A Brief History of SEM

Overview

1. What is SEM?
2. A History Lesson
3. From ANOVA to SEM: An experimental example
4. From Experiments to Observation

1.1 What is SEM?

1.1 What is SEM?

Structural Equation Modeling

1.1 What is SEM?

Structural

There is hypothesized underlying *structure* to nature (a cause and an effect)…

Equation

Modeling

1.1 What is SEM?

Structural

There is hypothesized underlying *structure* to nature (a cause and an effect)…

Equation

…that can be translated to a series of mathematical *equations*…

Modeling

1.1 What is SEM?

Structural

There is hypothesized underlying *structure* to nature (a cause and an effect)…

Equation

…that can be translated to a series of mathematical *equations*…

Modeling

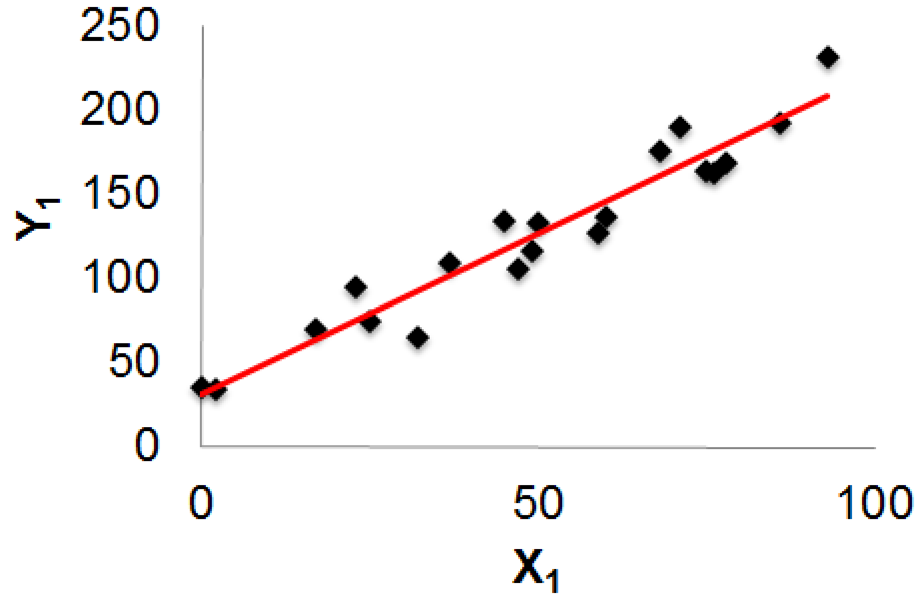
…which can be *modeled* against data to support or refute the proposed structure

1.1 What is SEM? By any other name …

- Structural equation modeling (SEM)
- (Confirmatory) path analysis (observed variables)
- Latent variable modeling (unobserved variables)
- Confirmatory factor analysis
- Directed acyclic graphs

1.1 What is SEM? A graphical approach

Graphical form

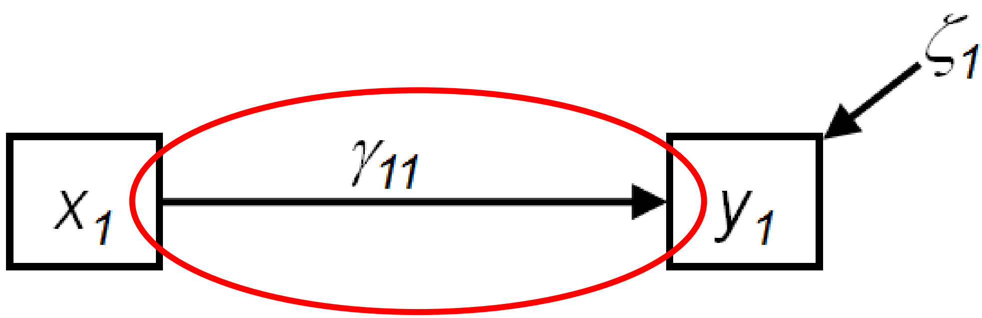


Equation form

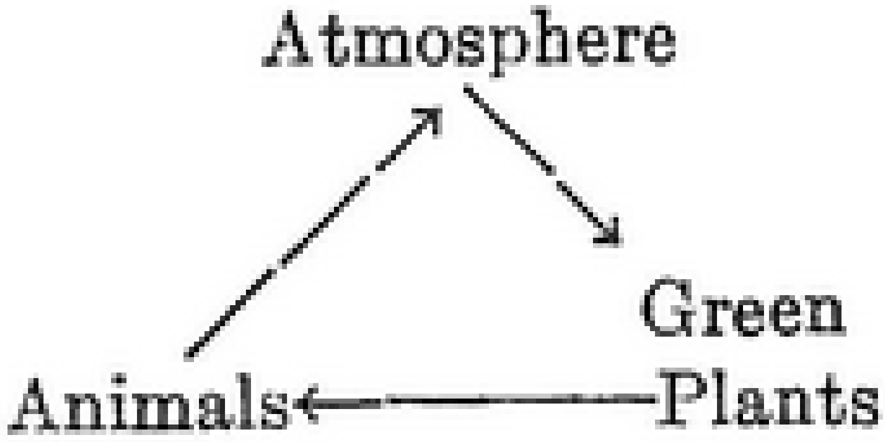
$$y_1 \sim \alpha_1 + \beta_1 X_1 + \varepsilon$$

$$y_{11} = \alpha_1 + \gamma_{11} x_1 + \zeta_1$$

Graphical form



1.1 What is SEM? A graphical approach



Lotka, "Elements of Physical Biology" (1925, p. 221)

1.1 What is SEM? A graphical approach

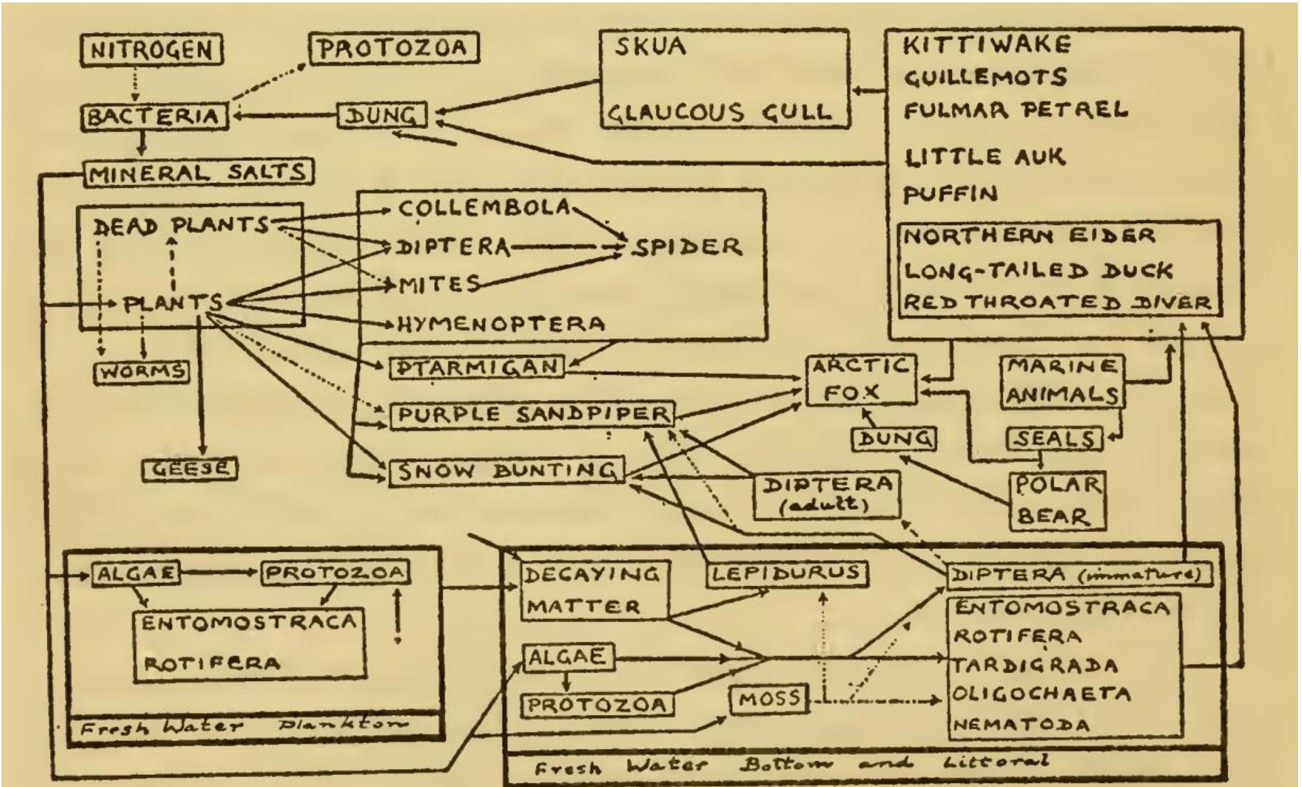
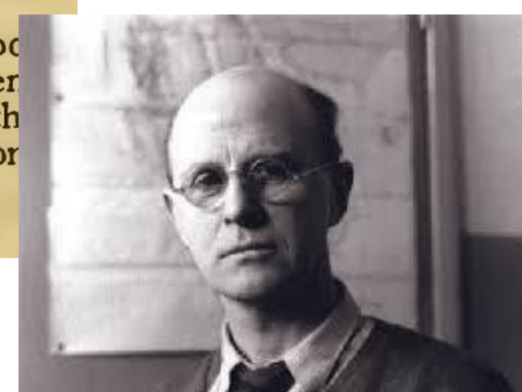


FIG. 4.—Food-cycle among the animals on Bear Island, a barren spo in the arctic zone, south of Spitsbergen. (The dotted lines represen probable food relations not yet proved.) The best way to read th diagram is to start at "marine animals" and follow the arrows. (Fror Summerhayes and Elton.[25])

Charles Elton, "Animal Ecology" (1927, p.58)



1.1 What is SEM? A graphical approach

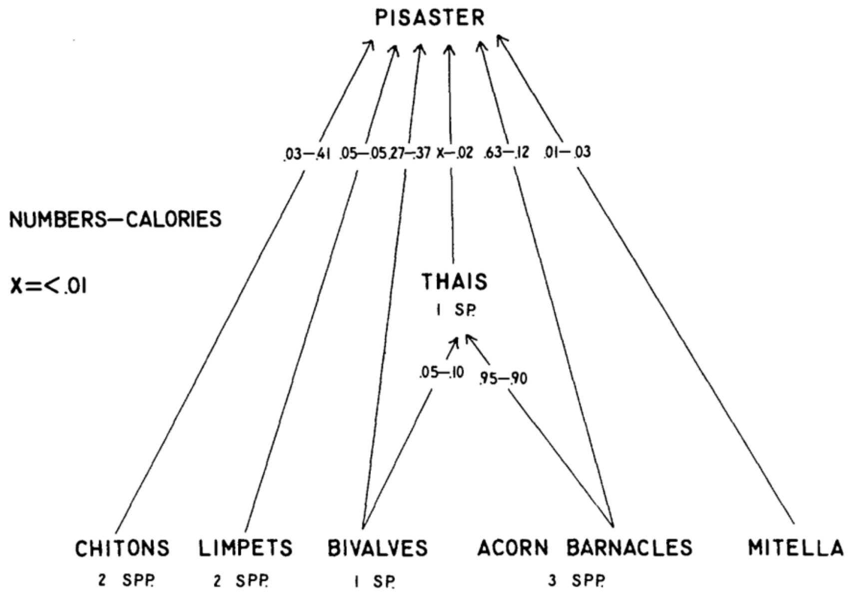
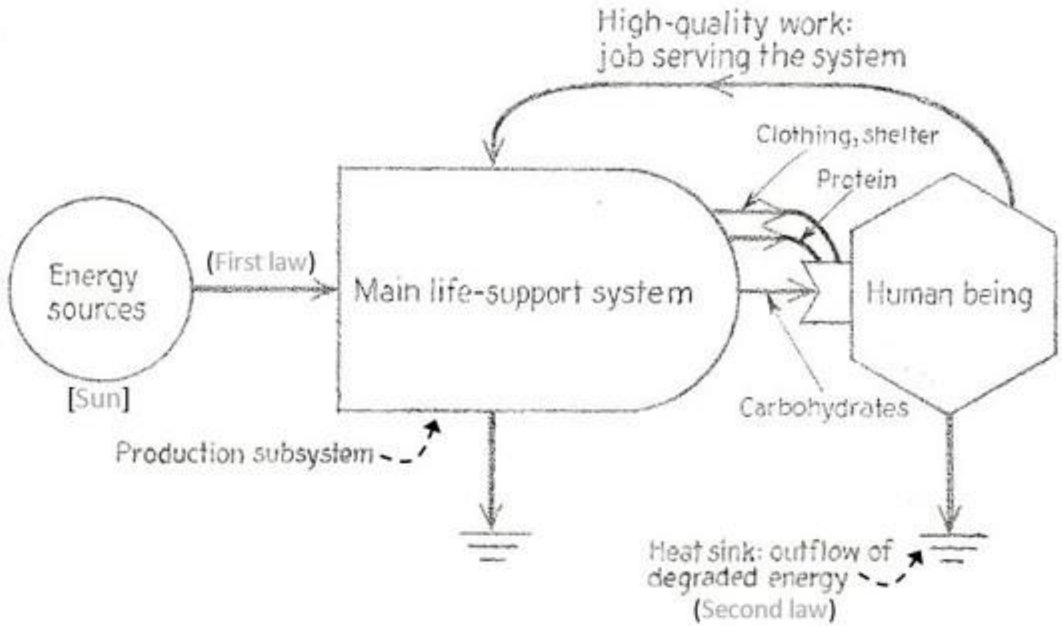


FIG. 1. The feeding relationships by numbers and calories of the *Pisaster* dominated subweb at Mukkaw Bay. *Pisaster*, N = 1049; *Thais*, N = 287. N is the number of food items observed eaten by the predators. The specific composition of each predator's diet is given as a pair of fractions; numbers on the left, calories on the right.

Paine, 1966

1.1 What is SEM? A graphical approach

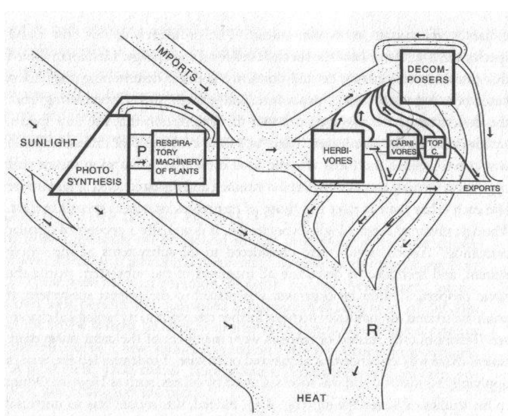


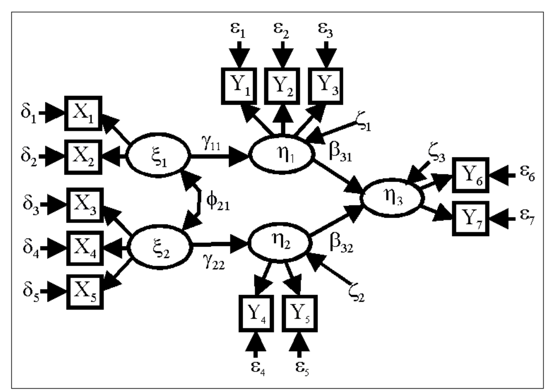
Basic Human | Energy Flow Diagram

Odum & Odum, "Energy basis for Man and Nature" (1976)

1.1 What is SEM? SEM vs. Ecosystem models

Ecosystem models	Structural equation models
Fit to observed and unobserved data	Fit entirely to observed data (sometimes)
Complex functional responses	Linear or simplified non-linear forms
Can be modularized	Simultaneous solution (sometimes)
Generalized system (e.g., Lotka-Volterra)	Specific hypotheses
Validation	

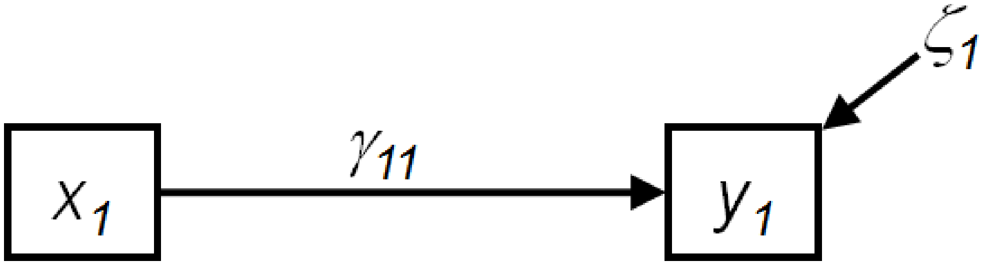




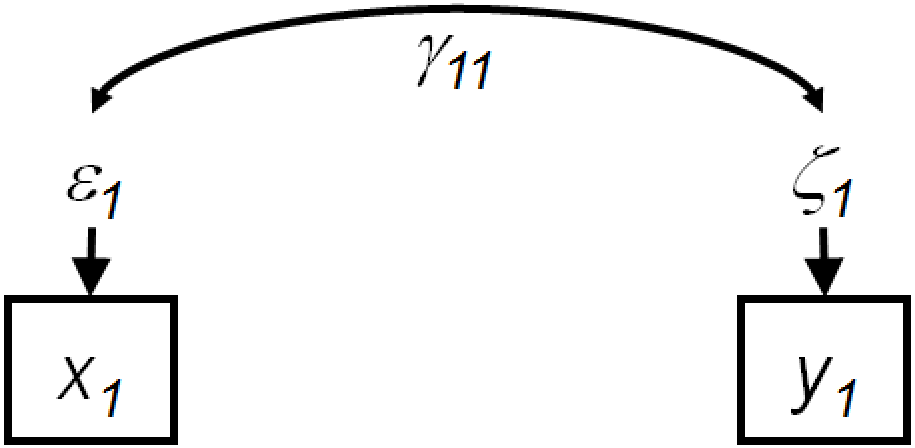
1.1 What is SEM? A graphical approach

- SEM can therefore be thought of as all over the following:
  - Unifying conceptual framework
  - Capture field of knowledge
  - Workflow process (x leads to y leads to…)
  - Means of testing hypotheses (does x cause y?)
  - Method of learning (why didn’t my data suggest x causes y?)

1.1 What is SEM? Implies directionality

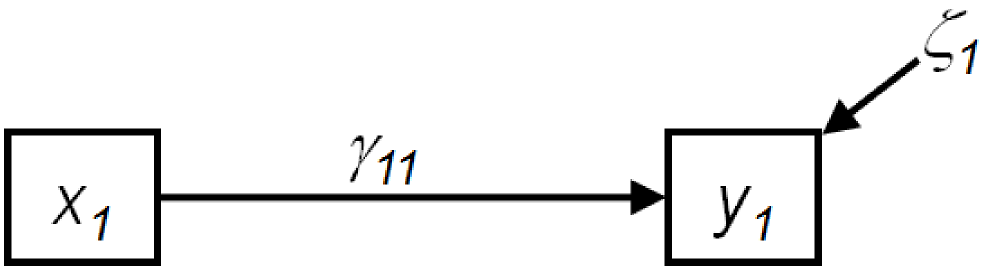


x_1 leads to y_1…



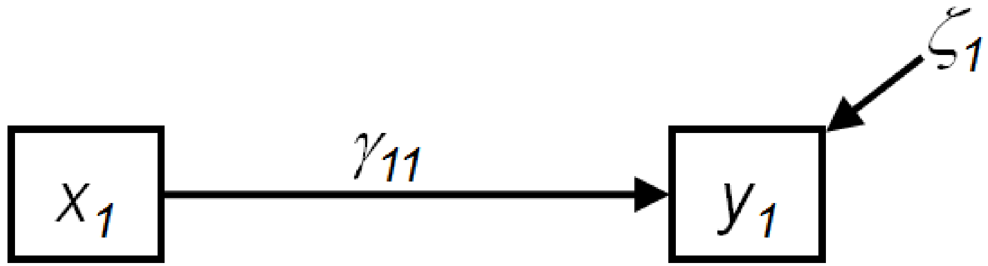
x_1 is associated with y_1

1.1 What is SEM? The elephant in the room



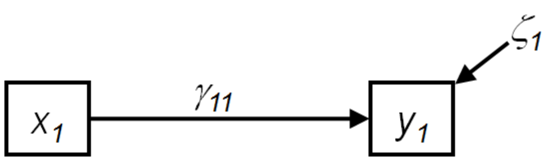
"An equation…can be said to be *structural* if there exists sufficient evidence from all available sources to support the interpretation that x_1 has a causal effect on y_1." (Grace, 2006)

1.1 What is SEM? What is *causation*?

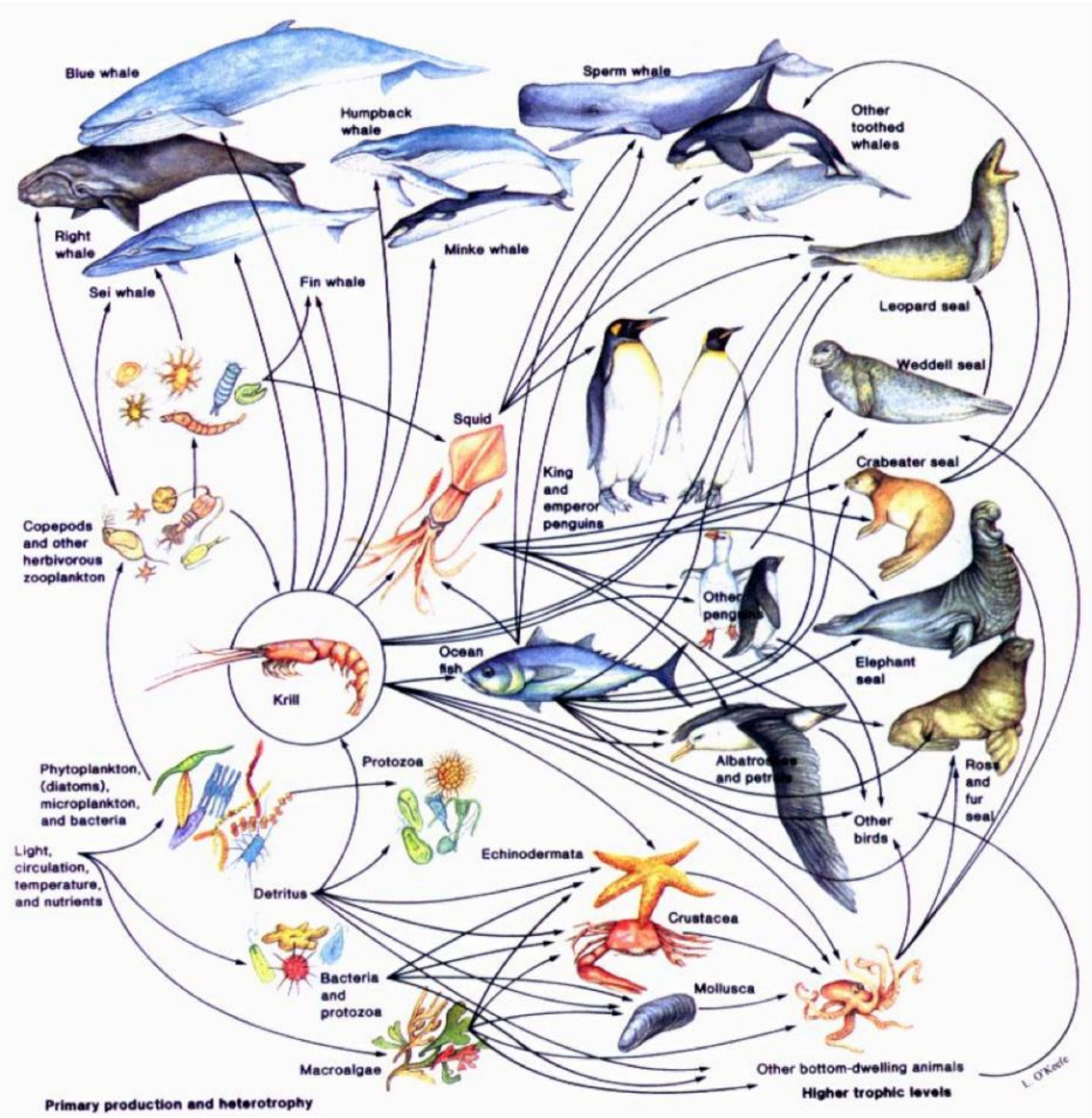


- **Key Point #1:** SEM assumes that *x* causes *y*
  - Prior observation
  - Prior statistical tests
  - Prior experimentation
  - Some or all of the above
- Does not assume ultimate causation

1.1 What is SEM? Nature is complex

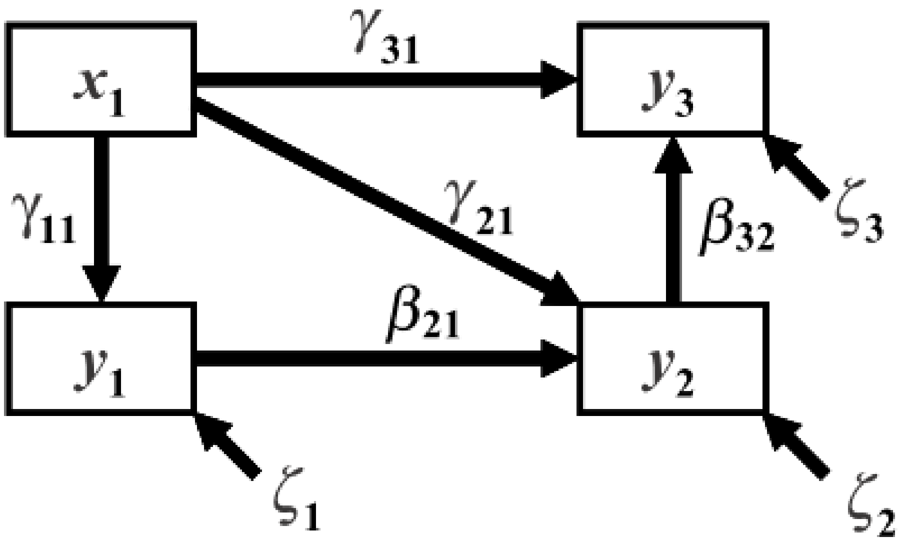


vs.



1.1 What is SEM? Incorporating complexity

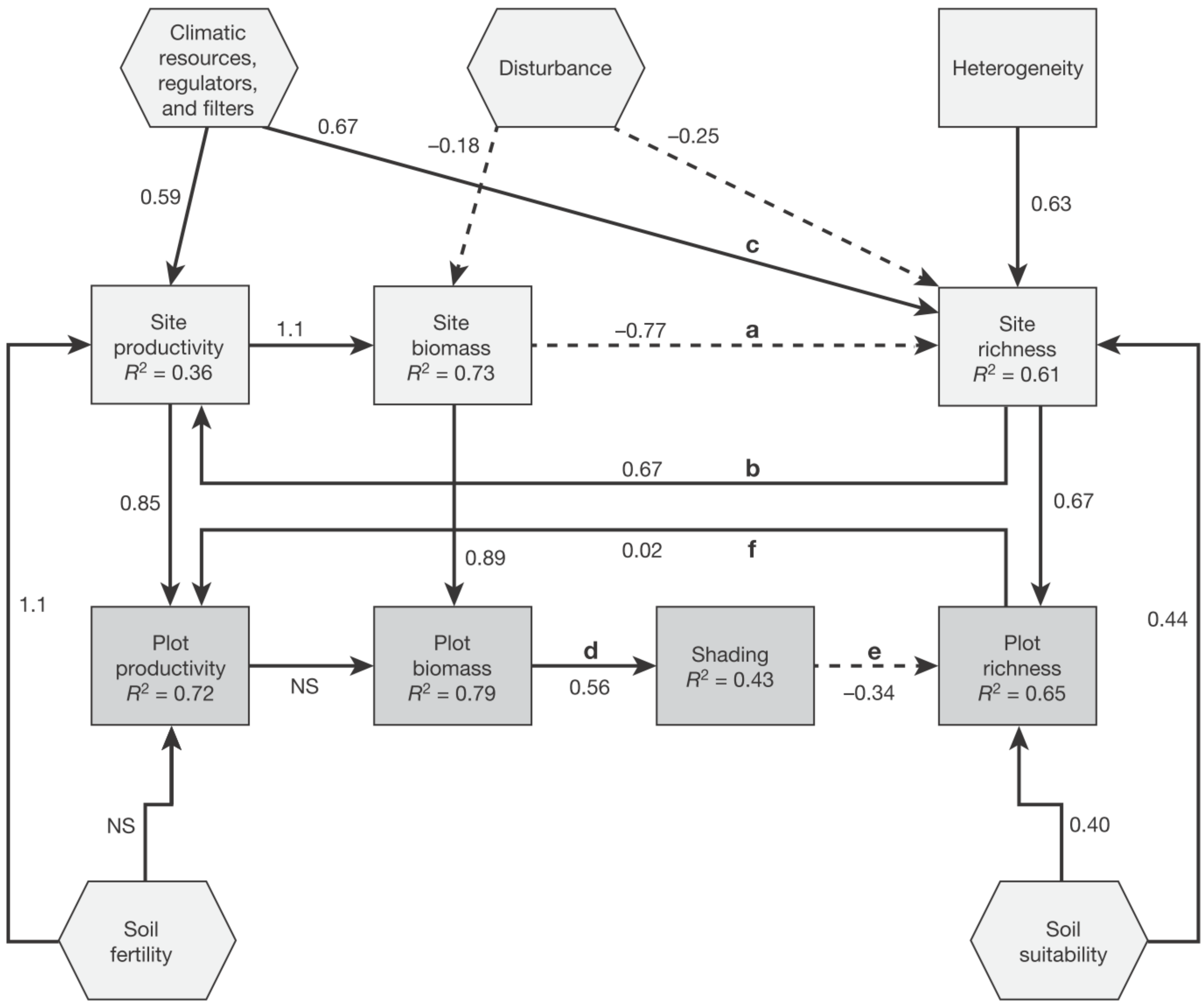
Graphical model



List of equations

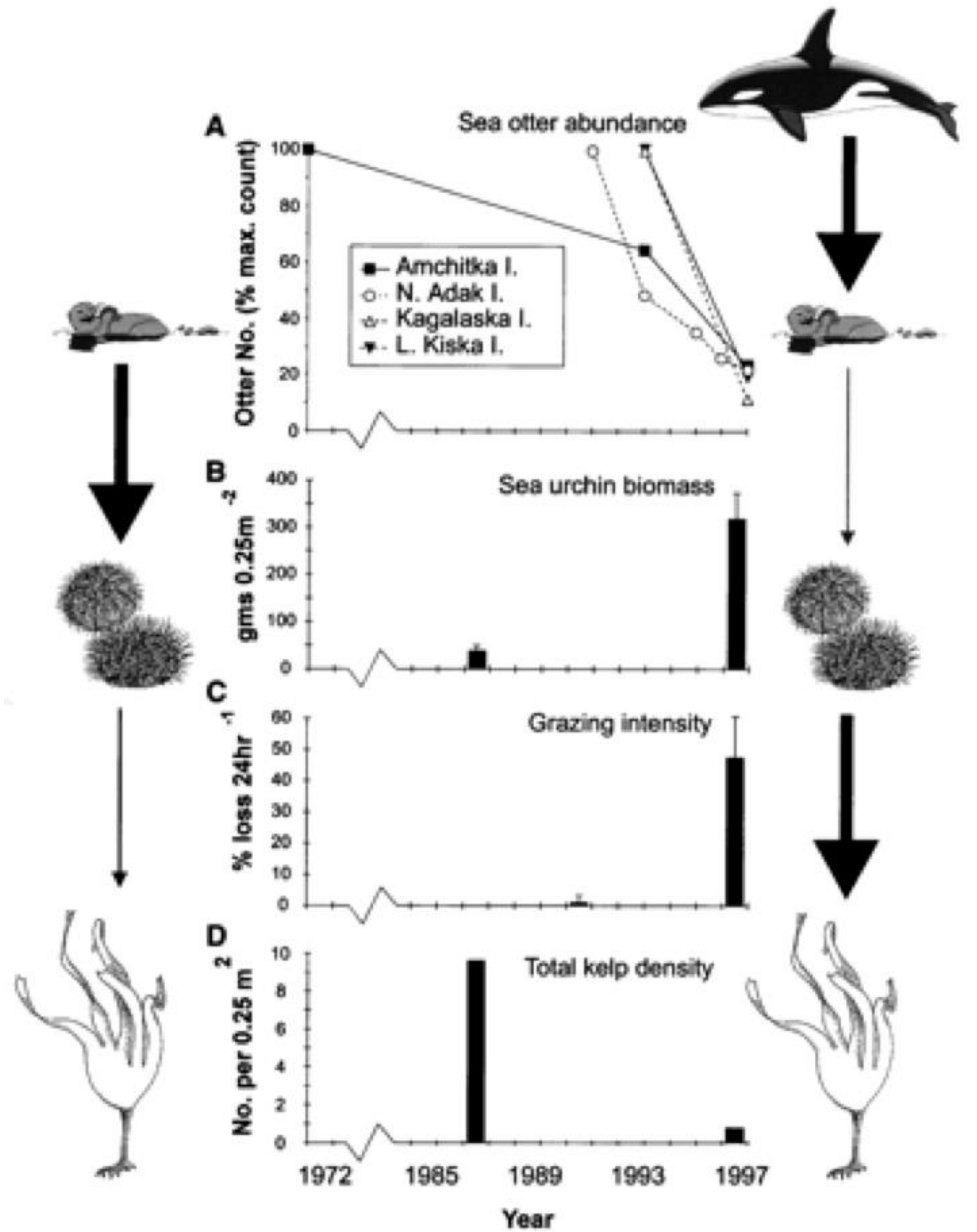
$$y_1 = \alpha_1 + \gamma_{11} x_1 + \zeta_1$$
$$y_2 = \alpha_2 + \beta_{21} y_1 + \gamma_{21} x_1 + \zeta_2$$
$$y_3 = \alpha_3 + \beta_{32} y_2 + \gamma_{31} x_1 + \zeta_3$$

1.1 What is SEM? Building up



1.1 What is SEM? A complicated network

- **Key Point #2:** By combining inferences across multiple equations, SEM addresses both direct and indirect effects in a system



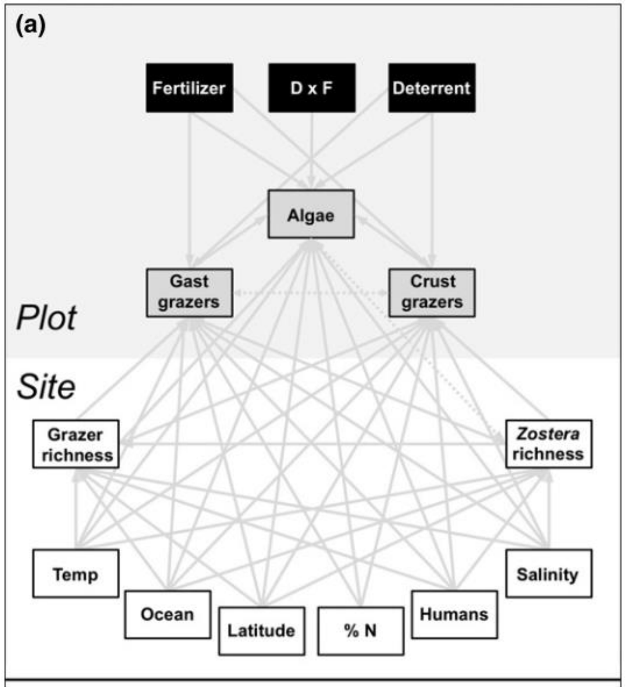
Estes et al. 1998 *Science*

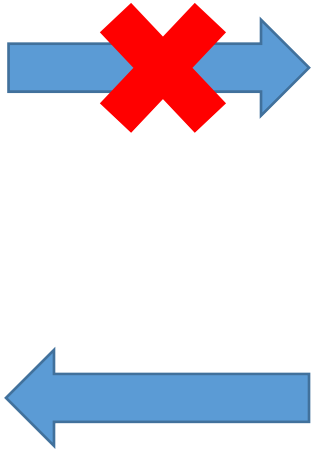
1.1 What is SEM? Putting it all together

- **Key Point #1:** SEM assumes that *x* <u>causes</u> *y*
- **Key Point #2:** By combining inferences across multiple equations, SEM addresses both direct (proximate) and indirect (ultimate) effects in a system

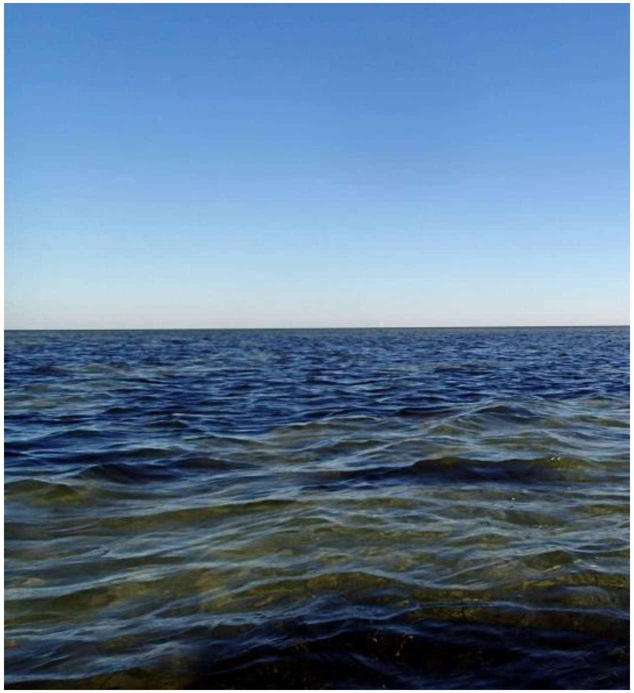
1.1 What is SEM? Reality vs. model

Model





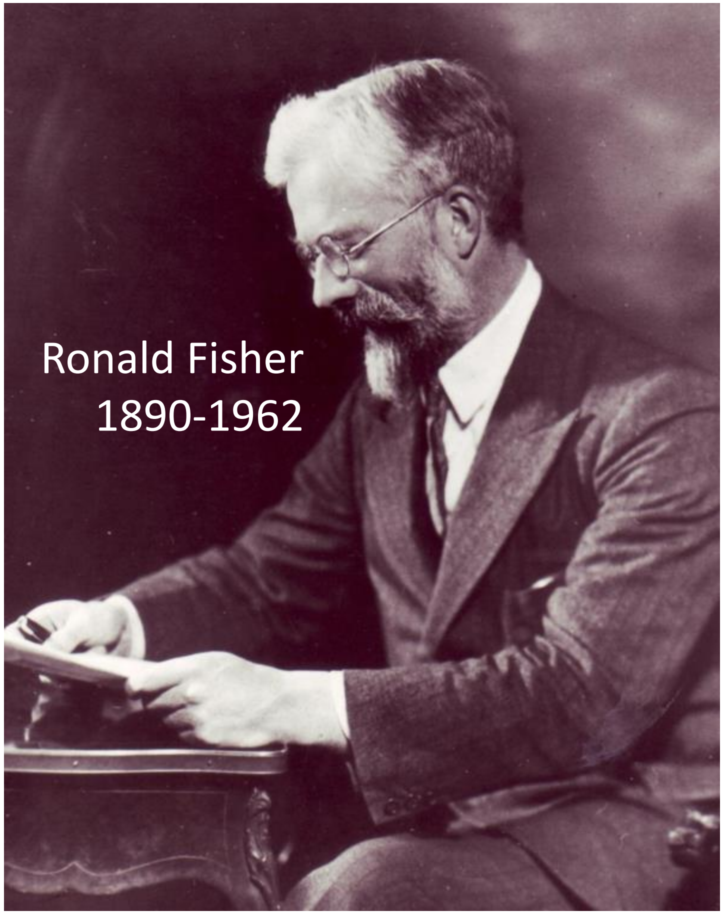
Real world



Real world informs the model, not the other way around!

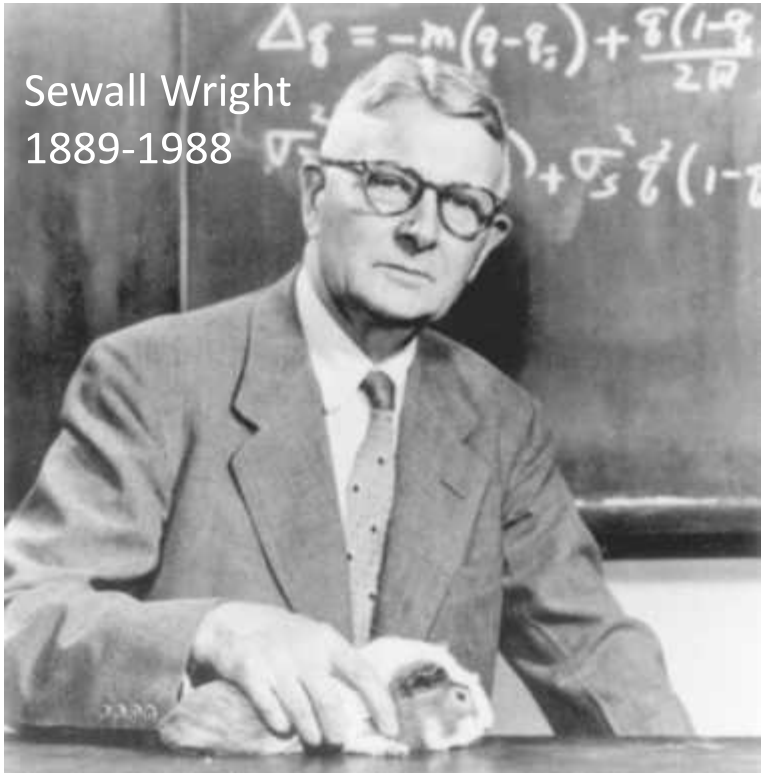
1.2 A History Lesson

1.2 History. Fit, correlation, and testing models



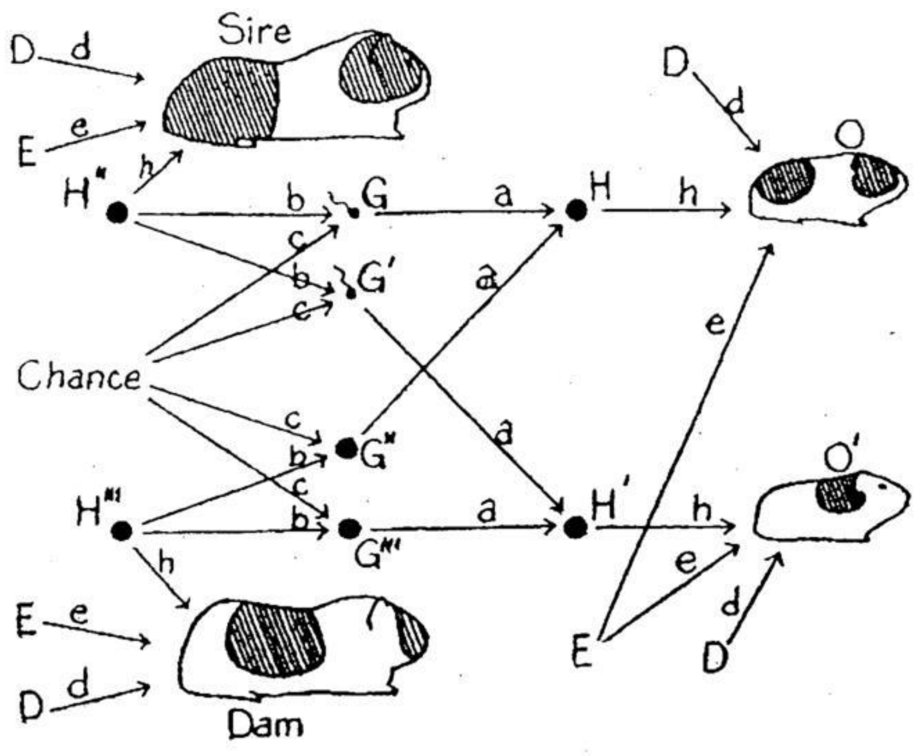
Numerical strength of association (Pearson product moment correlation, *r)*
Evaluate model fit (Chi-squared goodness of fit, $\chi^{2)}$

Test hypotheses (ANOVA)
Derive effect sizes (maximum likelihood estimation)



Sewall Wright
1889-1988

Path analysis



1.2 History. Causation vs. correlation

“The **basic fallacy of the method appears to be the assumption that it is possible to set up *a priori* a comparatively simple graphic system which will truly represent the lines of action of several variables upon each other**, and upon a common result. . . . The pure mathematics by which this is shown is apparently faultless in the sense of algebraic manipulation, but it is based upon assumptions which are wholly without warrant from the standpoint of concrete, phenomenal actuality.” (Niles, 1922)

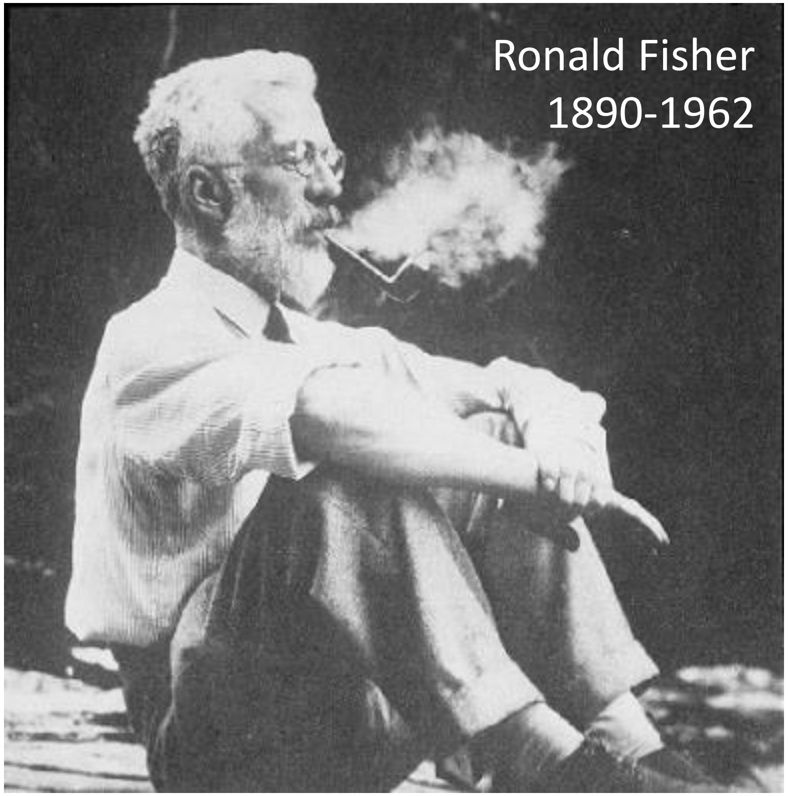
“The writer has never made the preposterous claim that **the theory of path coefficients provides a general formula for the deduction of causal relations**. He wishes to submit that the ***combination* of knowledge of correlations with knowledge of causal relations, to obtain certain results**, is a different thing from the *deduction* of causal relations from correlations implied by Niles’s statement. Prior knowledge of the causal relations is assumed as a prerequisite in the former case. Whether such knowledge is ever possible seems to be the subject of Niles’s philosophical discussion of the nature of causation.” (Wright, 1923)

1.2 History. Causation vs. correlation

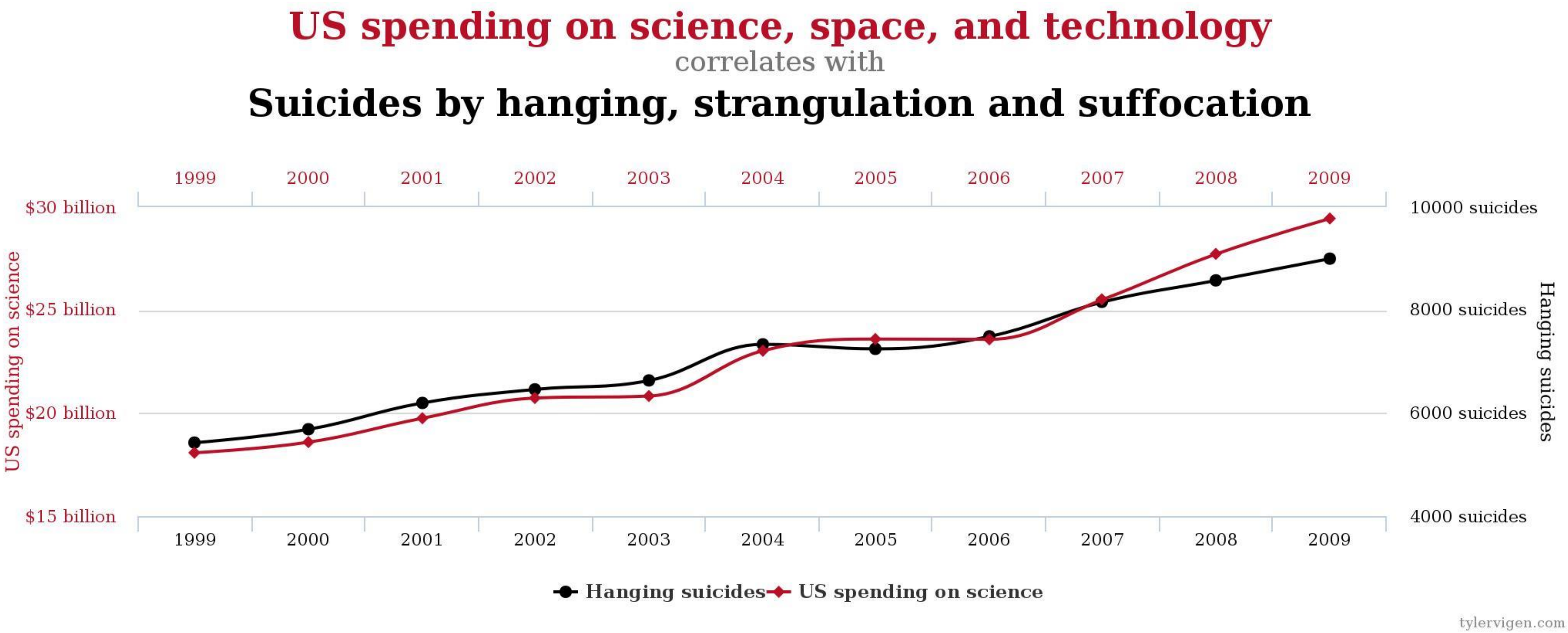
Smoking → Cancer

Cancer → Smoking

Smoking ← Gene → Cancer

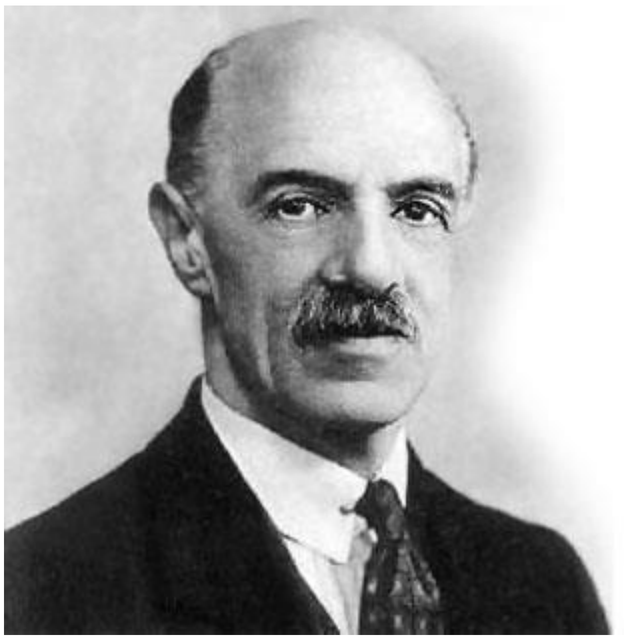


1.2 History. Causation vs. correlation



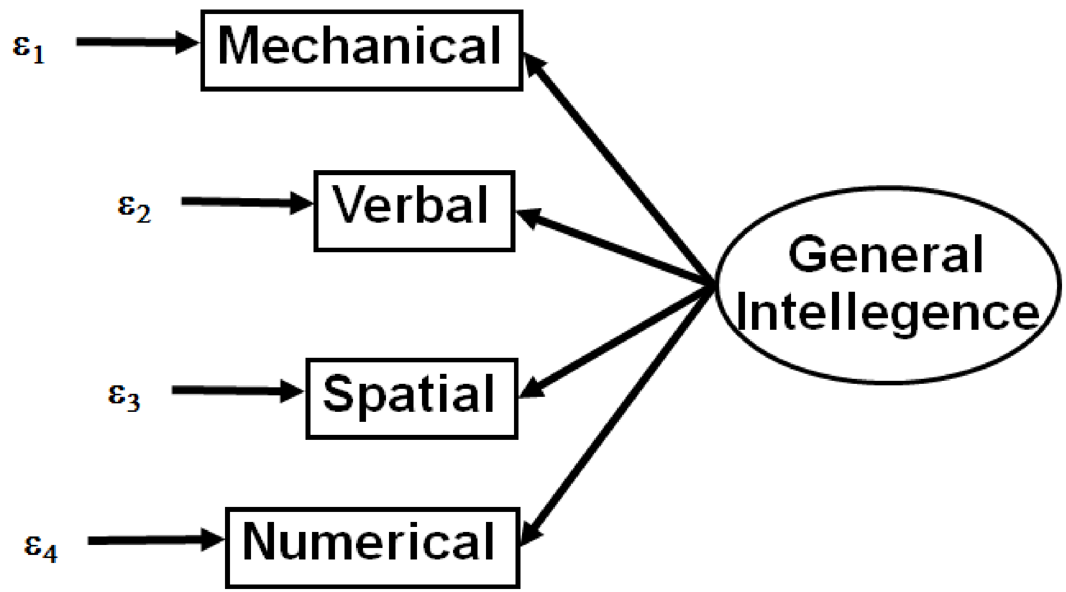
http://www.tylervigen.com/

1.2 History. Factor Analysis (Unobserved)

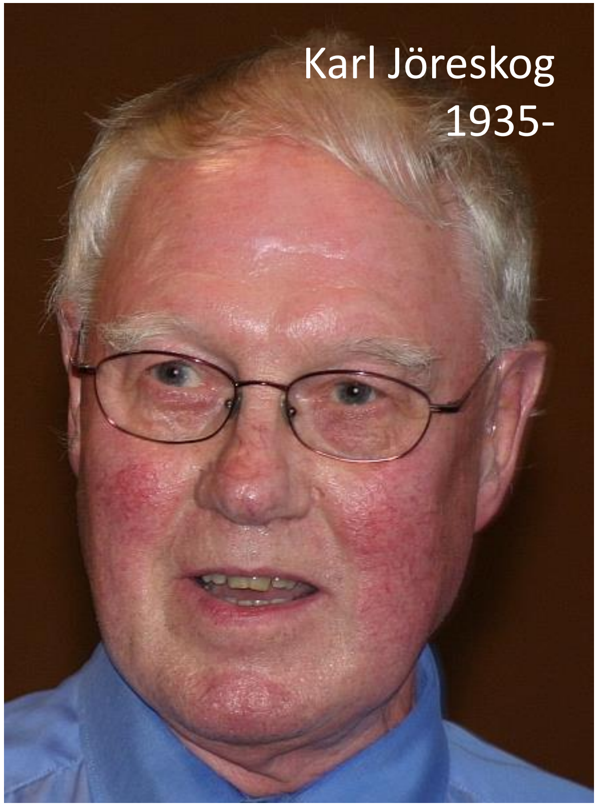


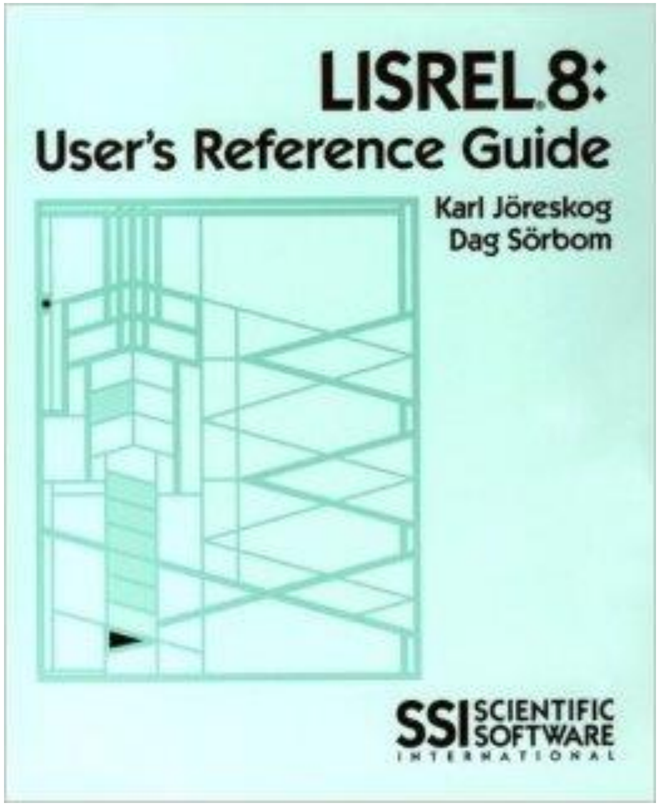
Charles Spearman
1863-1945

<u>The "g" factor</u>



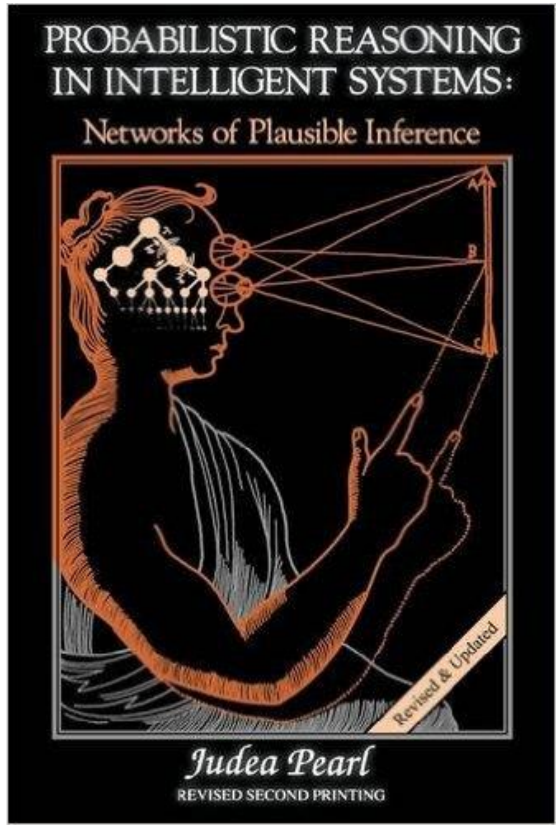
1.2 History. 2nd Generation SEM (Hybrid)





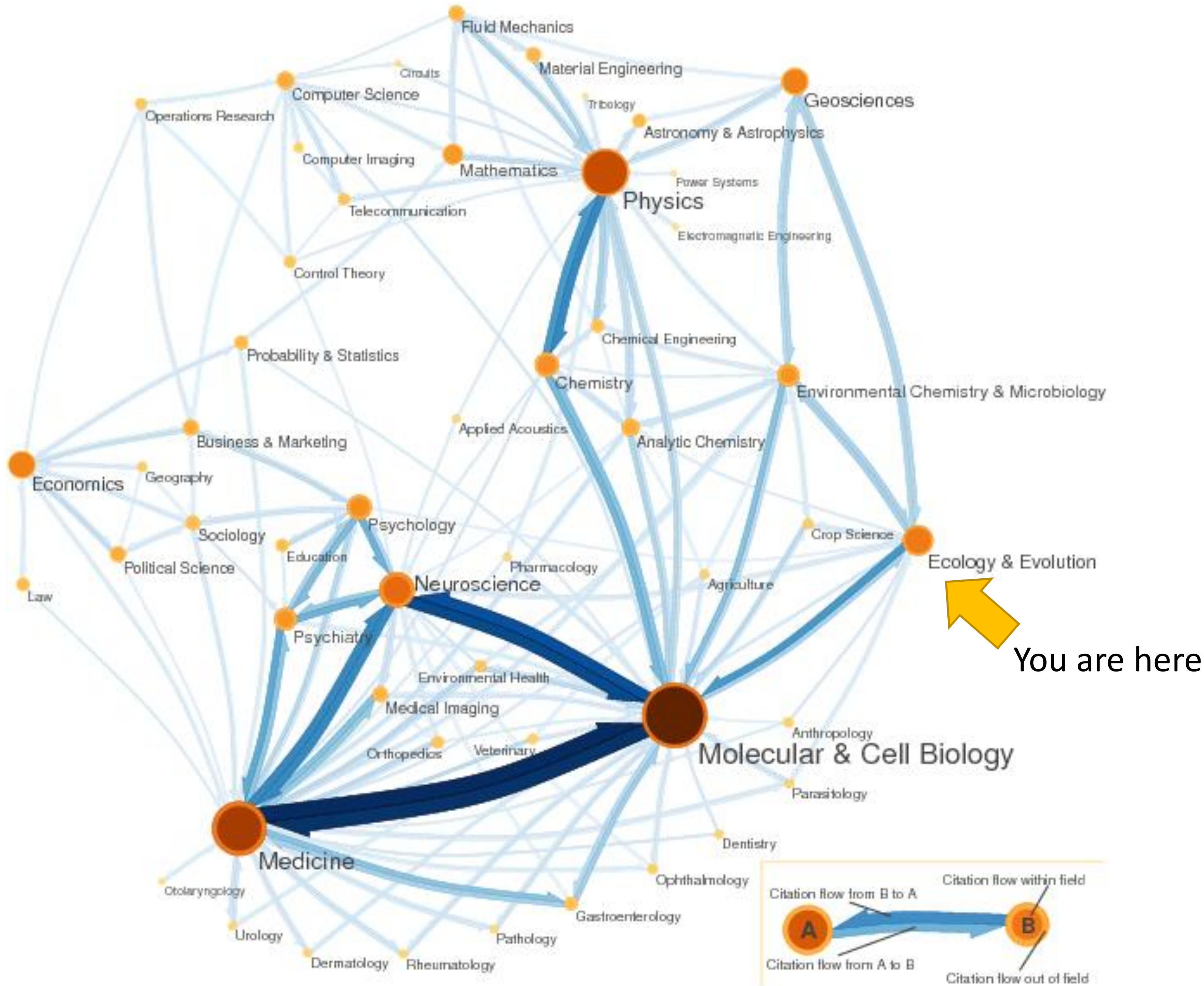
- LISREL = combine path and factor analysis
- Model fit using covariance and ML estimation
- Assess and compare fit of multivariate model

1.2 History. 3rd Generation SEM

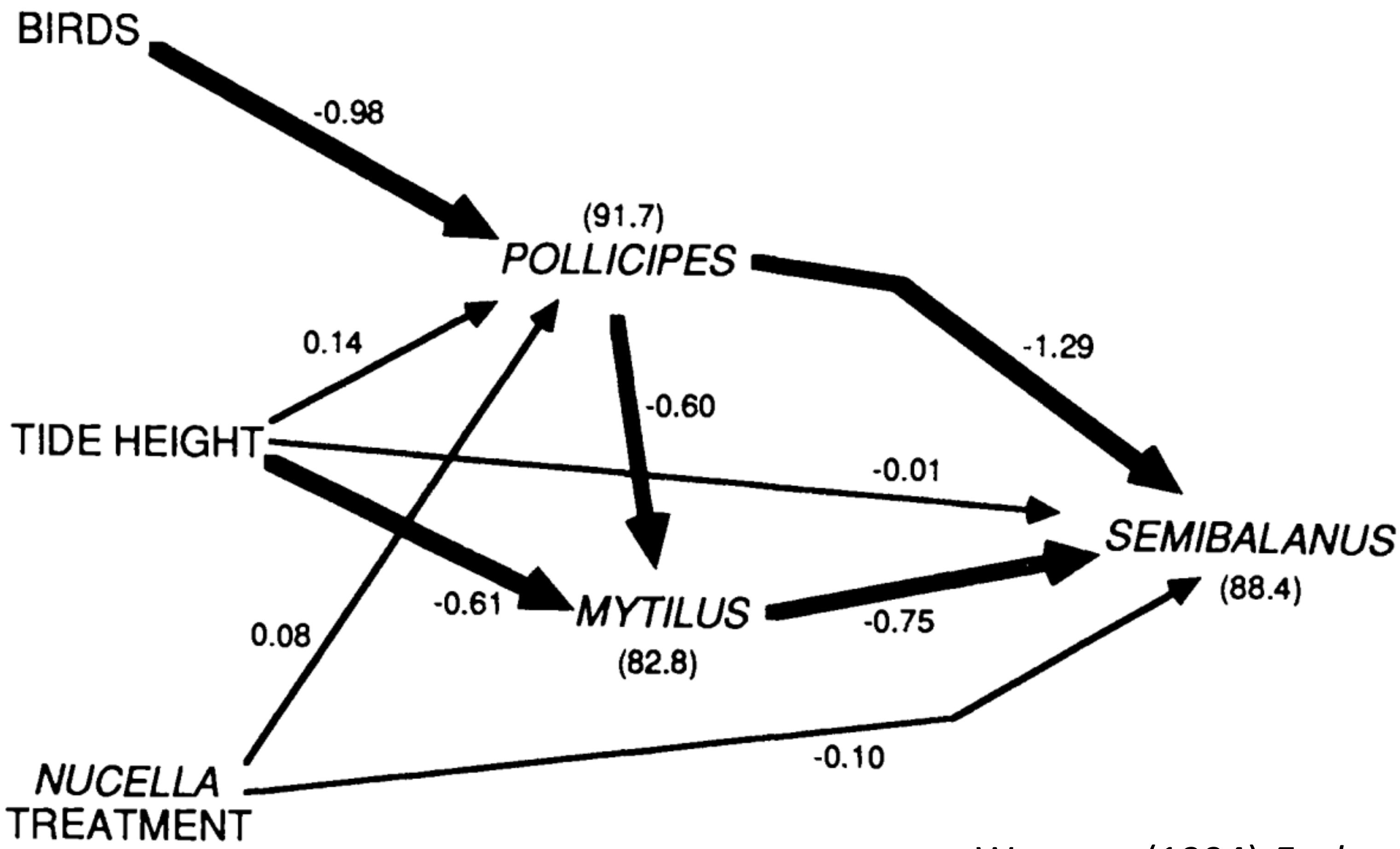


- Unite SEM with graph theory
- Causality is central
- Flexible methods with piecewise approach

1.2 History. SEM and Ecology

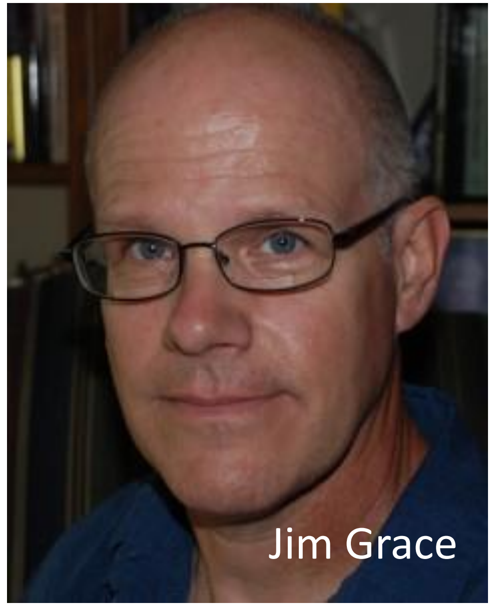


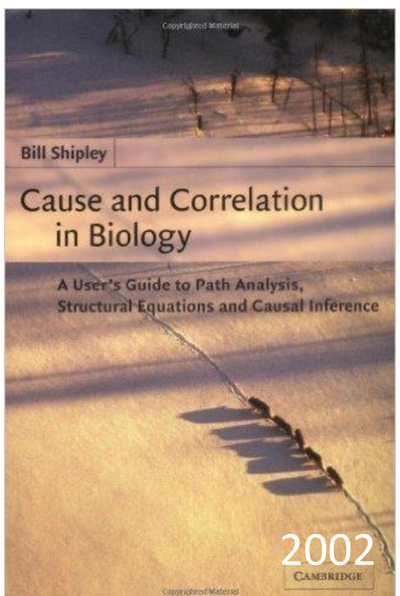
1.2 History. SEM and Ecology

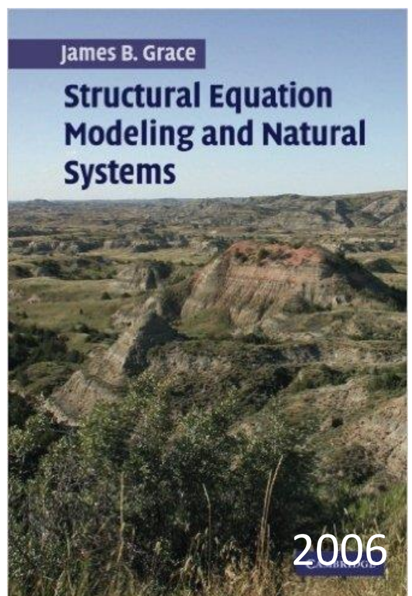


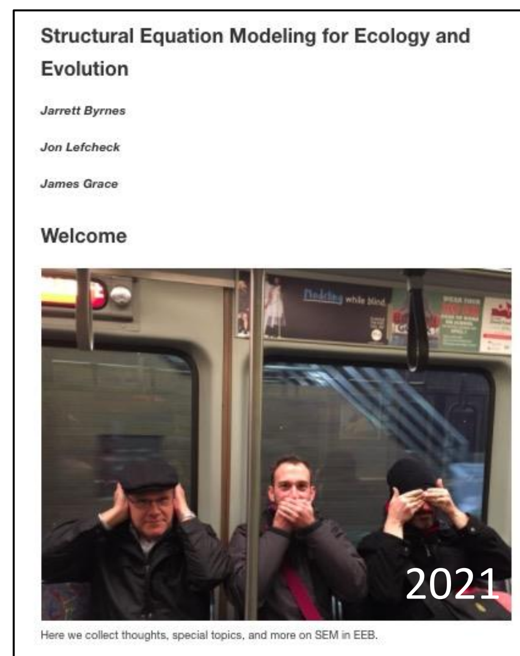
Wootton (1994) *Ecology*

1.2 History. SEM and Ecology









1.3 From ANOVA to SEM

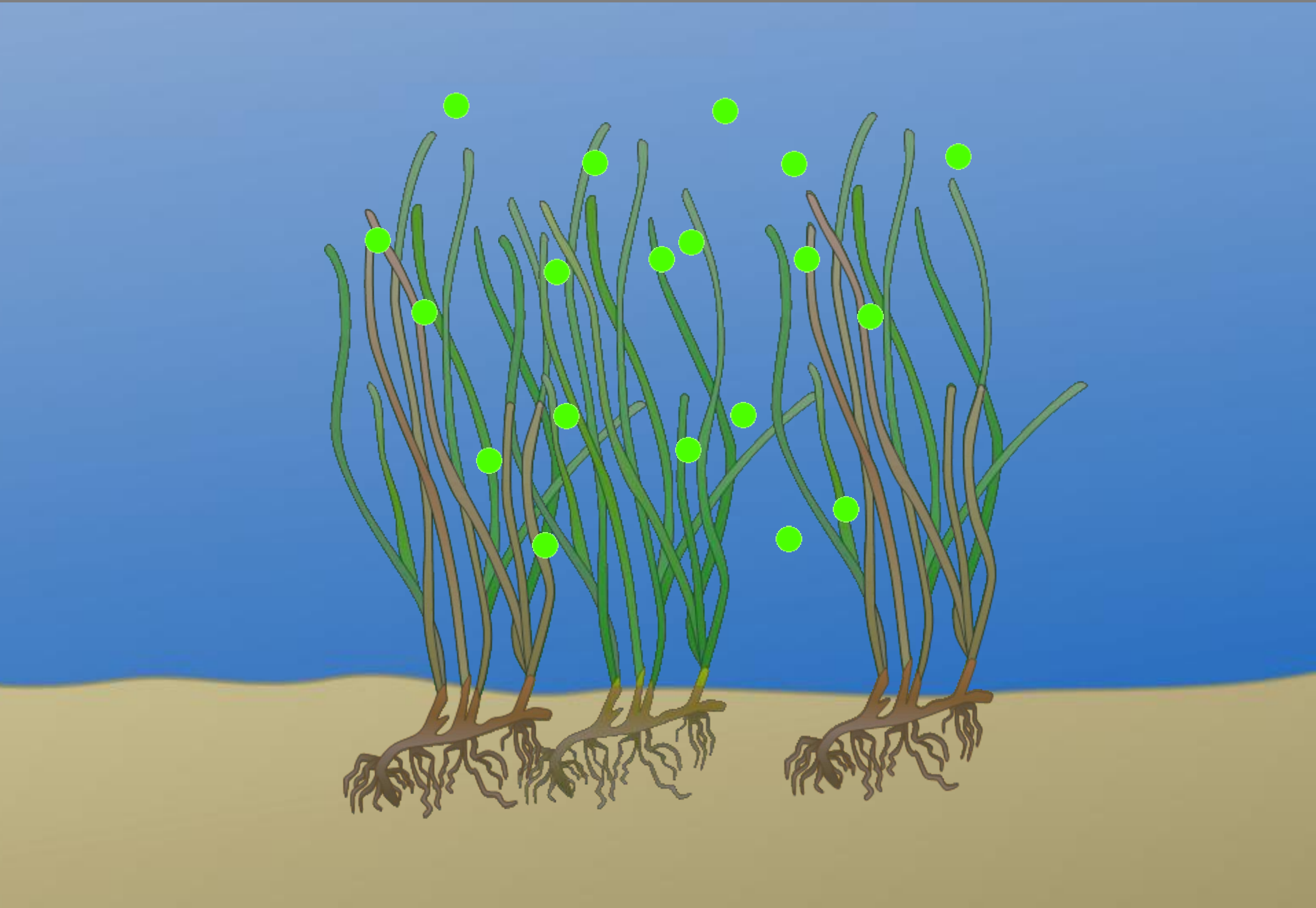
1.3 From ANOVA to SEM. Whalen et al. 2013

Ecology, 94(2), 2013, pp. 510–520

Temporal shifts in top-down vs. bottom-up control of epiphytic algae in a seagrass ecosystem

Matthew A. Whalen,[1,3] J. Emmett Duffy,[1] and James B. Grace[2]

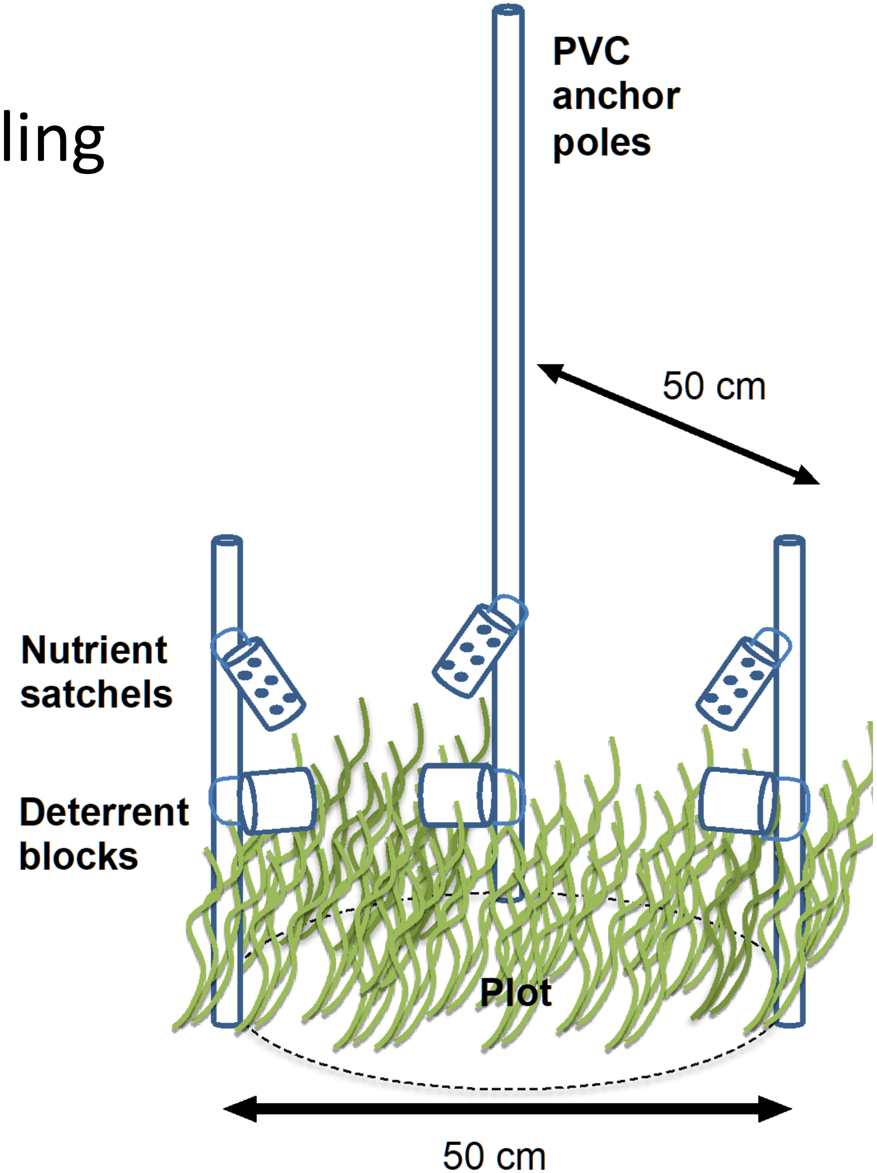
1.3 From ANOVA to SEM. Seagrass systems



1.3 From ANOVA to SEM. Experimental Design

What are the relative influence of top-down vs. bottom-up control in controlling seagrass ecosystems?

Deterrent \ Nutrients	-	+
+	**Control** (D-N-)	**+ Nutrients** (D-N+)
-	**+ Deterrent** (D+N-)	**+ Deterrent + Nutrients** (D+N+)



1.3 From ANOVA to SEM. Experimental Design

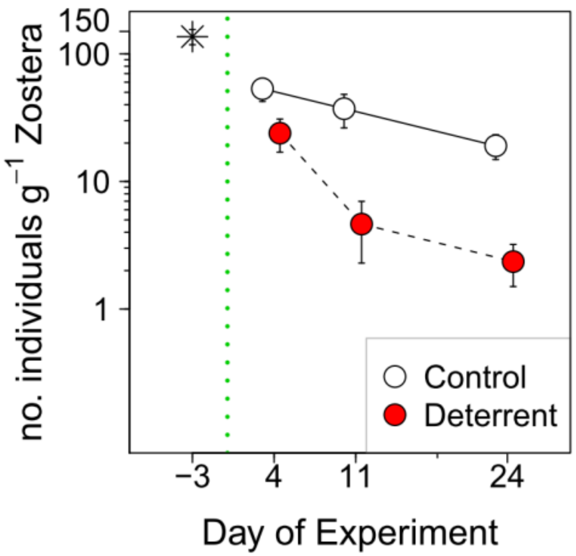
ZEN

Zostera Experimental Network

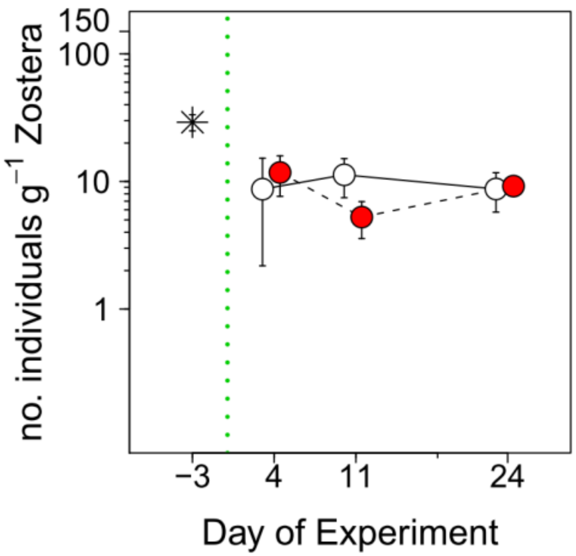
1.3 From ANOVA to SEM. Whalen et al. 2013

1.3 From ANOVA to SEM. Graphing results

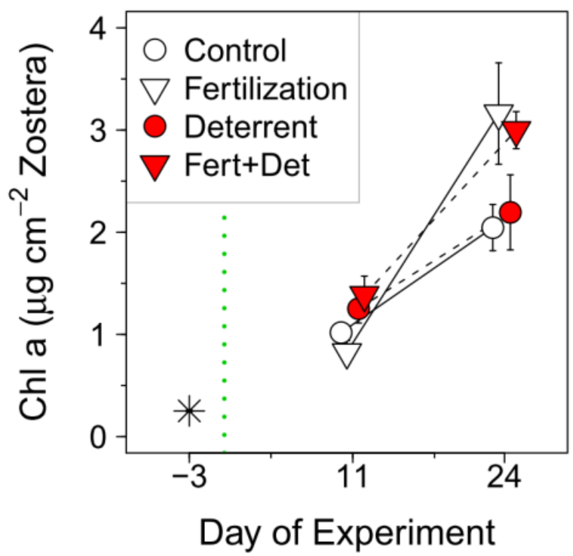
Crustaceans



Gastropods



Epiphytes



1.3 From ANOVA to SEM. Whalen et al. 2013

TABLE 1. Univariate analyses of mesograzer densities and epiphyte biomass from (A) fall and (B) summer experiments in an eelgrass (*Zostera marina*) bed in the York River, Virginia, USA.

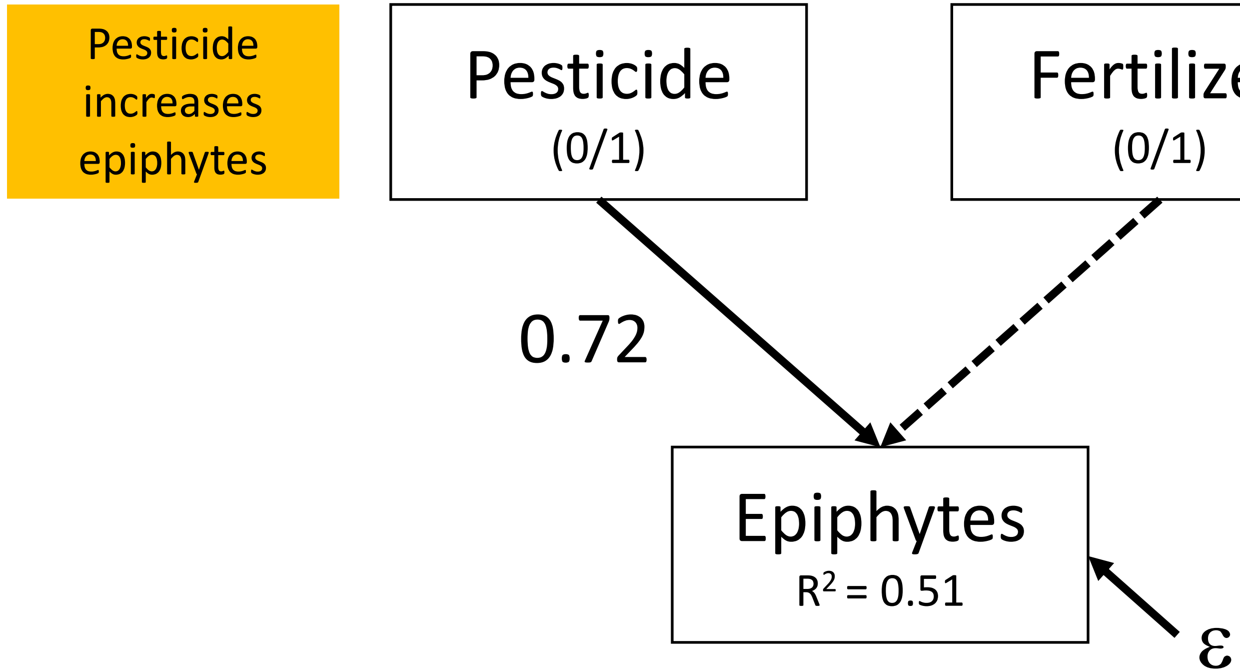
Experiment and response source	Crustaceans			Gastropods			Epiphytes		
	df	*F*	*P*	df	*F*	*P*	df	*F*	*P*
A) Fall									
Deterrent	1	42.84	**<0.001**	1	0.33	0.574	1	3.97	0.052
Fertilization							1	3.10	0.084
Sampling date	2	13.77	**<0.001**	2	0.12	0.887	1	78.24	**<0.001**
Det. × fert.							1	0.86	0.358
Det. × date	2	2.48	0.108	2	1.27	0.301	1	3.72	0.059
Fert. × date							1	7.00	**0.011**
Det. × fert. × date							1	0.81	0.371
Residual	21			21			51		
B) Summer									
Deterrent	1	129.24	**<0.001**	1	1.07	0.306	1	66.22	**<0.001**
Fertilization	1	0.00	0.958	1	0.01	0.920	1	2.19	0.145
Sampling date	1	0.89	0.349	1	11.00	**0.002**	1	0.83	0.367
Det. × fert.	1	0.10	0.756	1	2.00	0.163	1	1.00	0.322
Det. × date	1	0.58	0.448	1	2.96	0.091	1	6.21	**0.016**
Fert. × date	1	2.90	0.094	1	0.71	0.403	1	0.53	0.468
Det. × fert. × date	1	1.57	0.216	1	0.27	0.606	1	1.14	0.290
Residual	56			56			56		

DEATH BY F-TABLES!

Notes: ANOVA tables for linear models describe the effects of chemical deterrent, nutrient fertilization, and sampling date on crustacean mesograzer density, gastropod mesograzer density, and epiphyte biomass. All data were natural-log-transformed except summer gastropods (square-root transformed). Model terms were tested using *F* tests and type III sums of squares. Note that the analyses presented for the summer experiment are balanced. *P* values <0.05 are shown in boldface.

1.3 From ANOVA to SEM. ANOVA

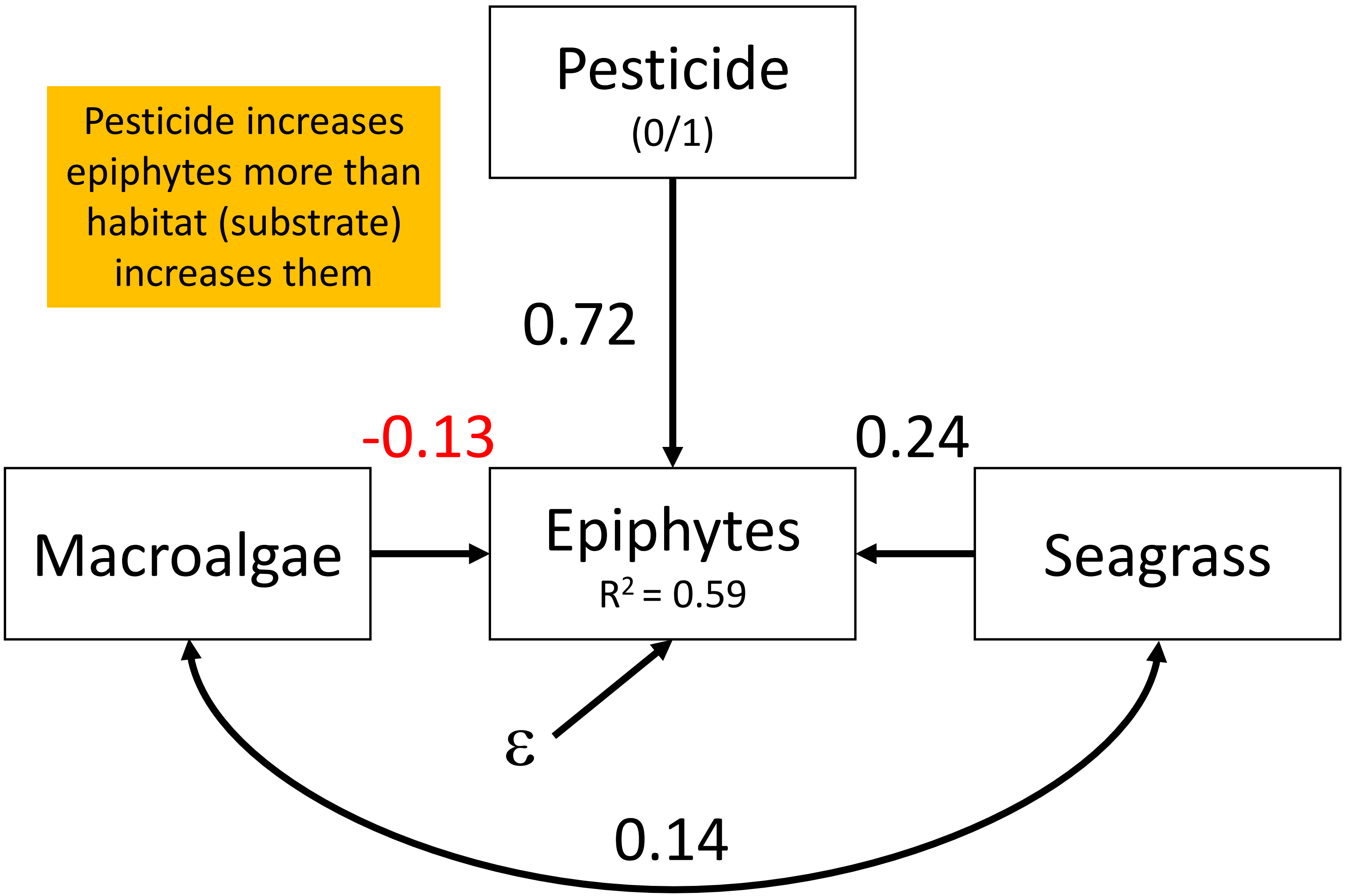
Epiphytes ~ Pesticide + Fertilizer



1.3 From ANOVA to SEM. ANCOVA

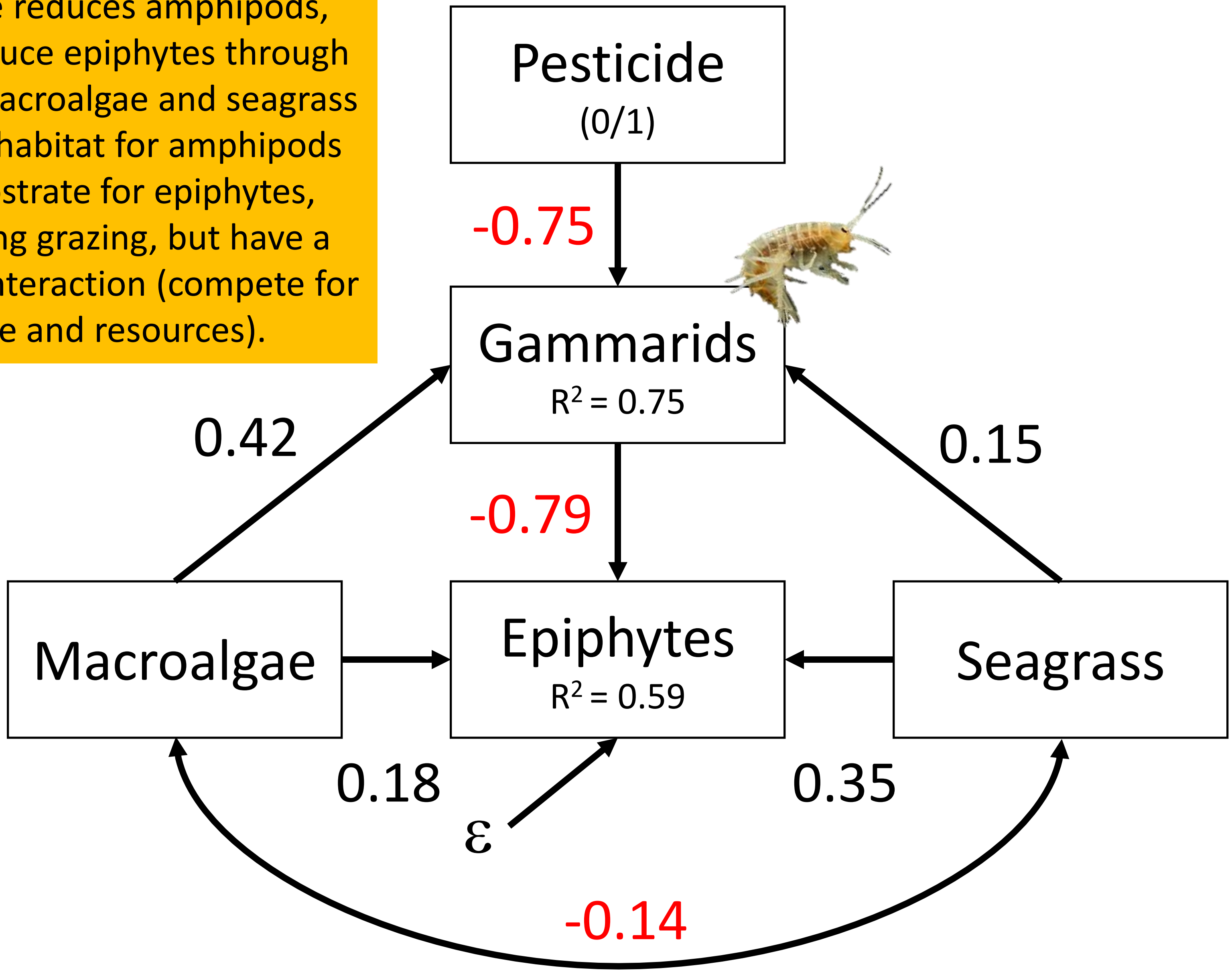
Epiphytes ~ Pesticide + Macroalgae + Seagrass

Pesticide increases epiphytes more than habitat (substrate) increases them

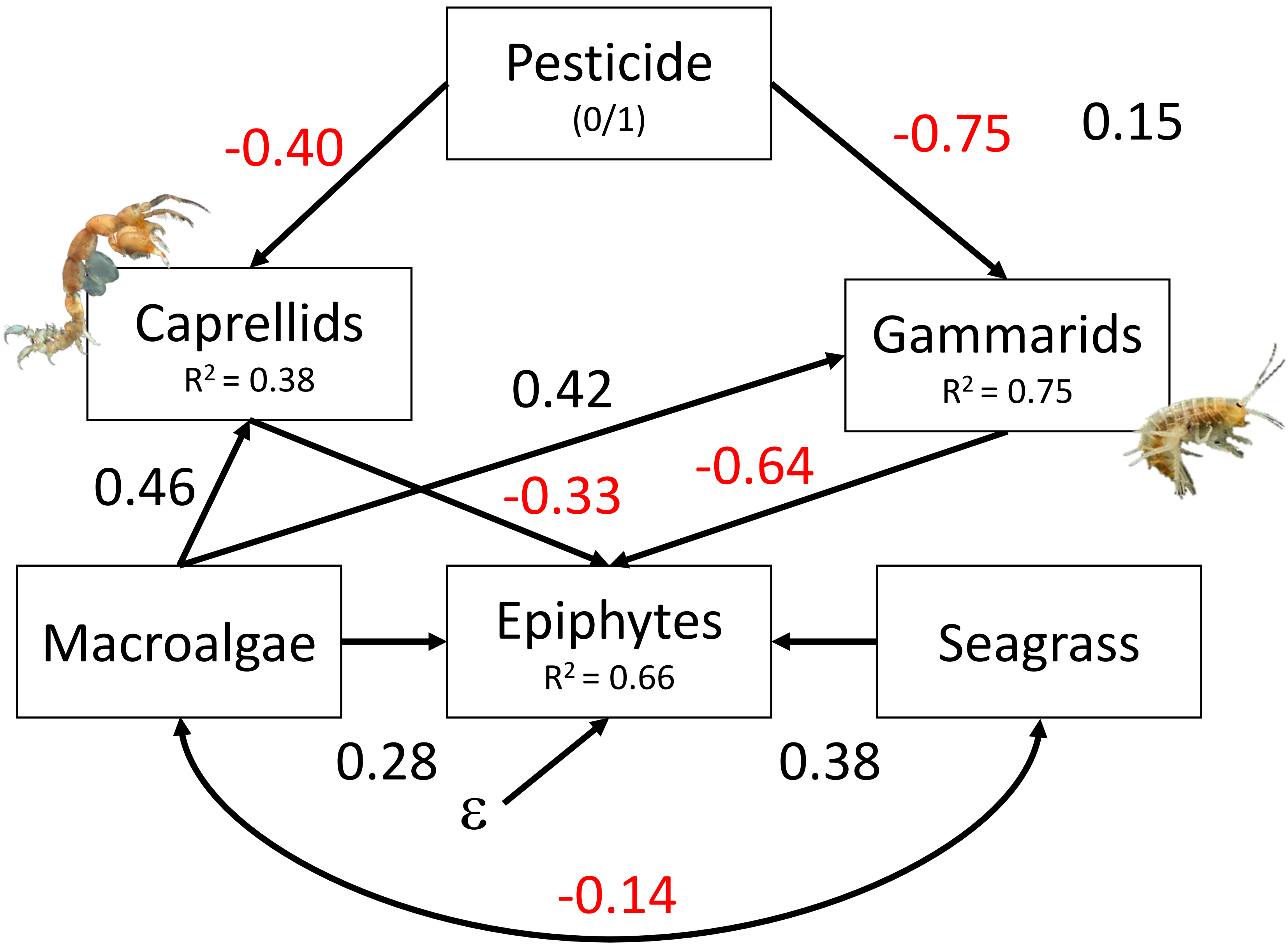


1.3 From ANOVA to SEM. Mediation

Pesticide reduces amphipods, which reduce epiphytes through grazing. Macroalgae and seagrass provides habitat for amphipods and substrate for epiphytes, promoting grazing, but have a negative interaction (compete for space and resources).



1.3 From ANOVA to SEM. Mediation x2



1.3 From ANOVA to SEM. Increasing inference

Pesticide reduces epiphytes

ANOVA

Pesticide increases epiphytes more than habitat (substrate) increases them

ANCOVA

Pesticide reduces amphipods, which reduce epiphytes through grazing. Macroalgae and seagrass provides habitat for amphipods and substrate for epiphytes, promoting grazing, but have a negative interaction (compete for space and resources).

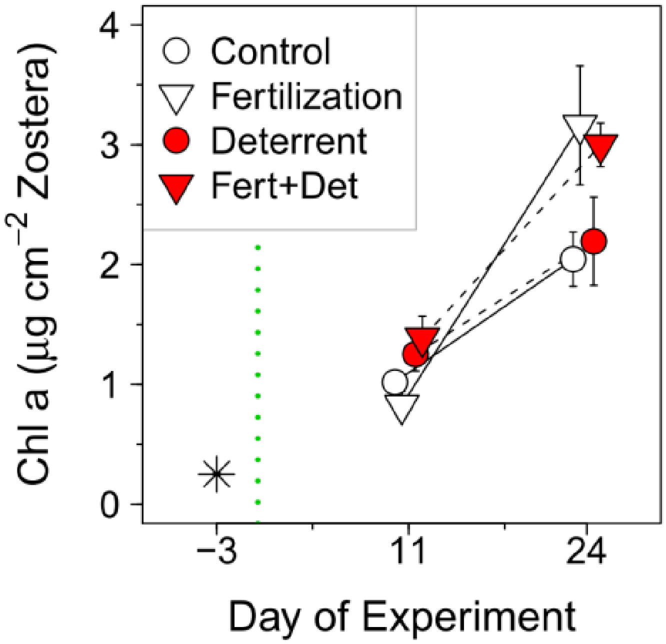
Mediation

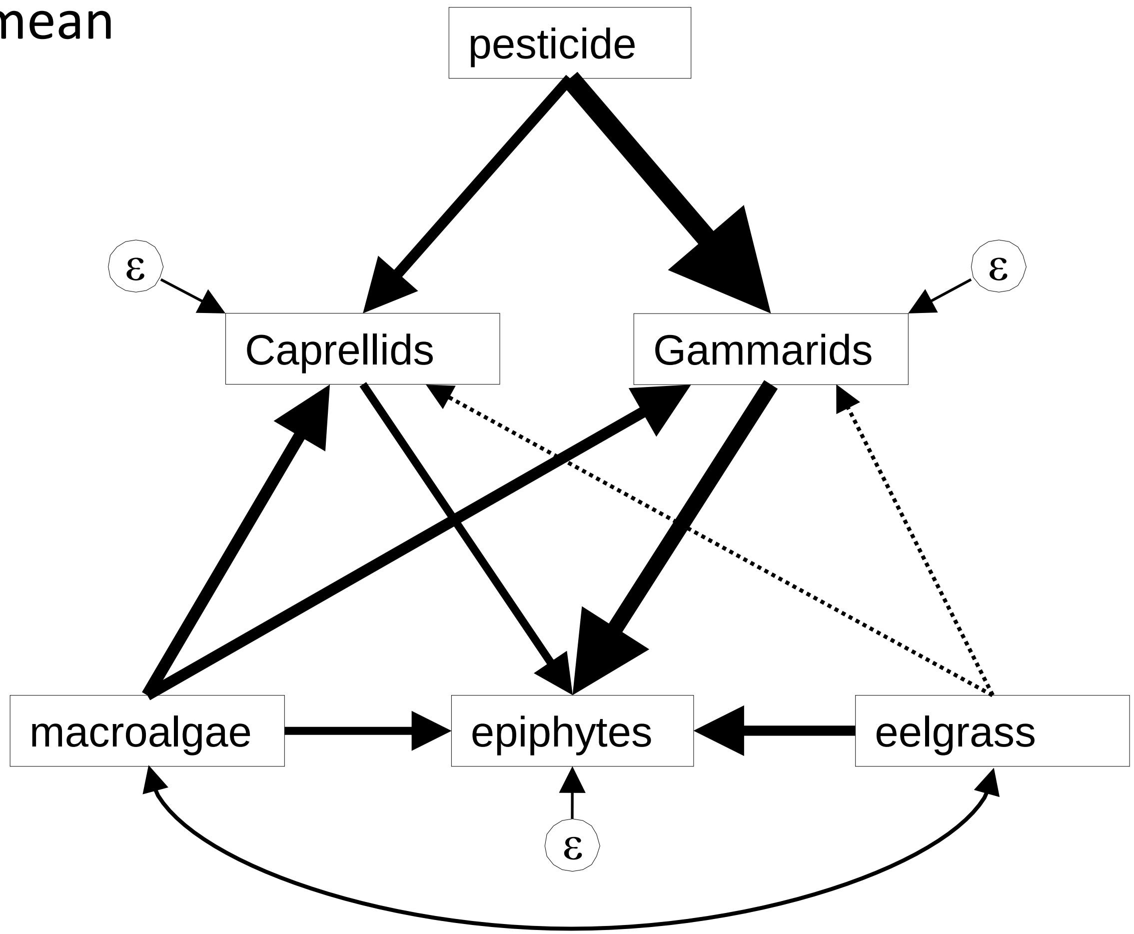
Pesticide reduces both gammarid and caprellid amphipods, which in turn releases epiphytes from grazing, although gammarids appear to be the predominant grazer. Macroalgae primarily provides habitat for amphipods, promoting grazing, while eelgrass primarily provides substrate for epiphytes. Seagrasses and macroalgae negatively influence one another.

Full SEM

1.3 From ANOVA to SEM. Increasing inference

Our model results imply that behind this summary of mean responses…





…is a network of effects like this.

1.3 From ANOVA to SEM. Increasing inference

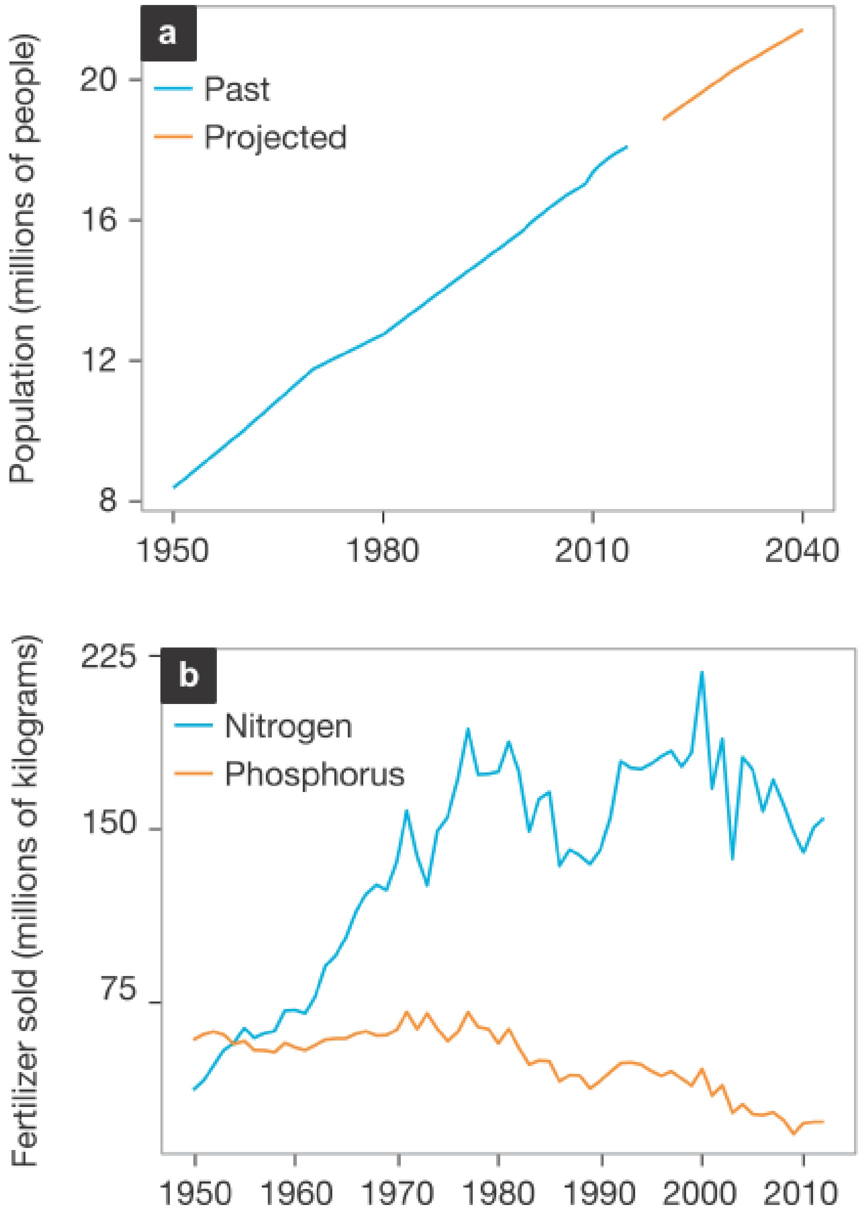
- Teases out *complex relationships*
- Identification and comparison of *direct vs. indirect effects* & potential mediators
- Precise *mechanistic* explanations
- Confirms long-standing hypotheses about the system

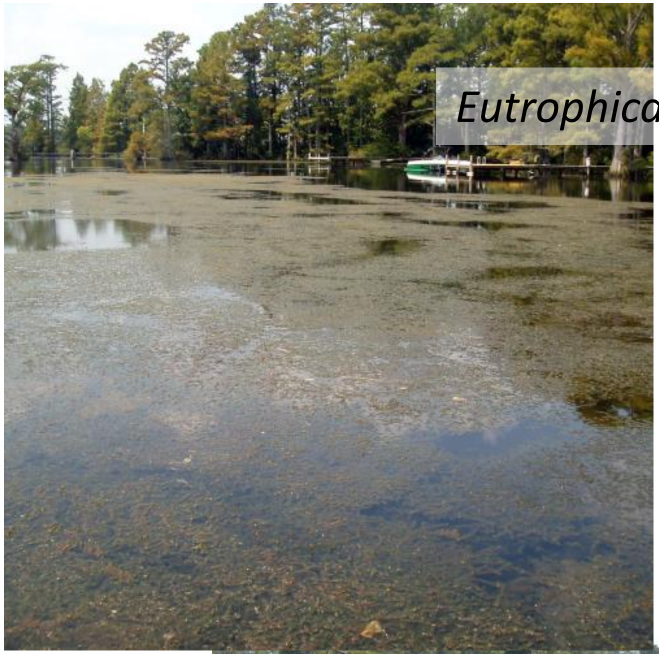
1.4 From Experiments to Observation

1.4 The Big Picture. 400 years of change

John Smith

1.4 The Big Picture. Impacts on the rise

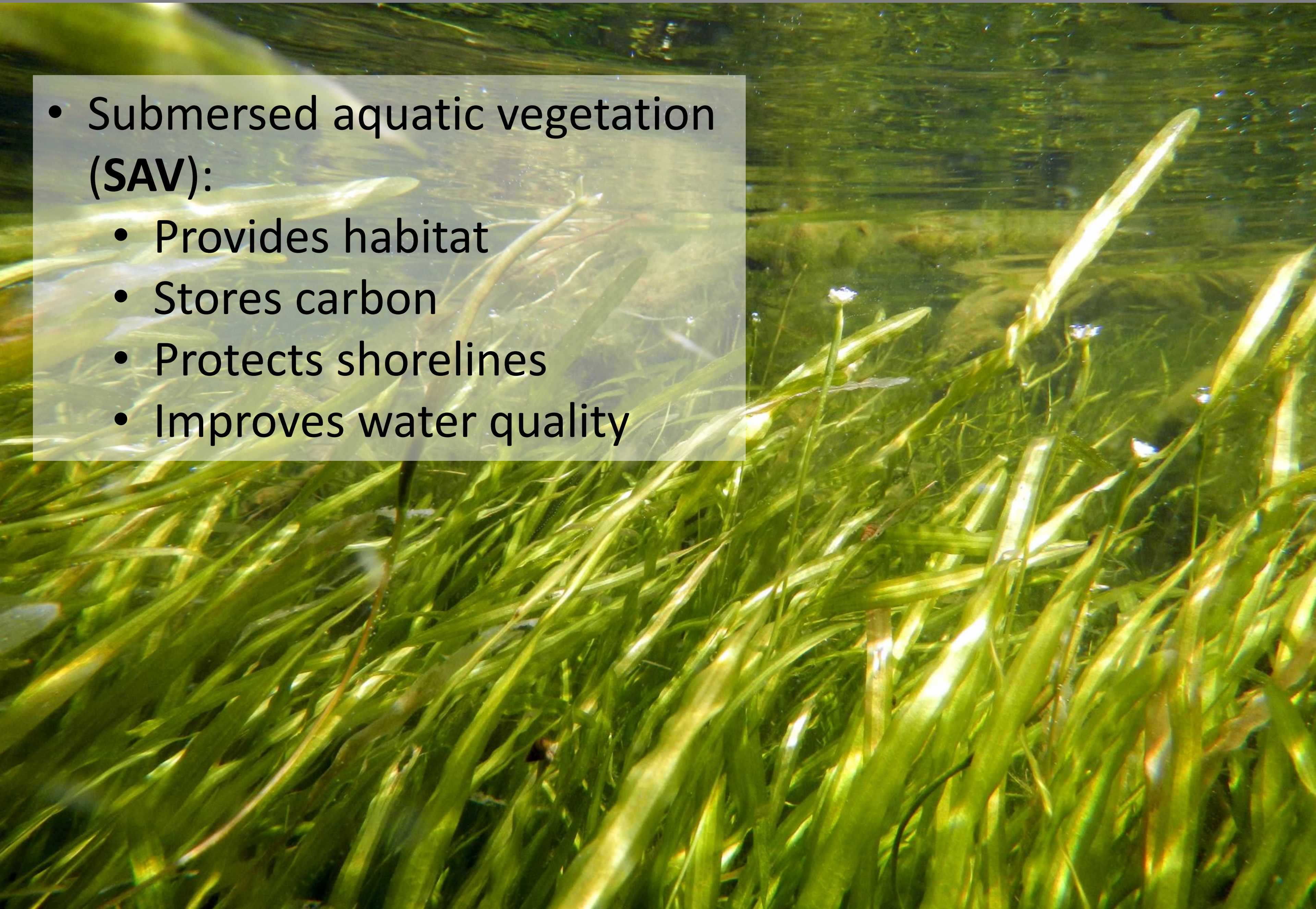




Orth *et al.* 2017 *BioScience*

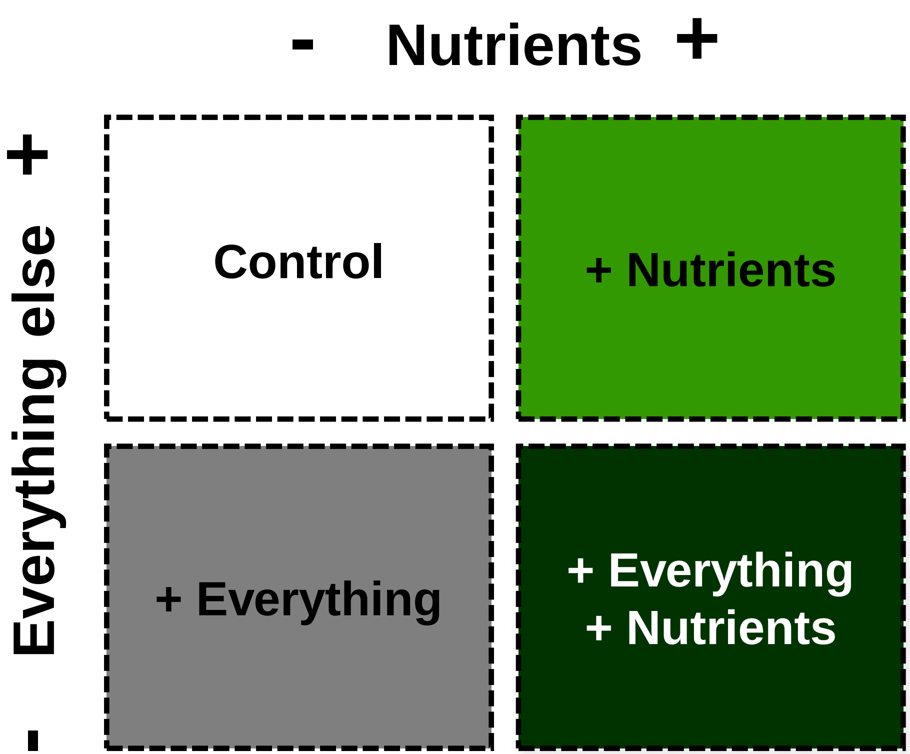
1.4 The Big Picture. Key foundational species

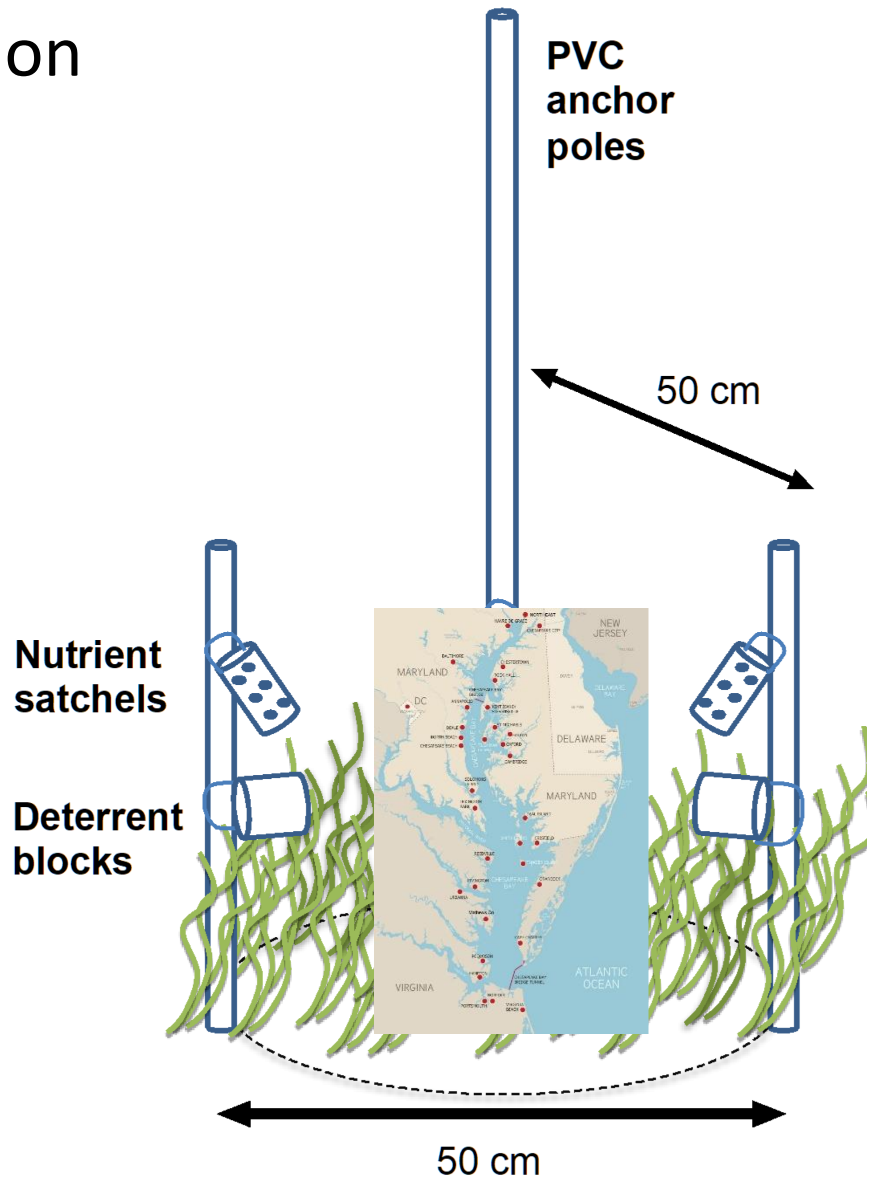
- Submersed aquatic vegetation (**SAV**):
  - Provides habitat
  - Stores carbon
  - Protects shorelines
  - Improves water quality



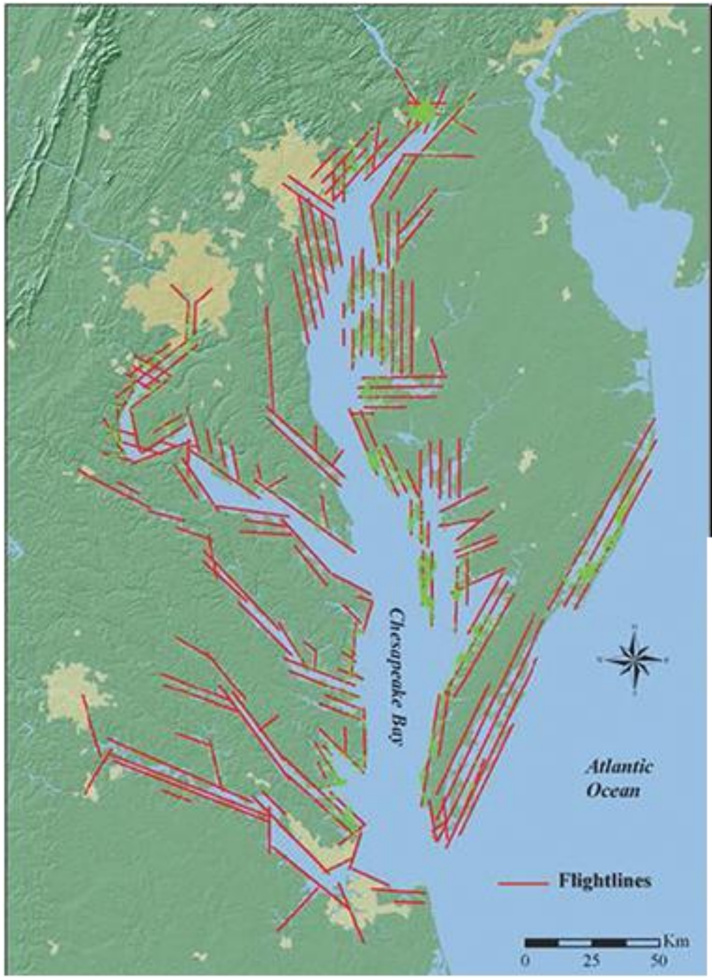
1.4 The Big Picture. A natural experiment

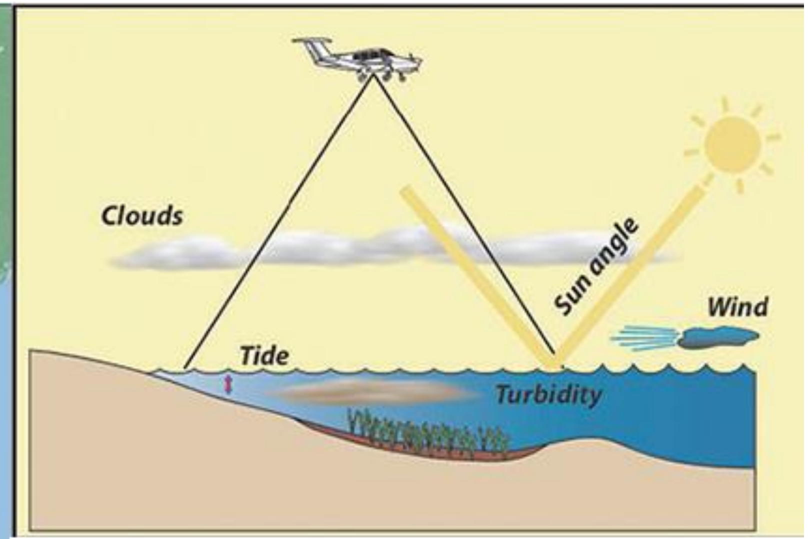
What are the relative influence of nutrients vs other factors on SAV in Chesapeake Bay?





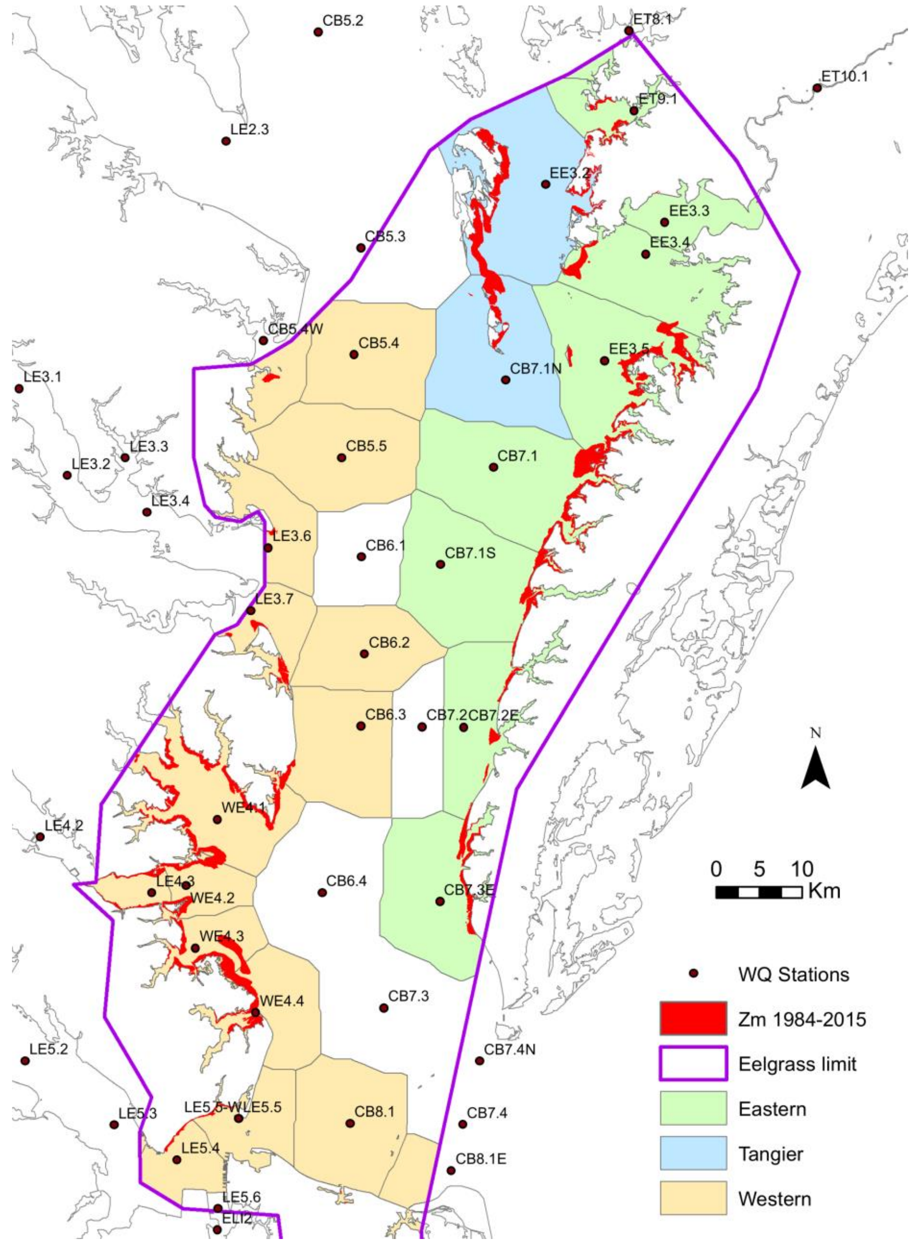
1.4 The Big Picture. Aerial monitoring



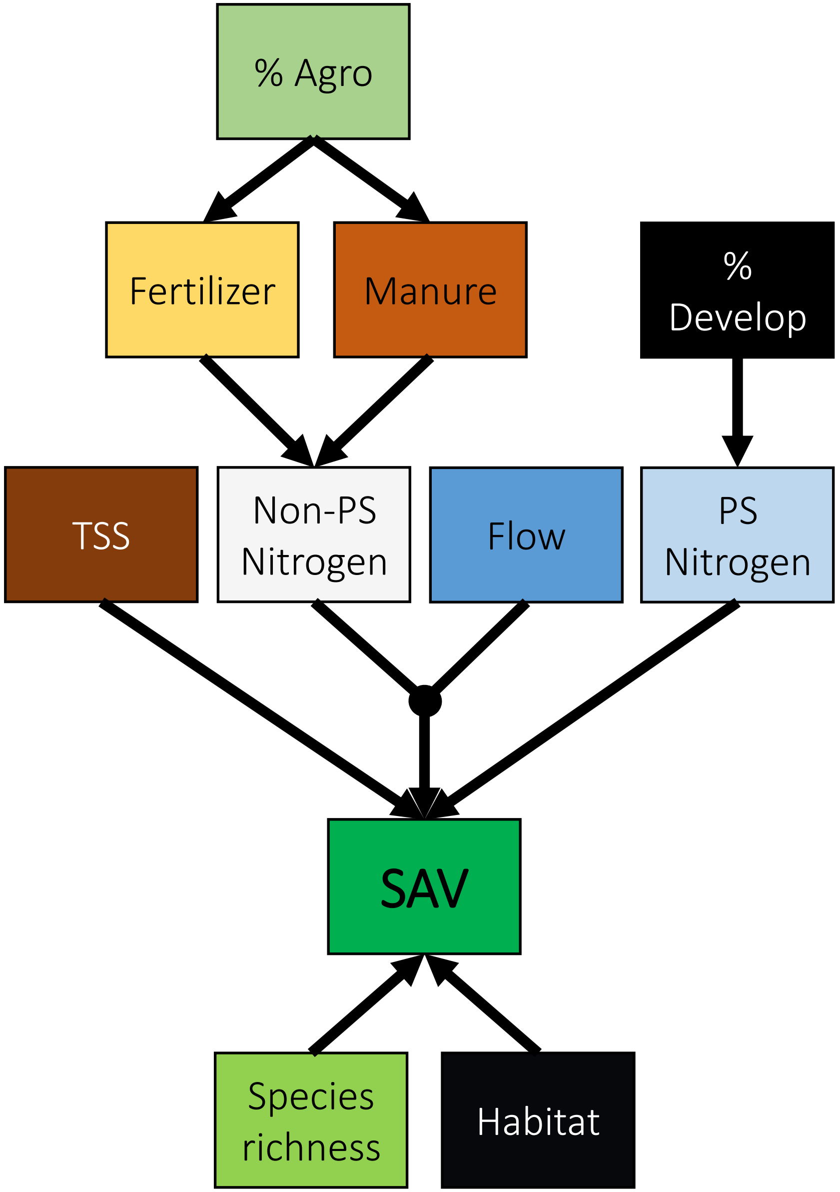


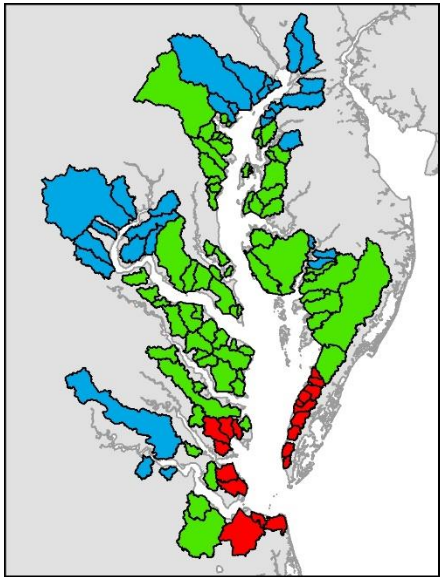
1.4 The Big Picture. Water quality monitoring

Chesapeake Bay Program
Science. Restoration. Partnership.

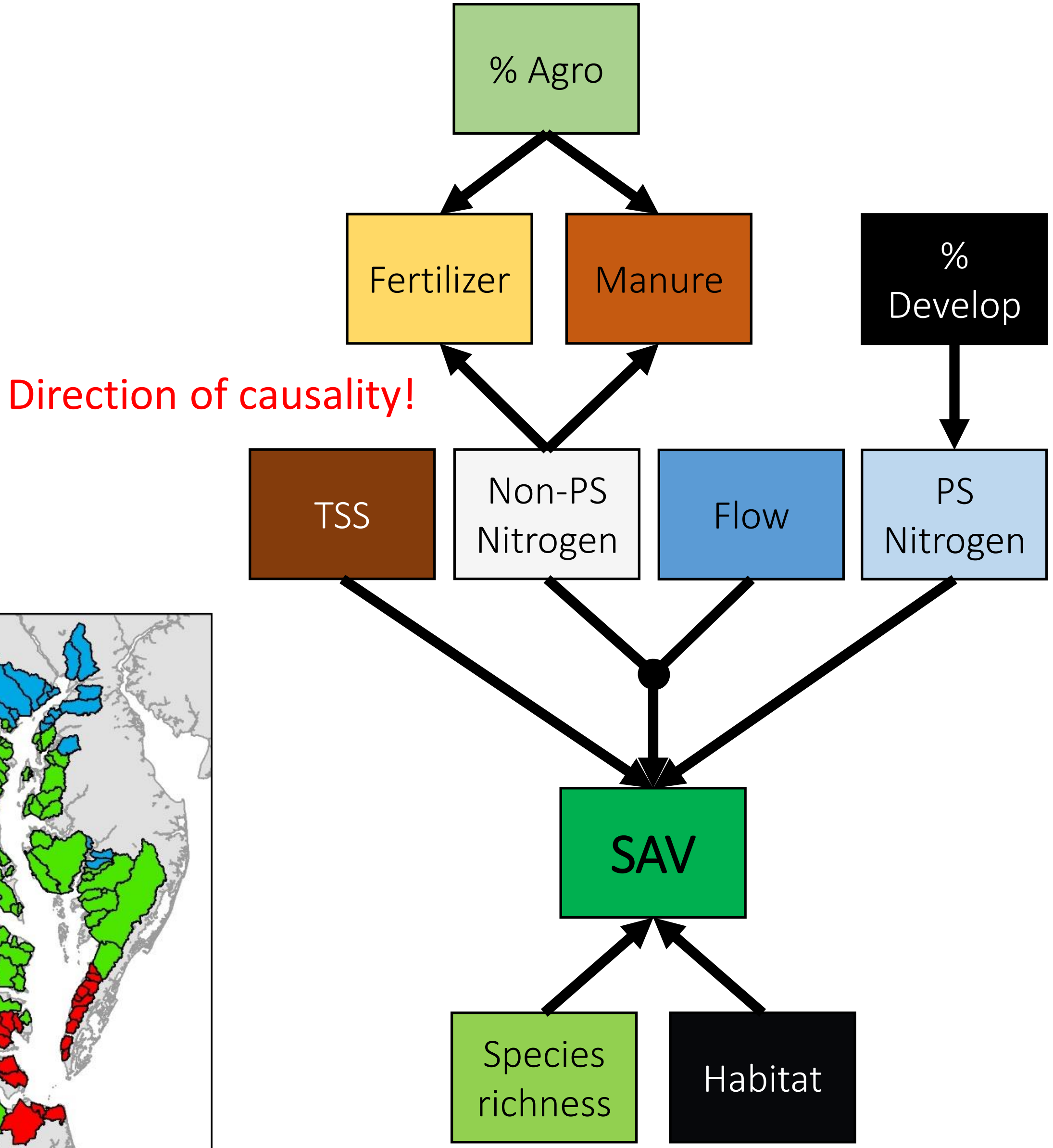


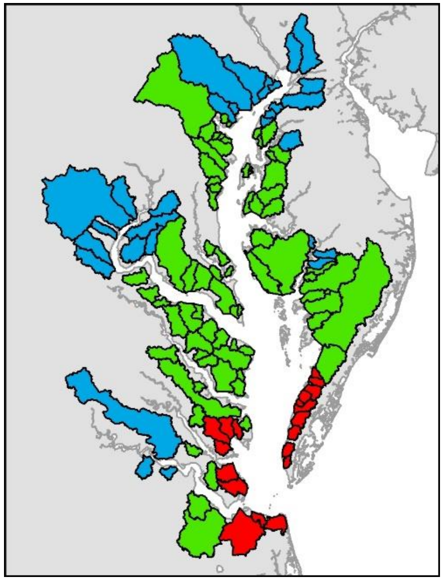
1.4 The Big Picture. Statistical controls



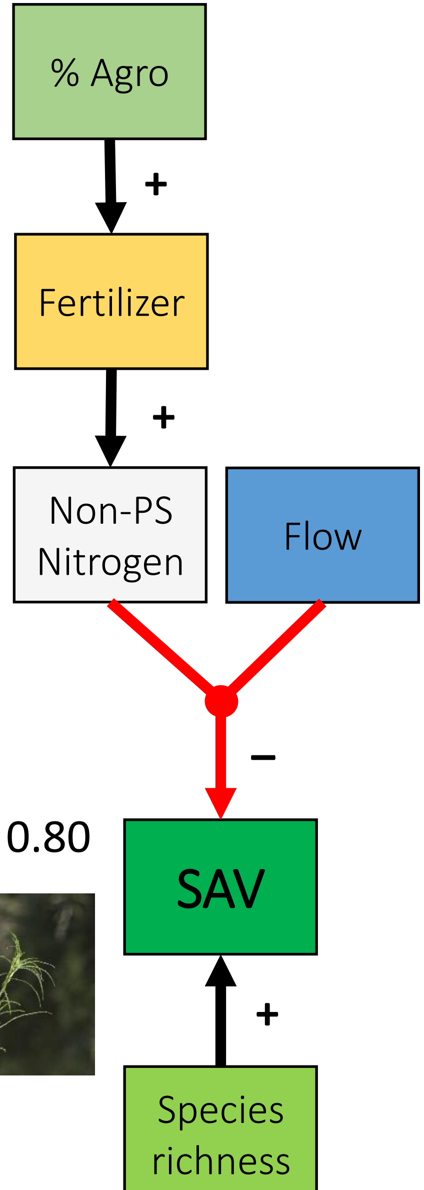


1.4 The Big Picture. Statistical controls





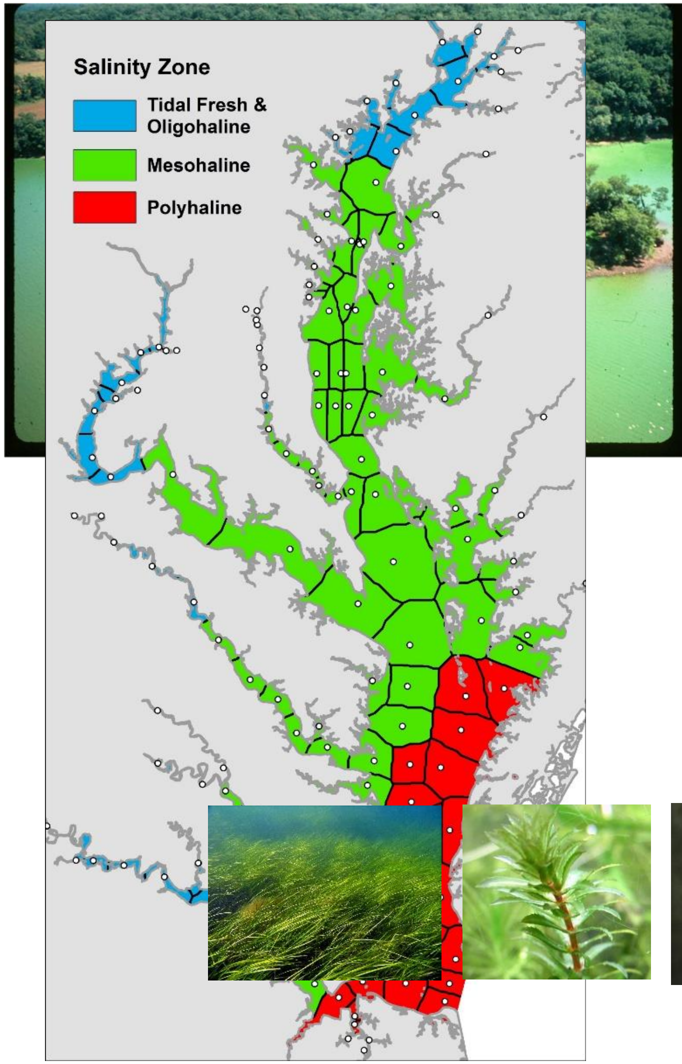
1.4 The Big Picture. Nutrients suck

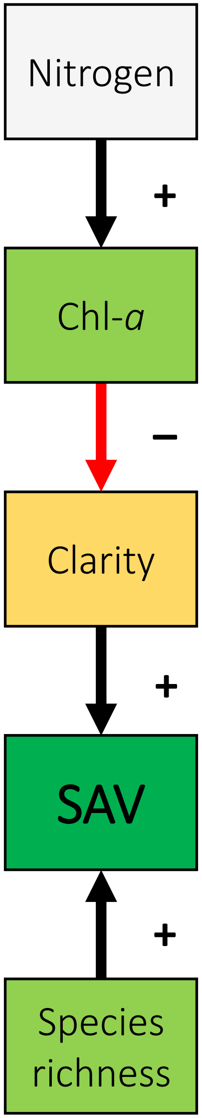


R^2 = 0.67 - 0.80

Lefcheck *et al.* 2018 PNAS

1.4 The Big Picture. How do nutrients suck?





$R^2 = 0.86$

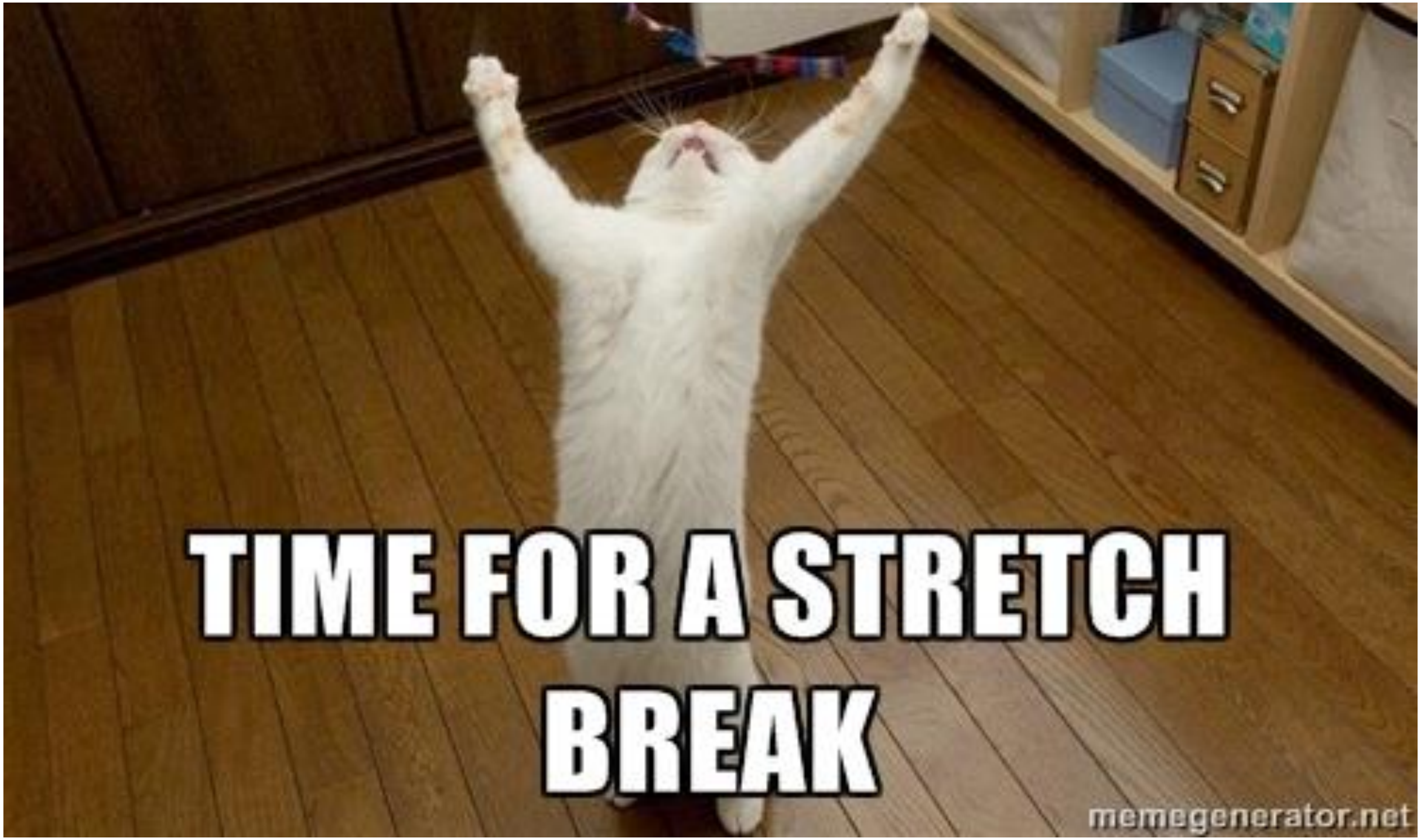
Lefcheck *et al.* 2018 PNAS

1.4 The Big Picture. Conclusions

- Implement statistical rather than experimental controls
- Deduce causal flow
- Leverage ‘big data’ from observations
- Incorporate spatial/temporal autocorrelation
- Gain deep insight into both macro- (landscape) and micro- (water column) phenomenon

Why SEM?

- SEM is a powerful tool for all kinds of data (the sky is the limit)
- “When you have a hammer, everything looks like a nail”
- I’m convinced…can you be?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