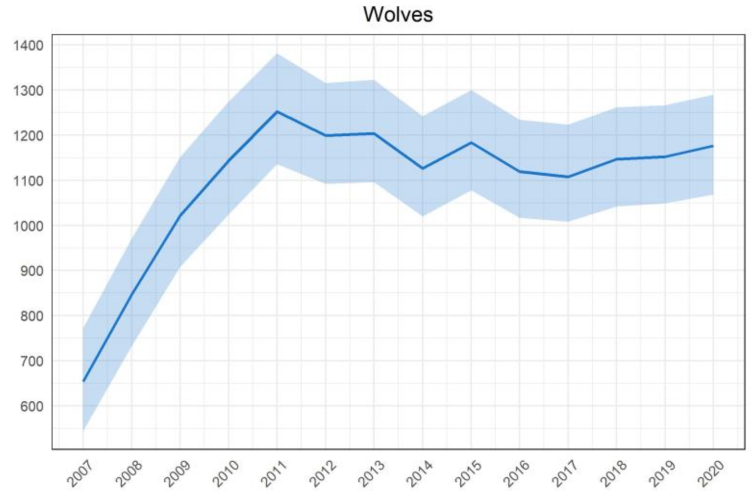
FIGURE 1 Simplified path diagram describing the hypothesized directionality (plus: Positive, bar: Negative association) regarding how environmental variables (i.e., sea-surface temperatures in the North Atlantic, fishery pressure, and fish production) influenced one another, as well as the indirect and direct pathways in which these sources of environmental variability influenced Royal tern mortality.

Cross-lags and wildlife harvest: better models for critical decisions



Let’s start controversially and close to home!

MT wolf population recovery and harvest (2008 – present)



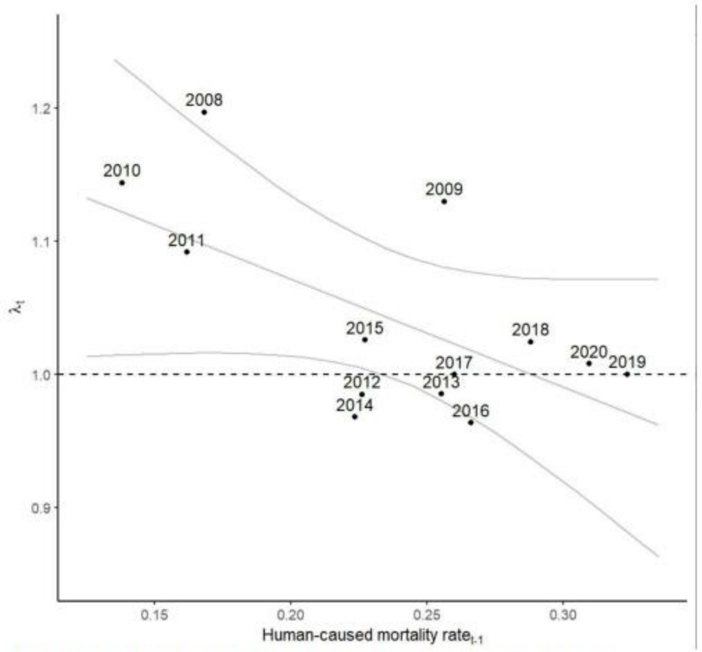
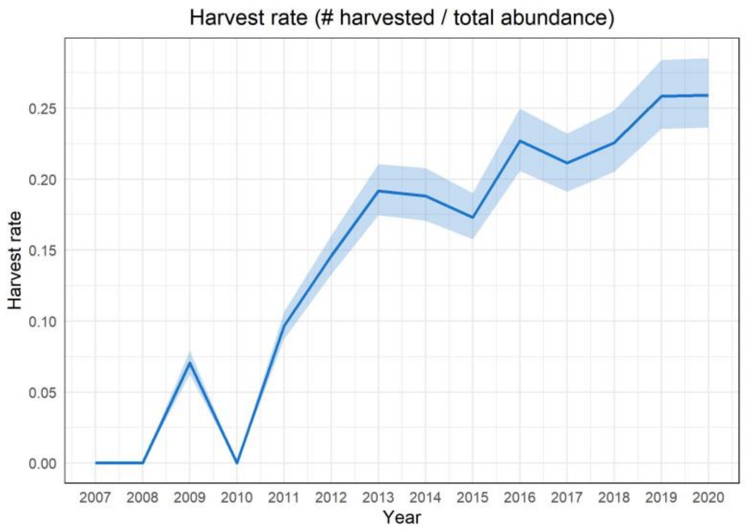
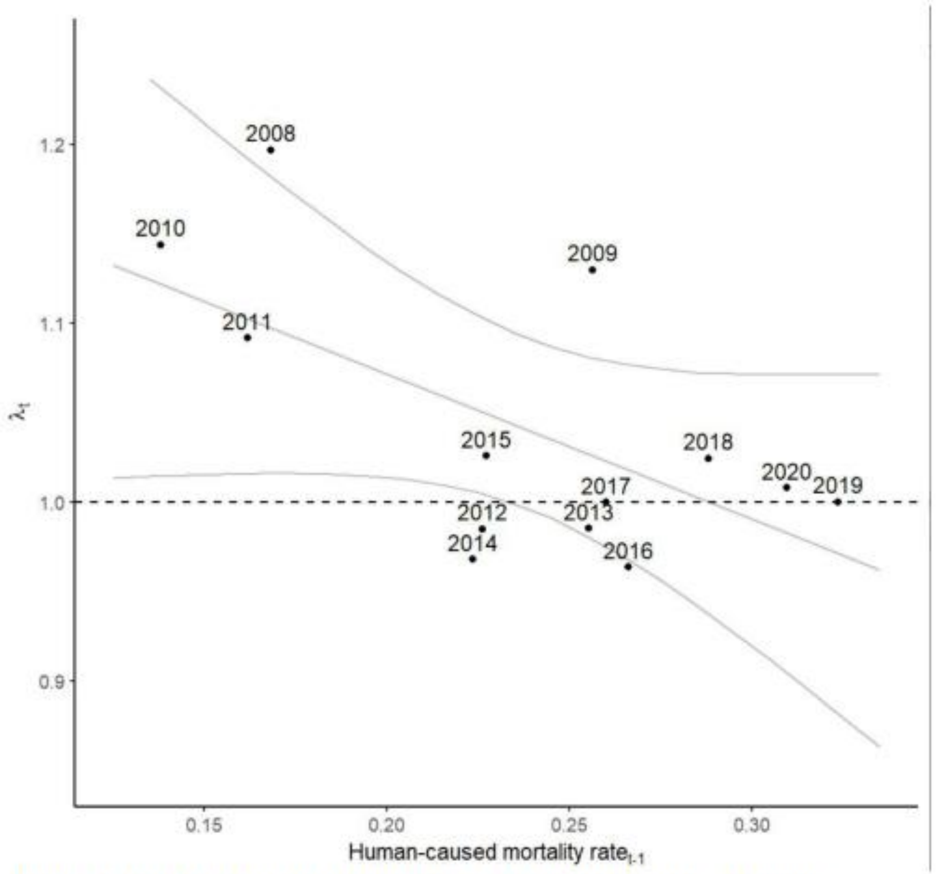


Figure 2. Estimated linear relationship and 90% credible intervals (grey lines) between annual population growth rate (λ_t) and human-caused mortality rate (human-caused mortalities$_t$ / iPOM wolves$_{t-1}$). The human-caused mortality rate resulting in an expected stable population (λ= 1) is approximately 29%.



Population is stable at m = 0.29?



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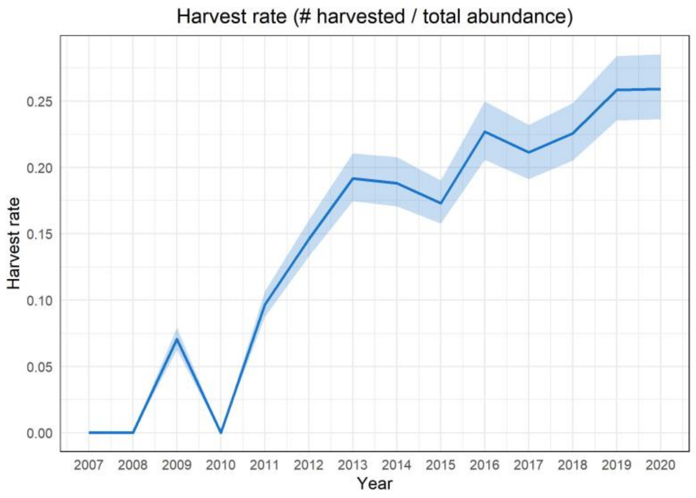
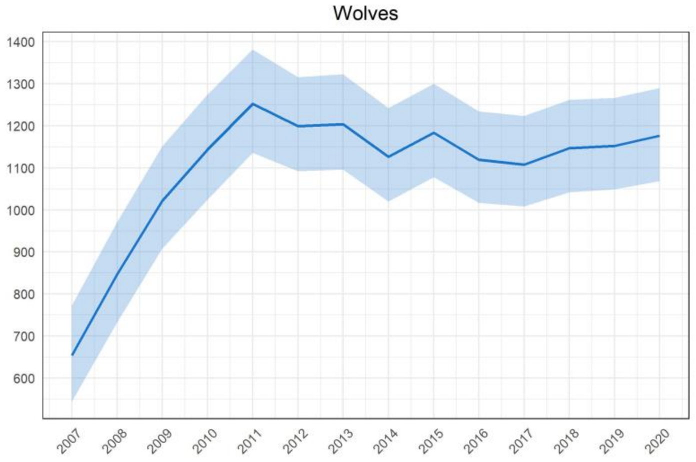
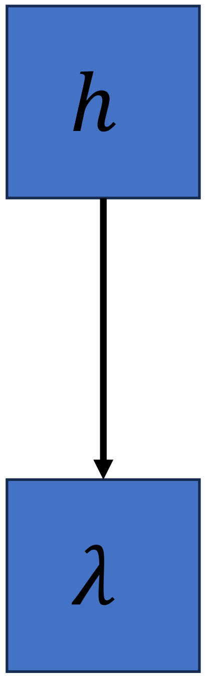
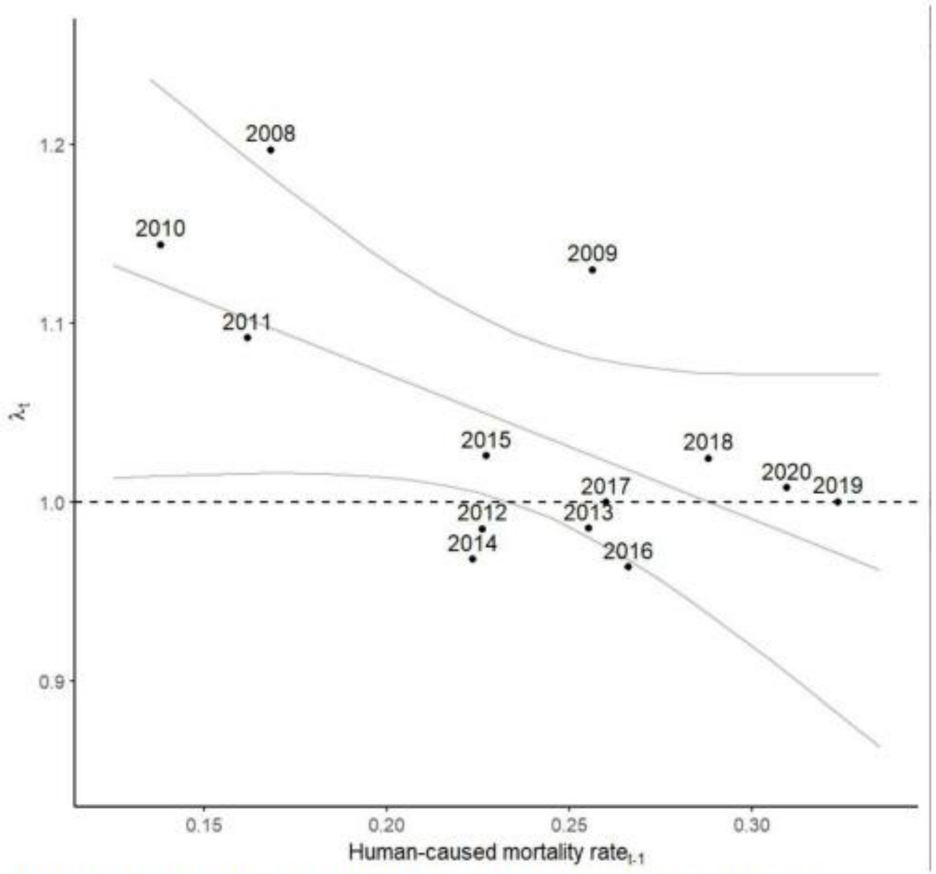






Ok, what about m = 0 [counter-factual]?



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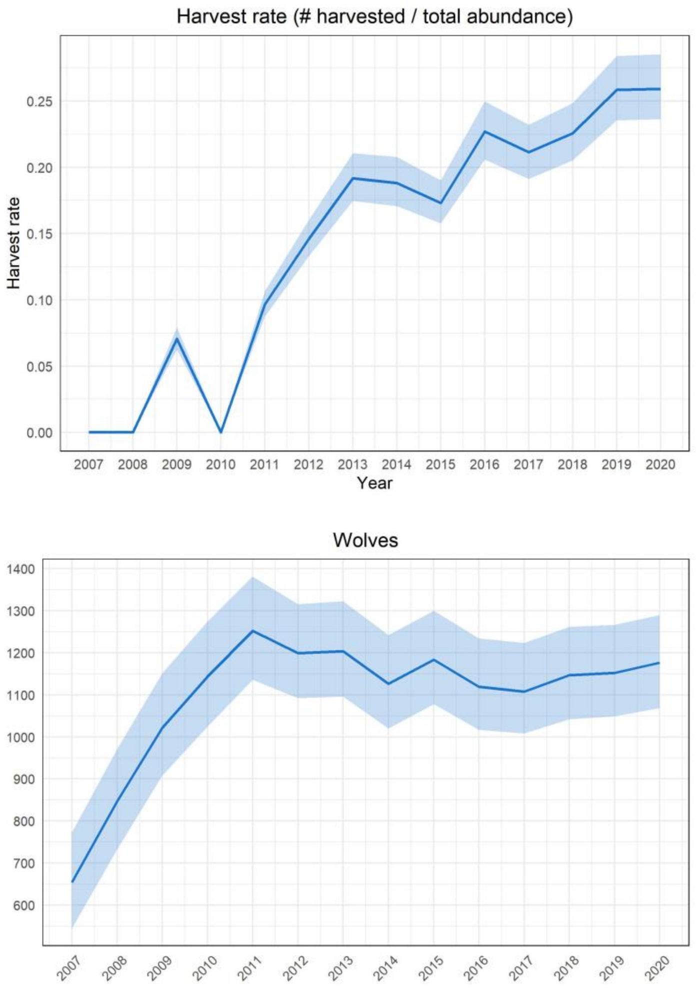
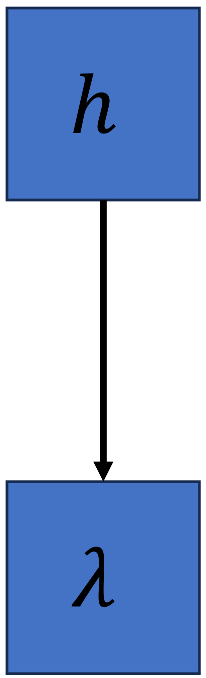
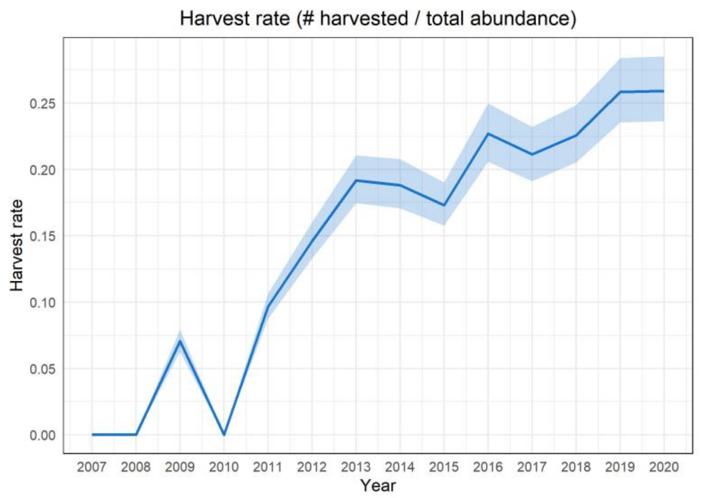
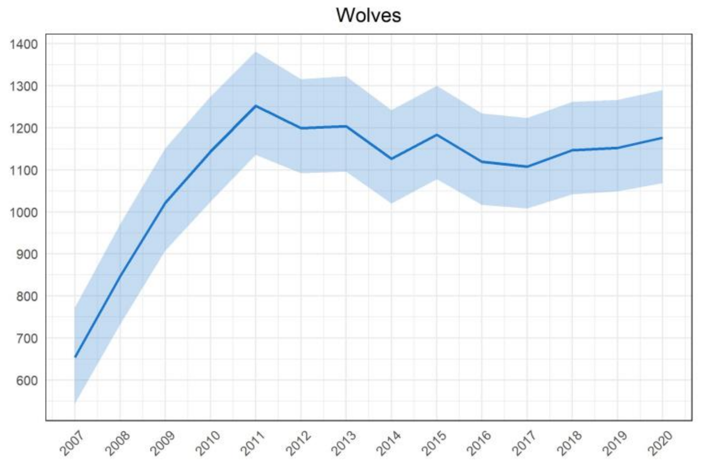


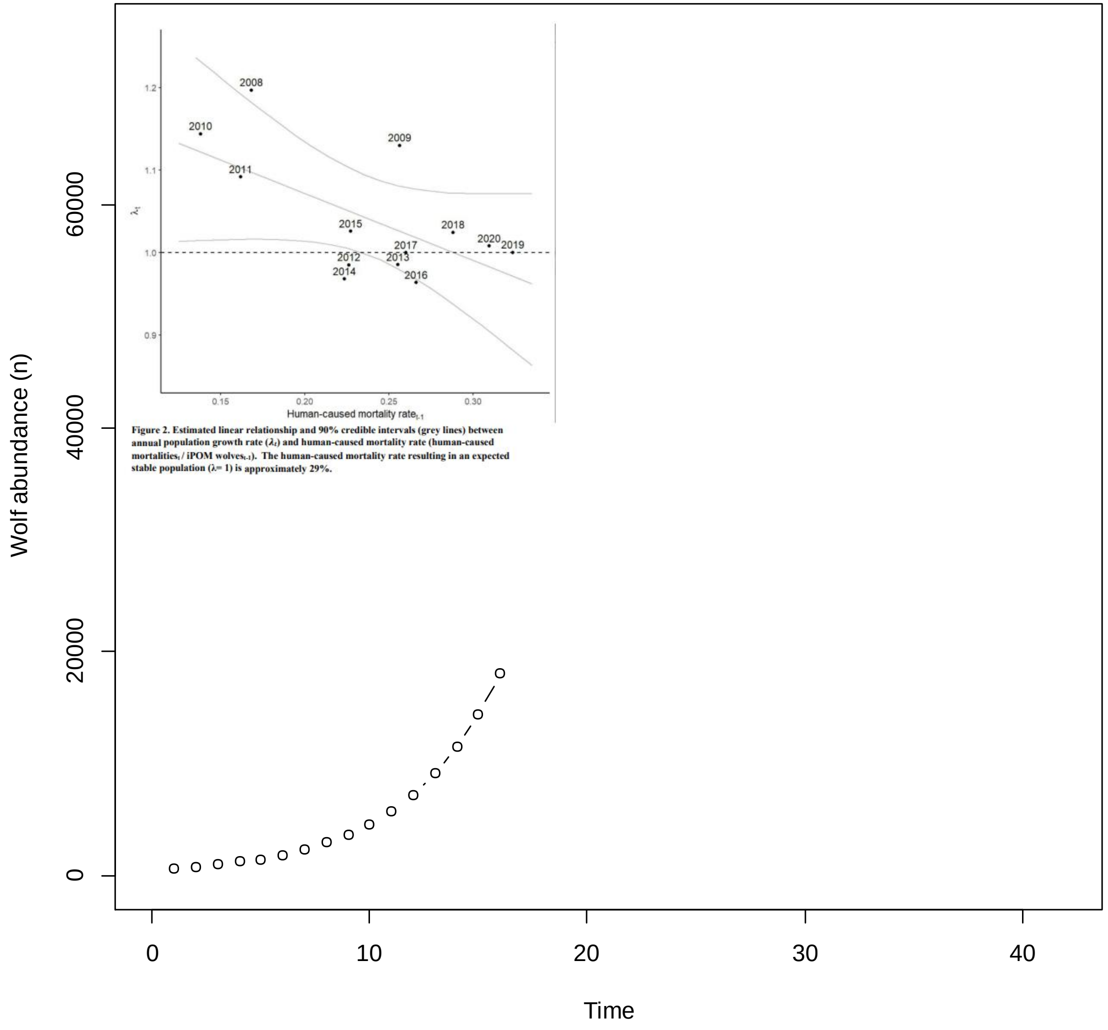


Population growth (λ) at m = 0 is approximately 1.25

Projected increase w/o harvest (16 years or 2024; 17k)

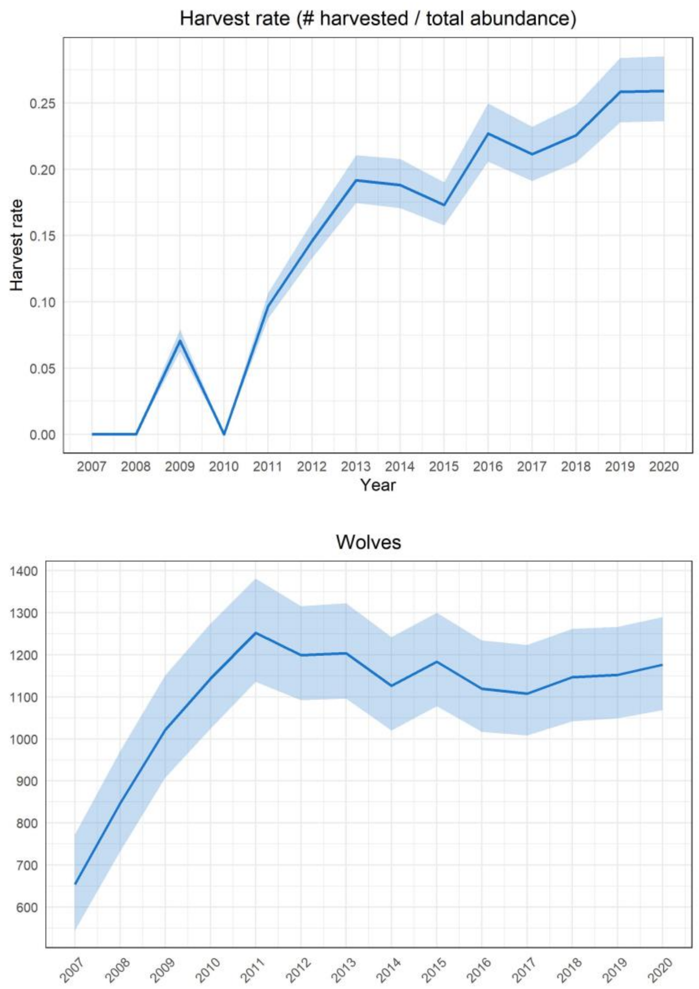


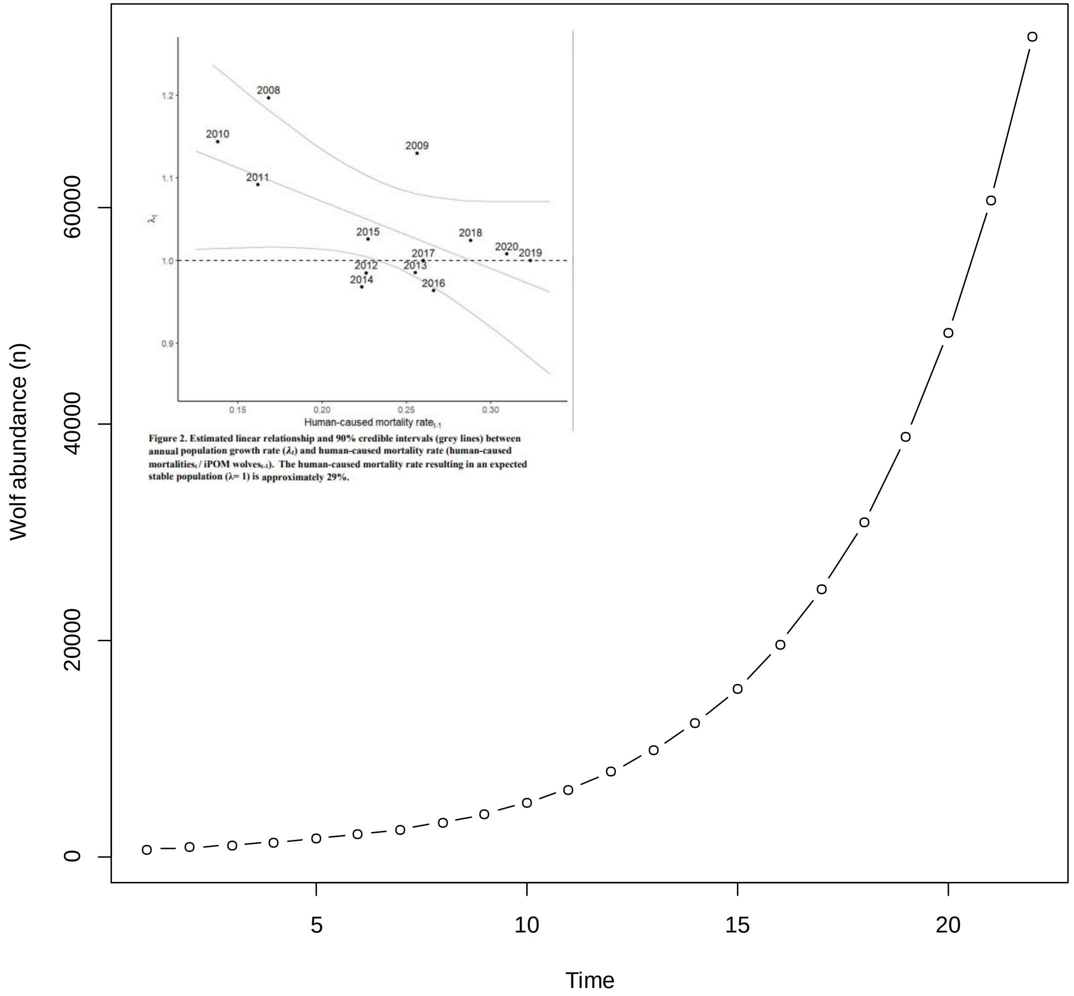




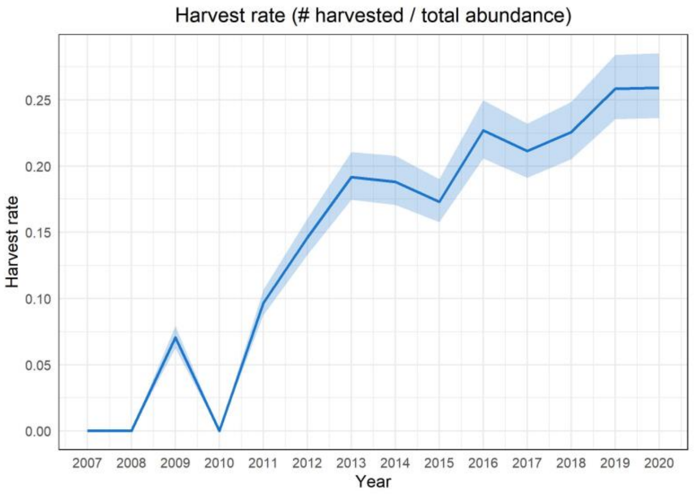
Population growth at m = 0 is approximately 1.25

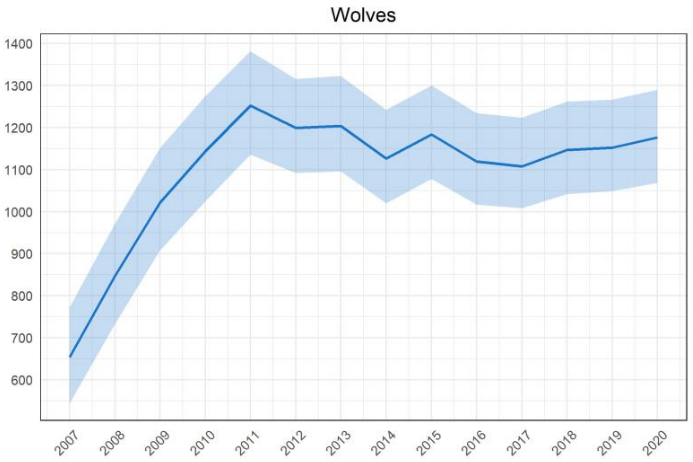
Projected increase w/o harvest (22 years or 2030; 75k)

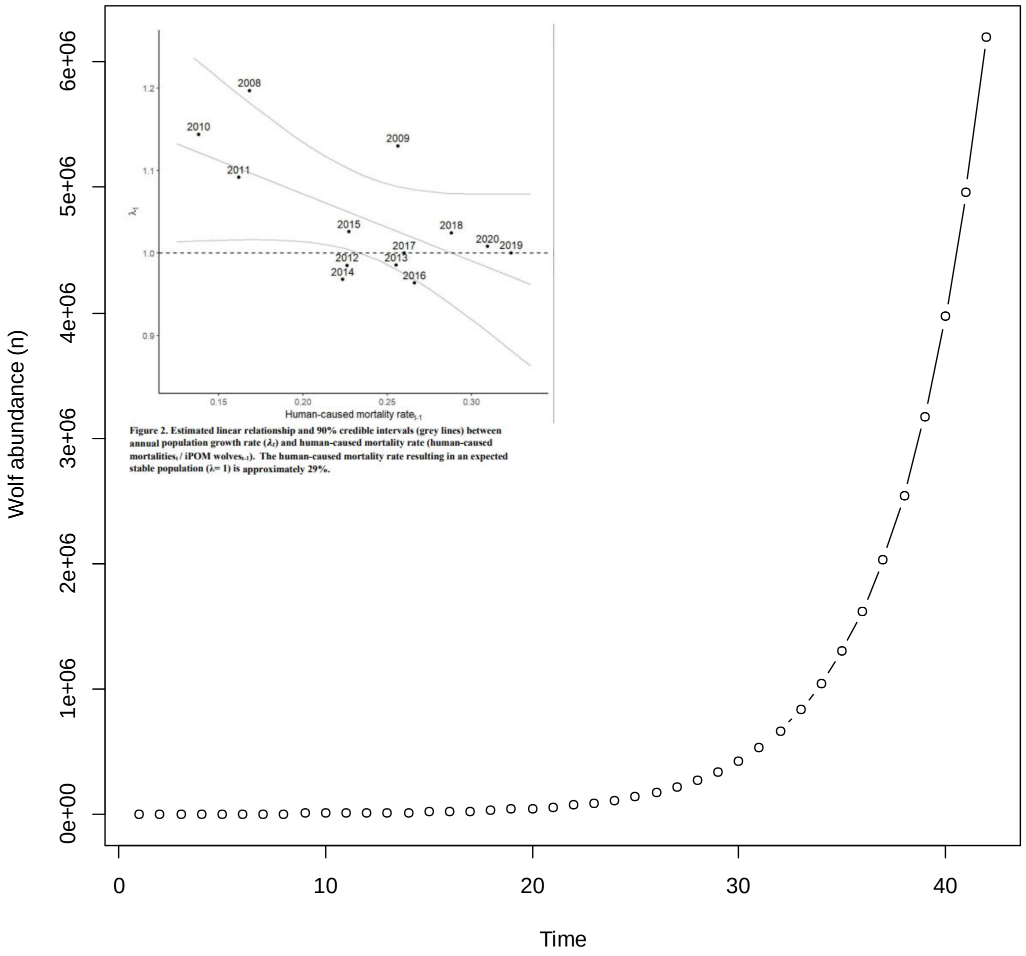




Projected increase w/o harvest (42 years or 2050; 600k)







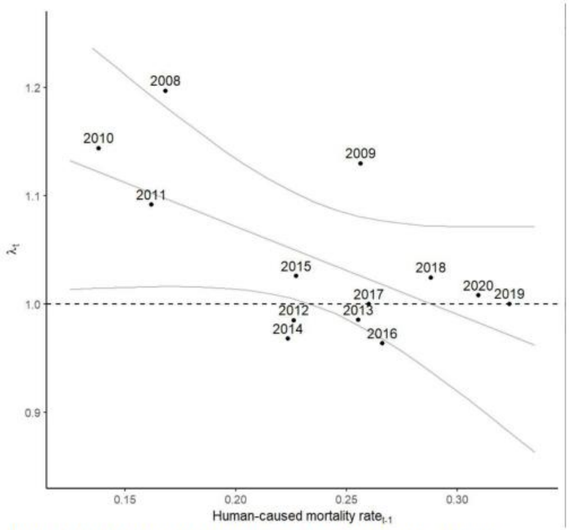


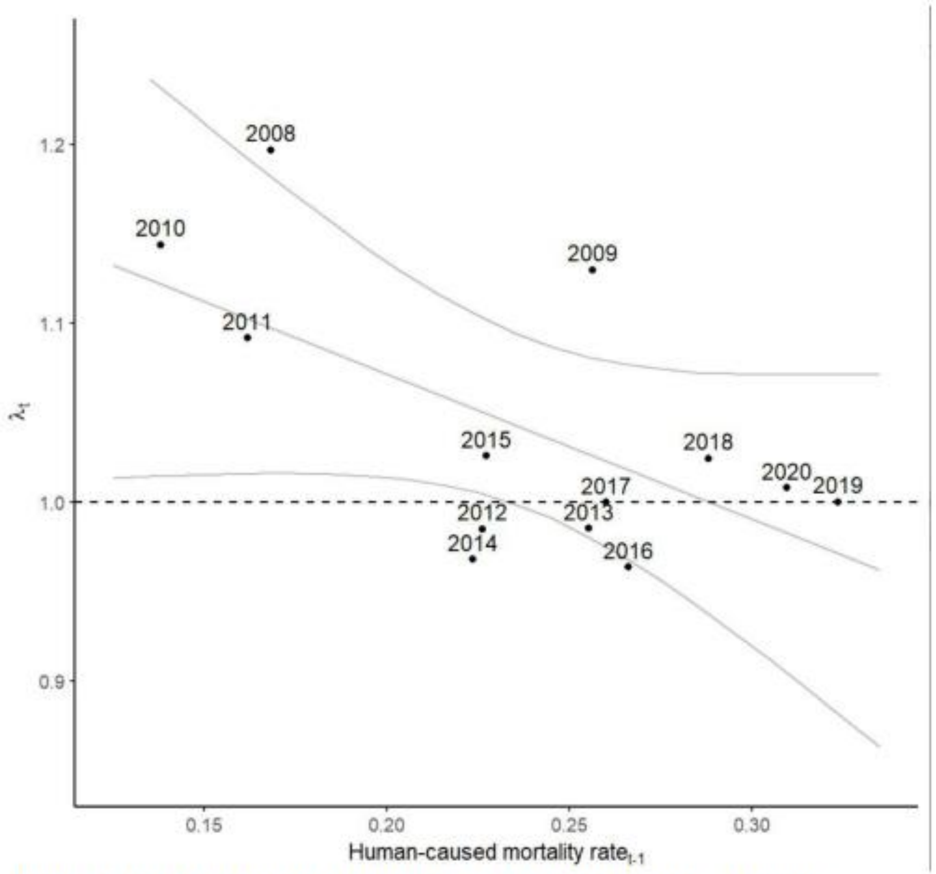
Figure 2. Estimated linear relationship and 90% credible intervals (grey lines) between annual population growth rate (λ_t) and human-caused mortality rate (human-caused mortalities$_t$ / iPOM wolves$_{t-1}$). The human-caused mortality rate resulting in an expected stable population (λ= 1) is approximately 29%.

It has been stable at h = 0.29…

I don't think it will increase at 25% forever at h = 0
(absurd <u>counterfactual</u>!)

What's happening?

It’s stable at h = 0.29 & N ~ 1100



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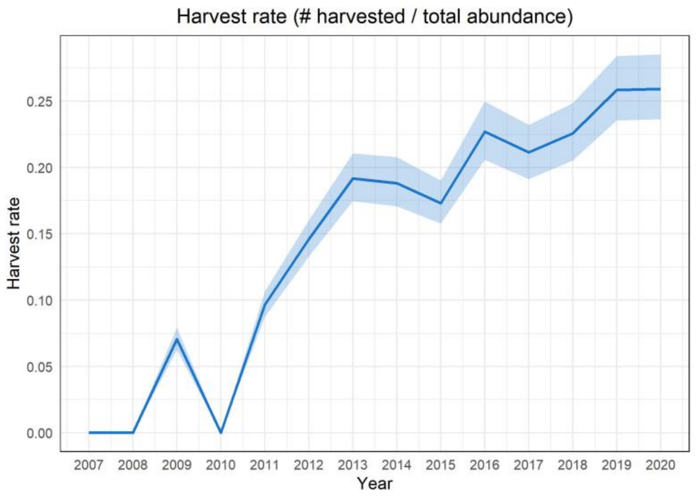
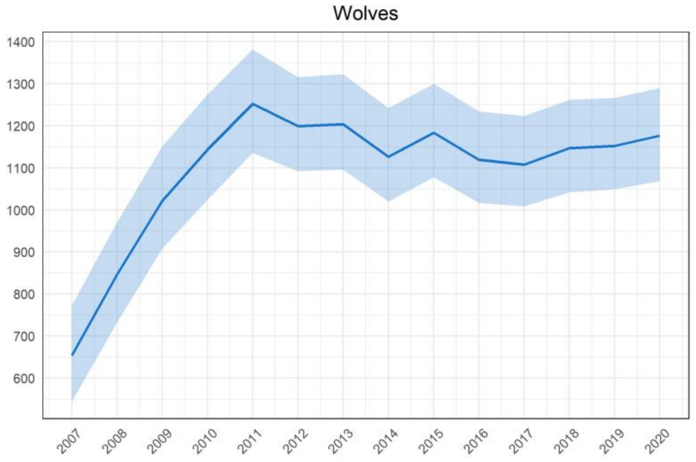
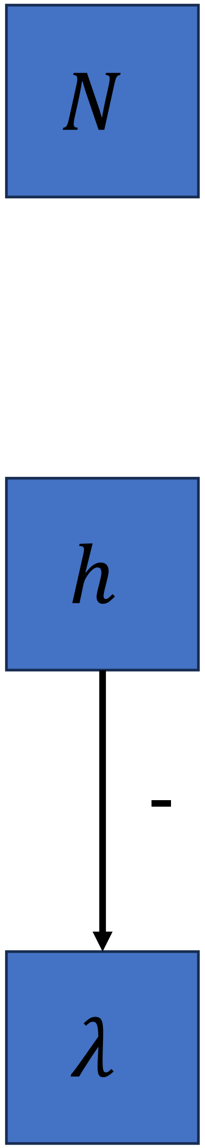
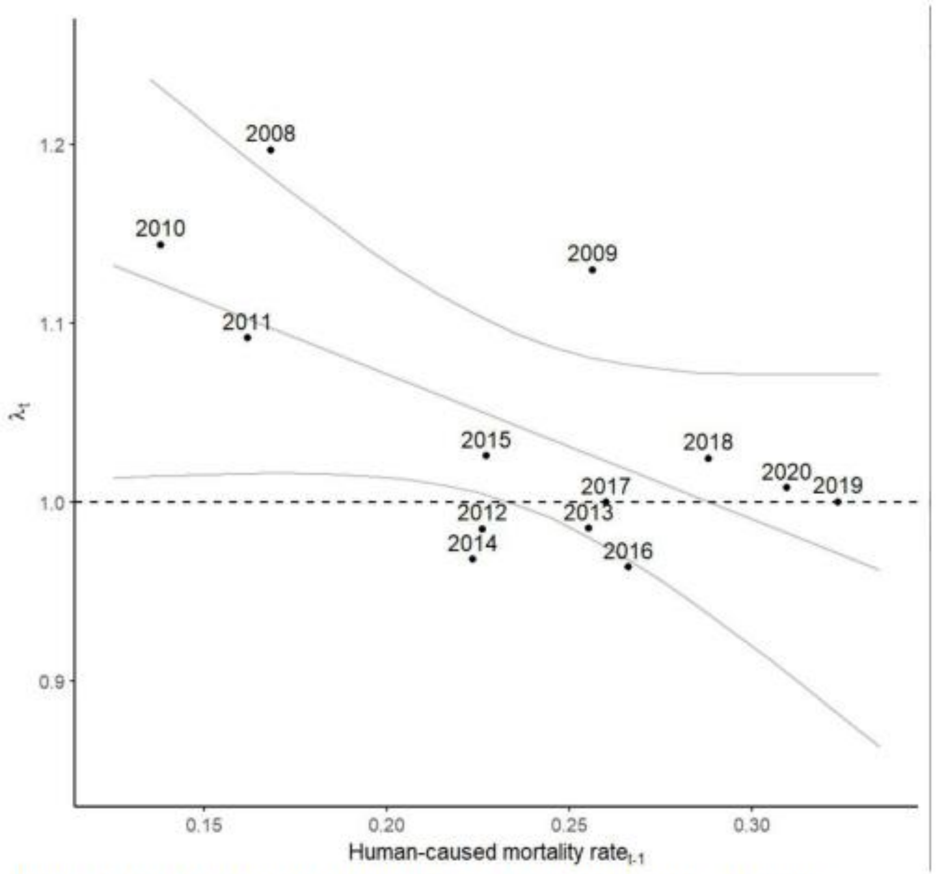






Abundance affects harvest rates



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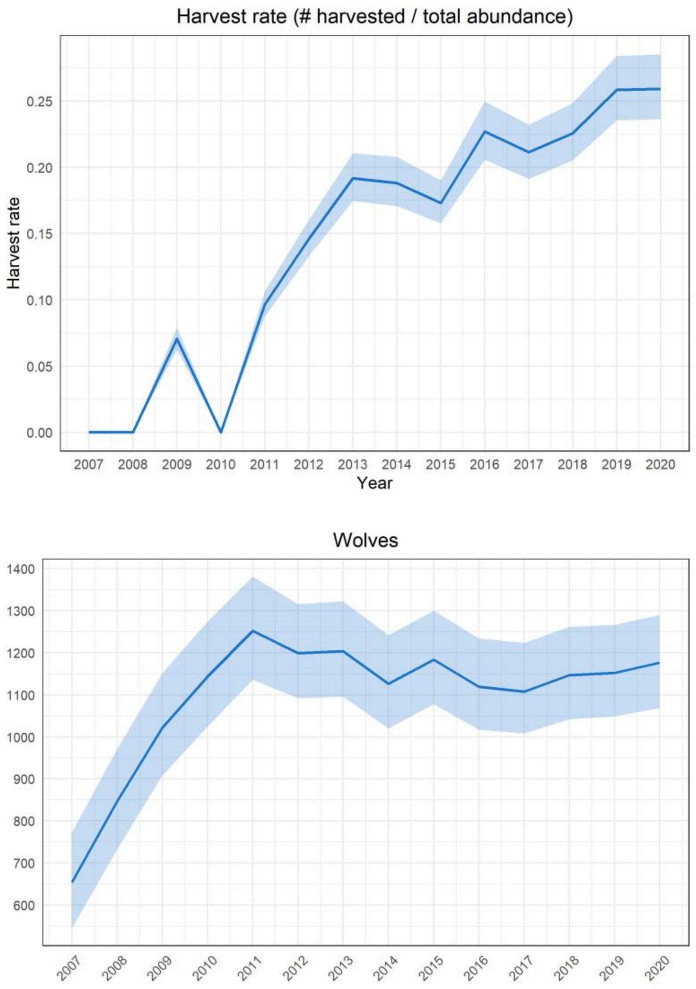
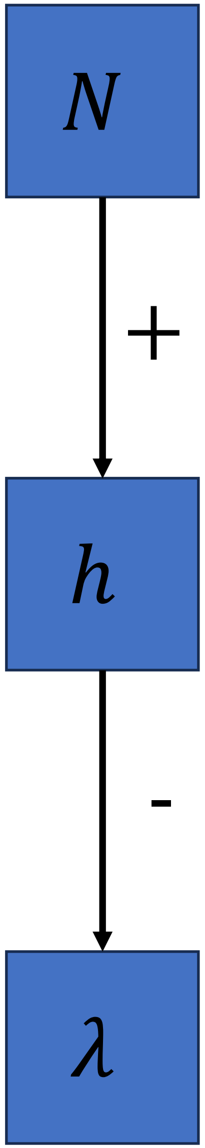
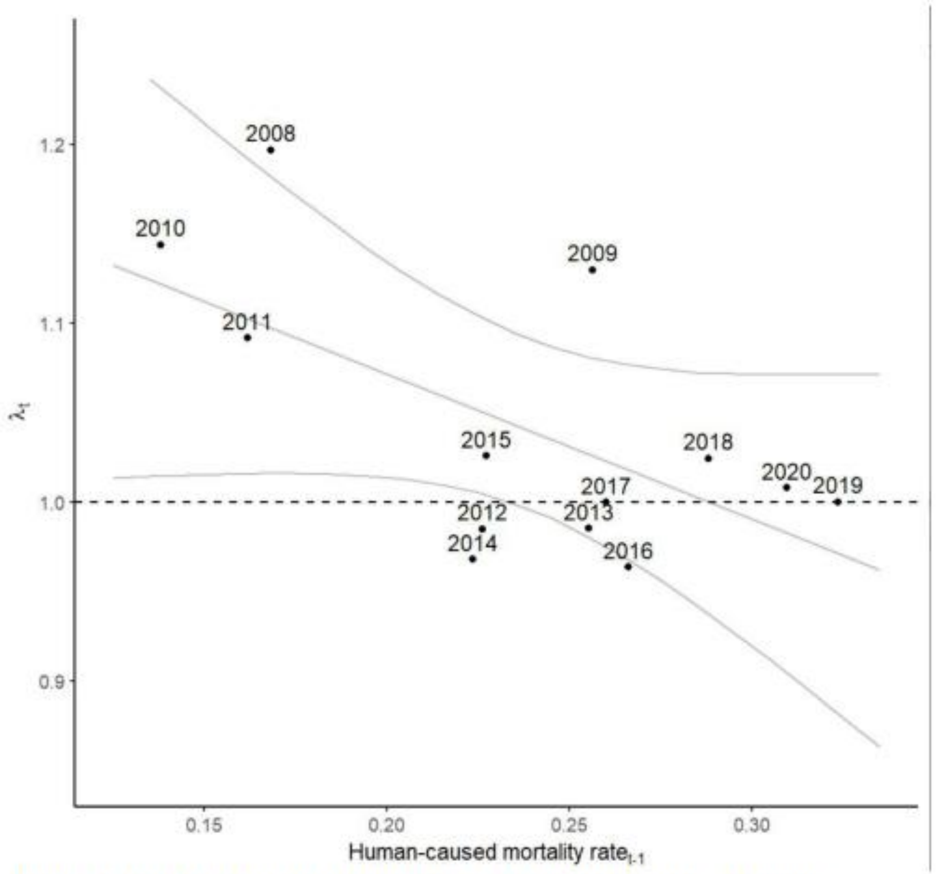




B/C federal laws (clear legal cause and effect) & ‘people’

Abundance affects population growth?



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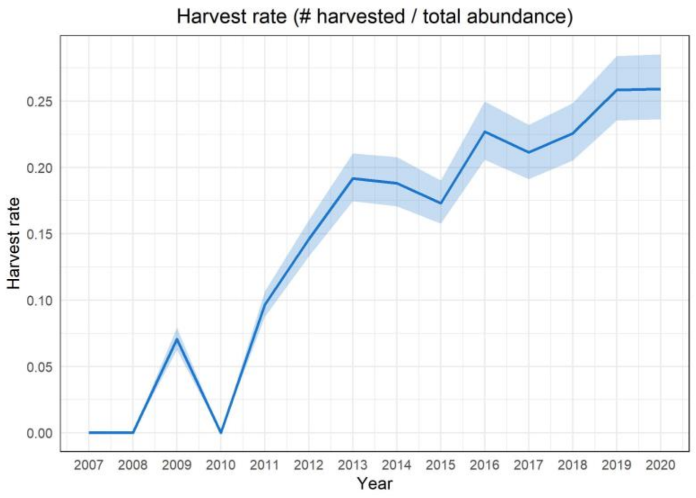
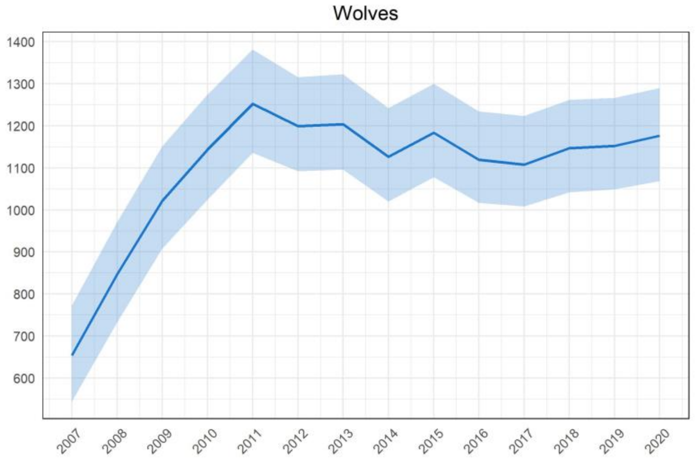
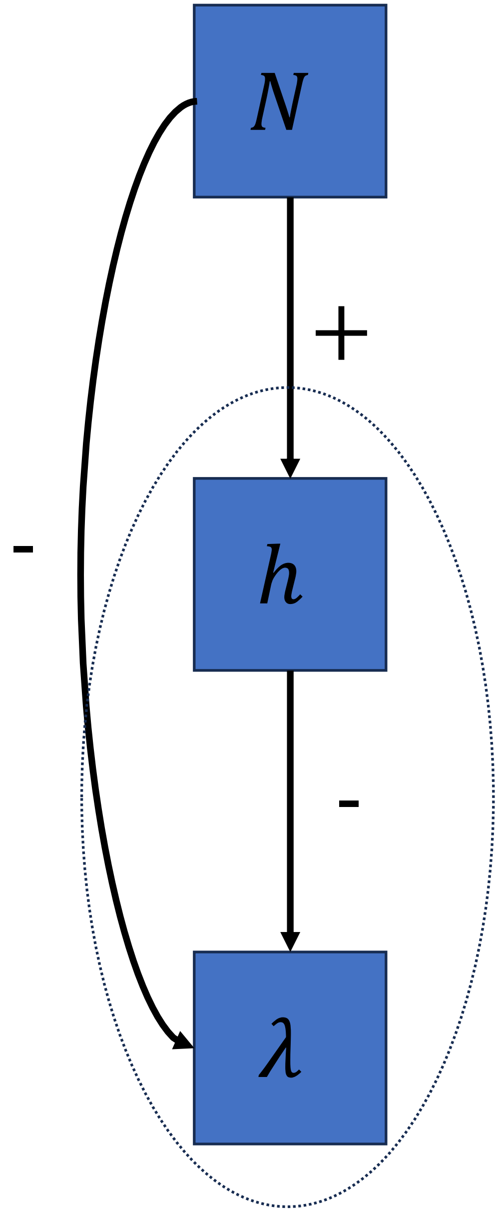
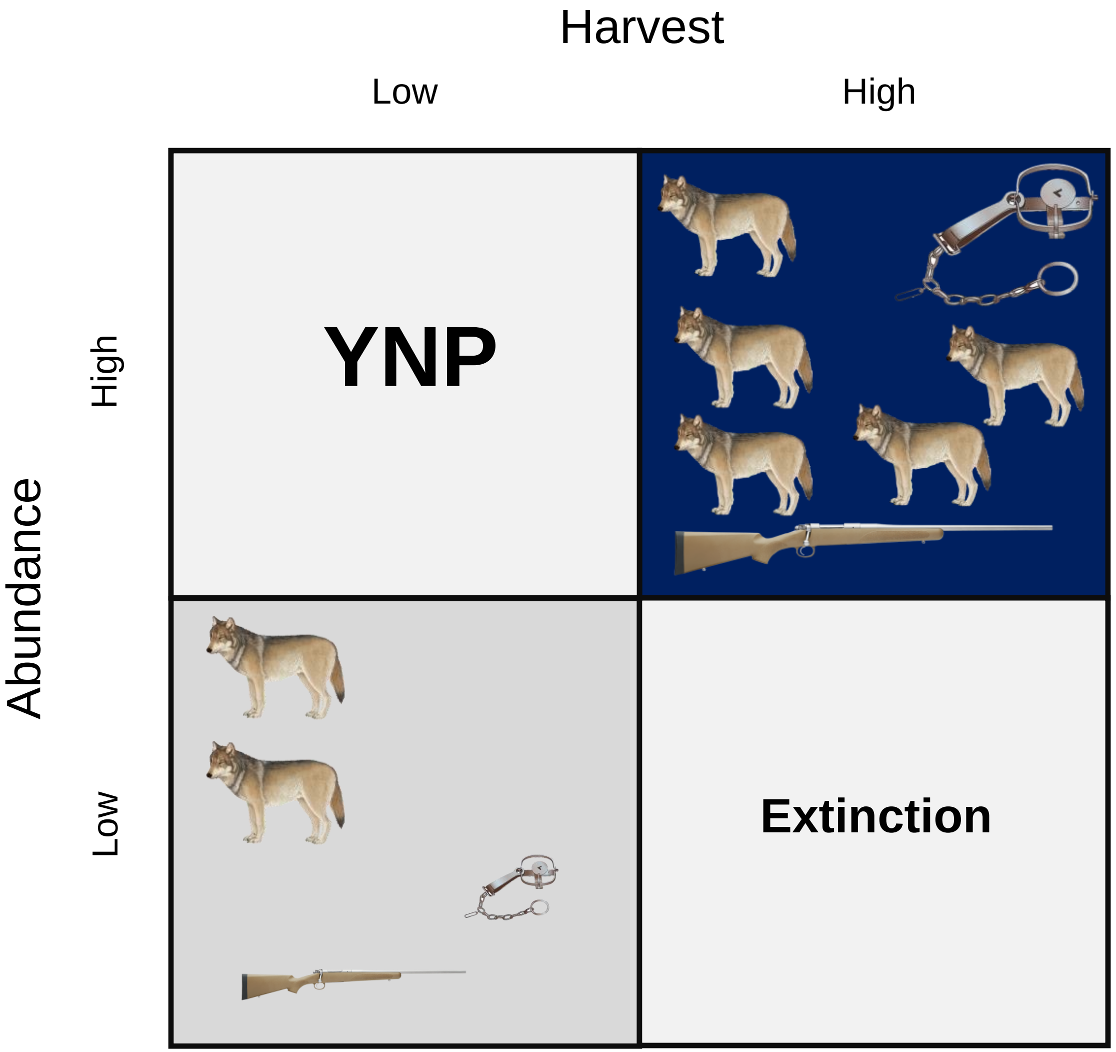


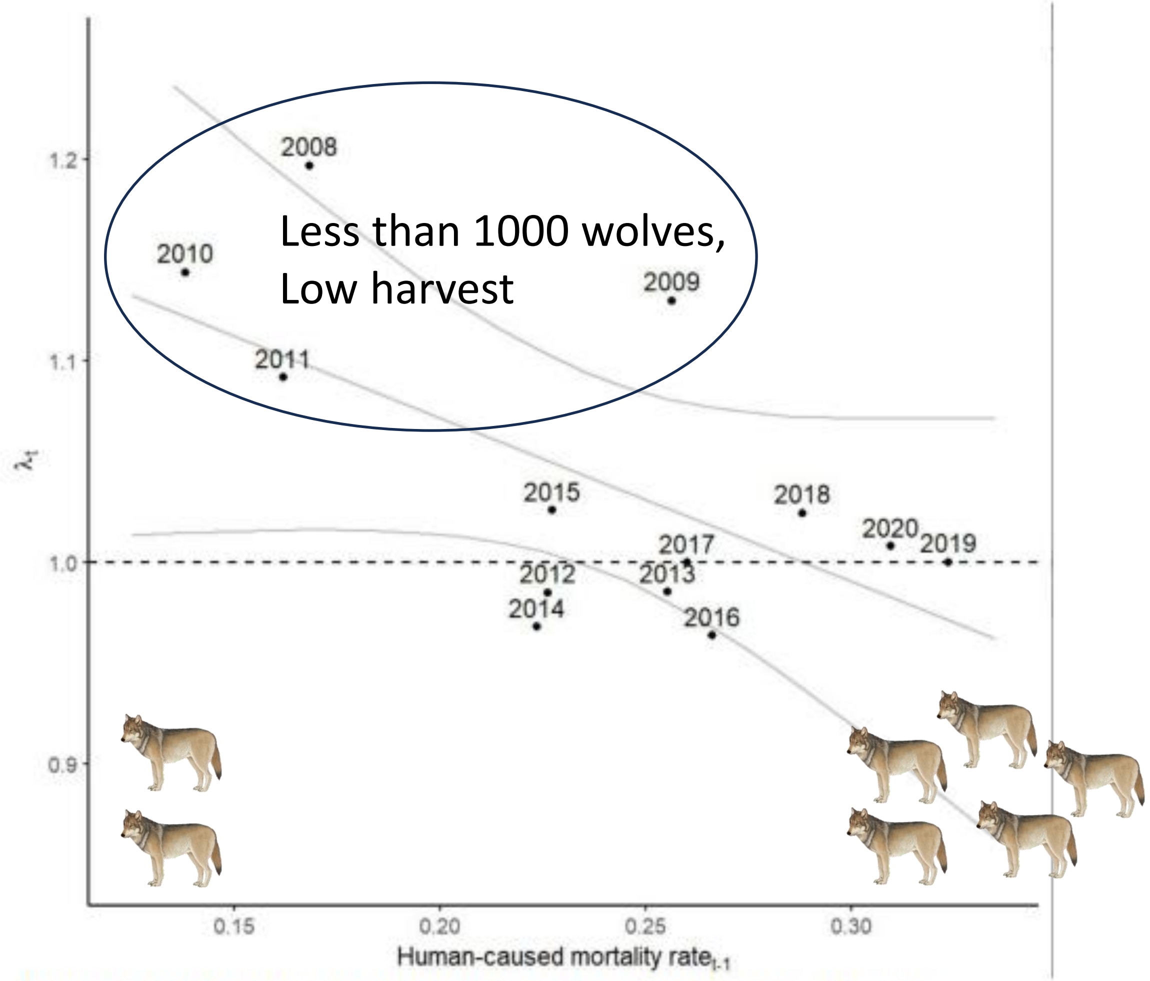




Density-dependence (‘Ecological law’)

?





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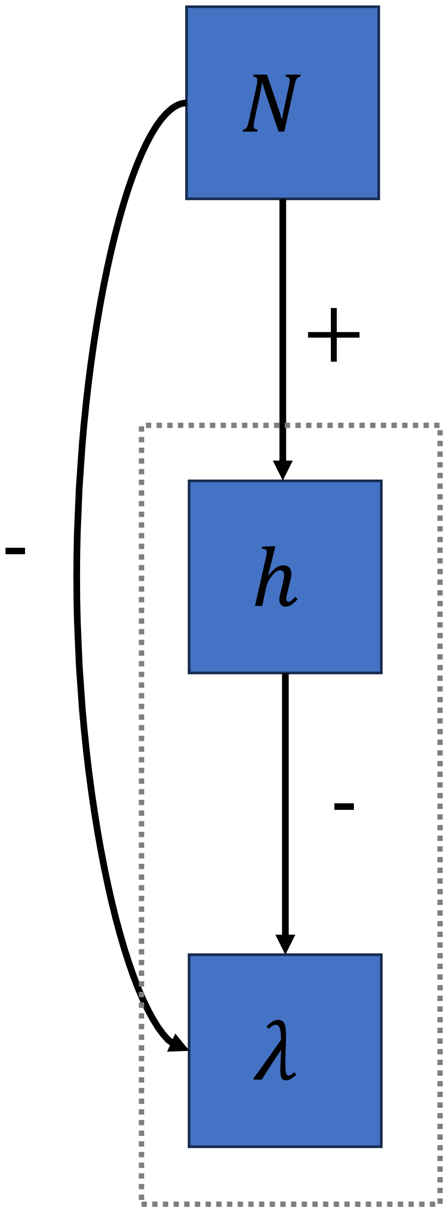

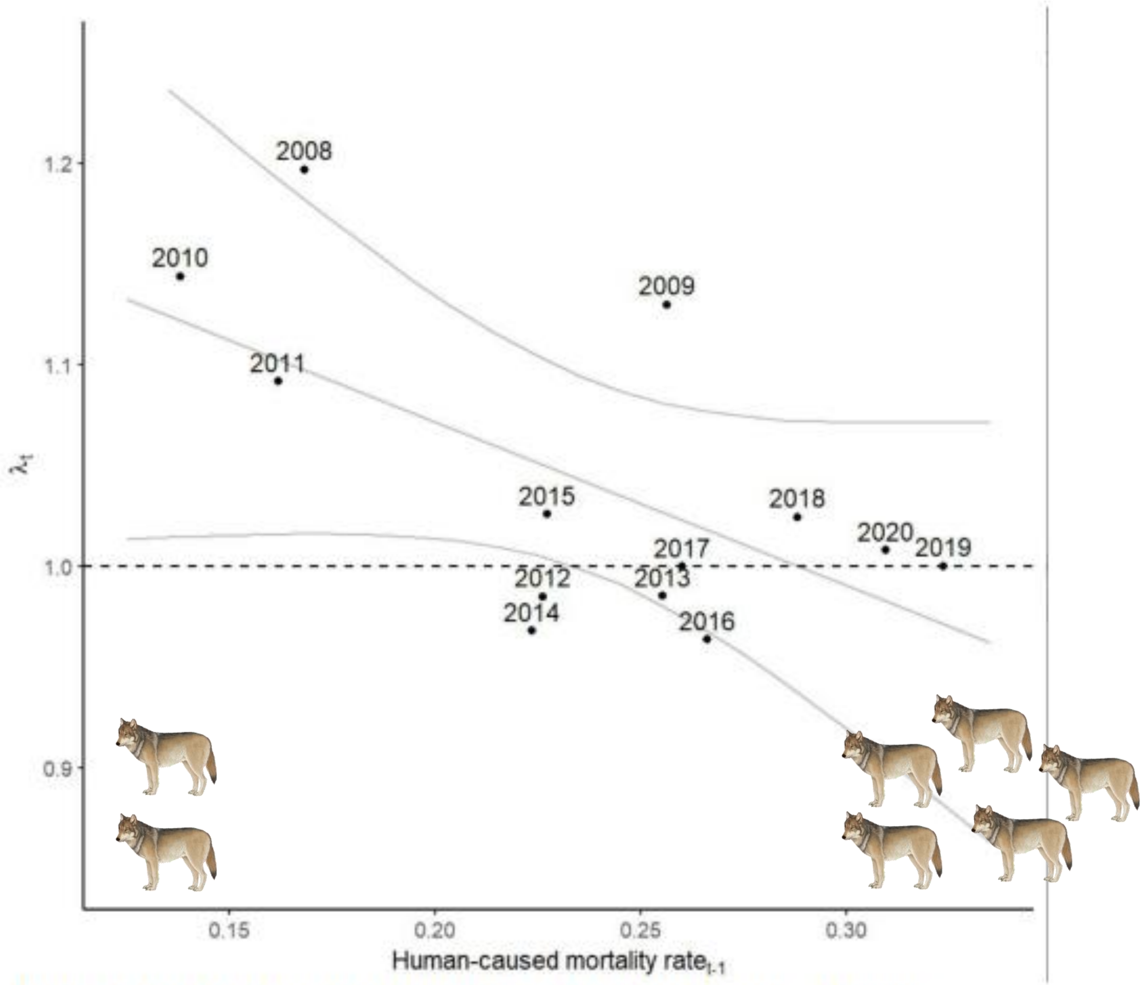

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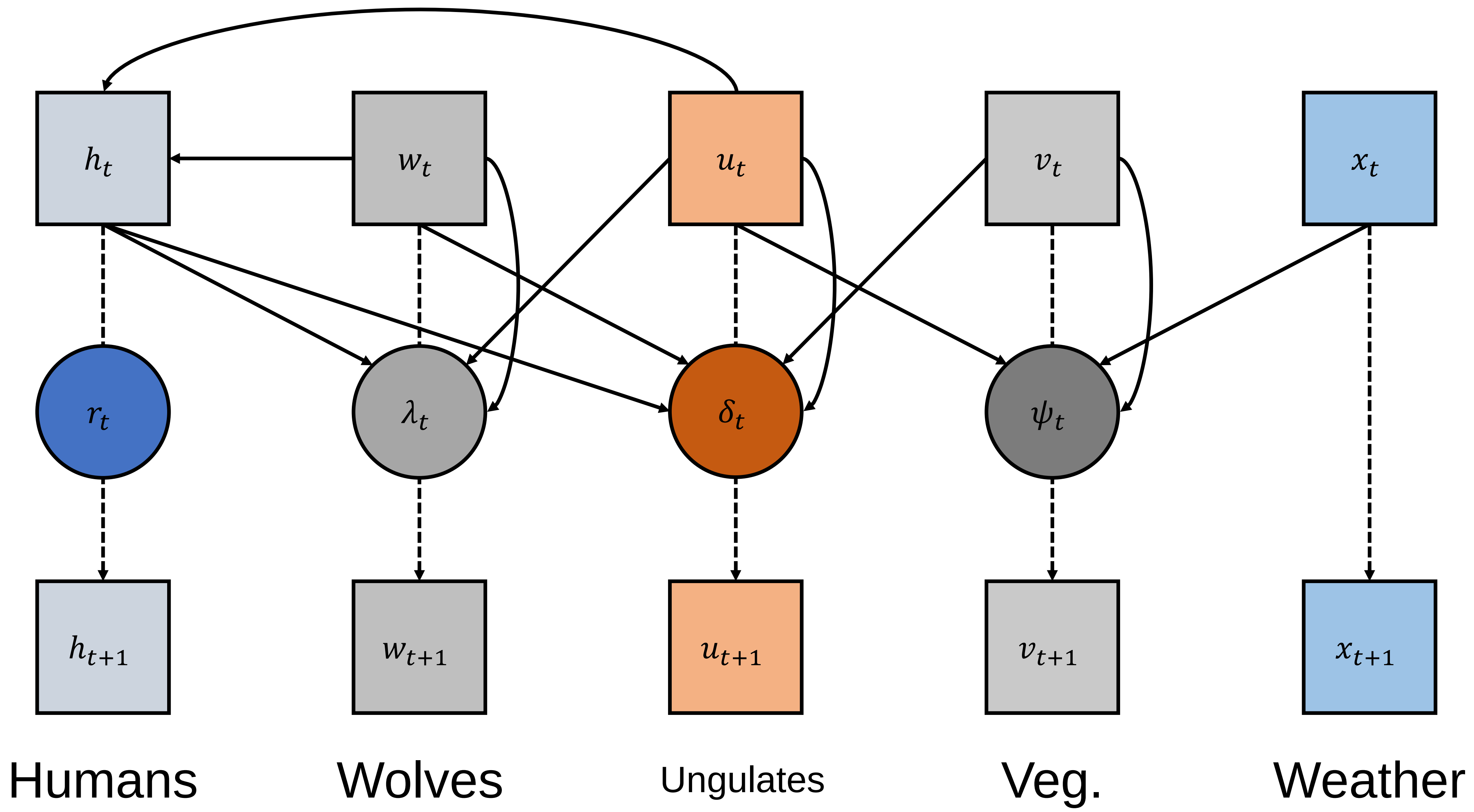
h_t
w_t
u_t
v_t
x_t
r_t
λ_t
δ_t
ψ_t
h_{t+1}
w_{t+1}
u_{t+1}
v_{t+1}
x_{t+1}
Humans
Wolves
Ungulates
Veg.
Weather

Questions to think about:

- How does my system work?
- Are my covariates truly ‘independent’?
- What type of data do I have? What can I acquire?