Adaptation and Resilience to Climate Change:
Understanding Impacts and Vulnerabilities
Faculty of Physics
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# Application of economic concepts in biophysical oceanography

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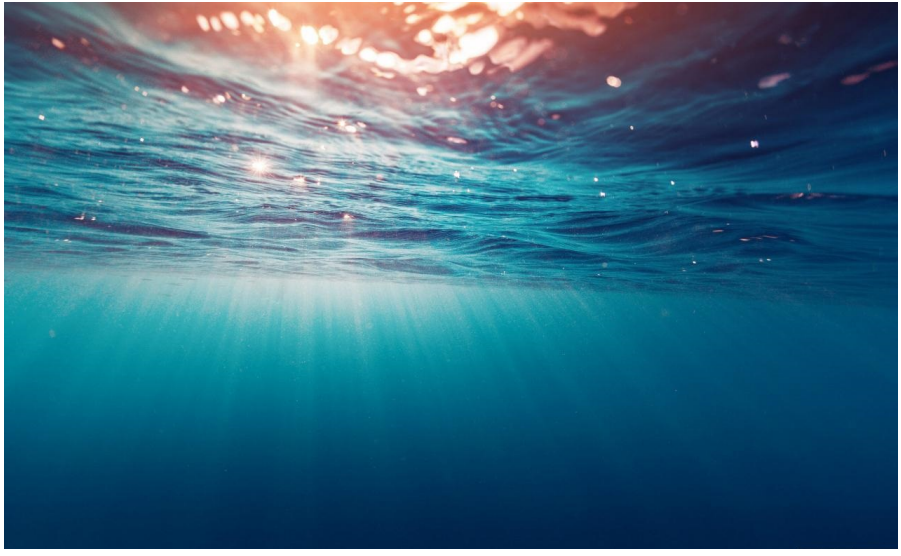
# The basic problem



## Mathematical description of the problem

$$\frac{\partial B}{\partial t} + w\frac{\partial B}{\partial z} = \Big(P^B(I) - L^B\Big)B + M\frac{\partial^2 B}{\partial z^2}$$

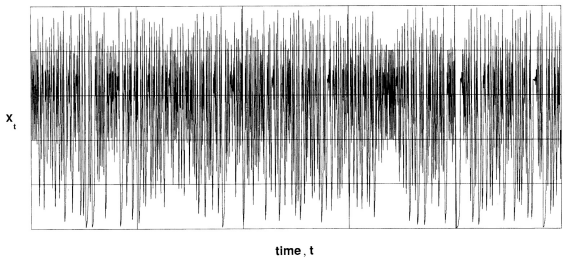
$$I(z,t) = I_0(t)\exp\left(-\int_0^z \Big(K_w + k_B B(z',t)\Big)\,\mathrm{d}z'\right)$$

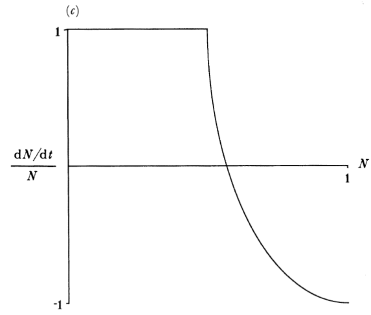
With respect to light $I$ the problem has all the qualities one seeks in physics:

**nonlinear** + **nonlocal** + **nonautonomous**

# Motivation

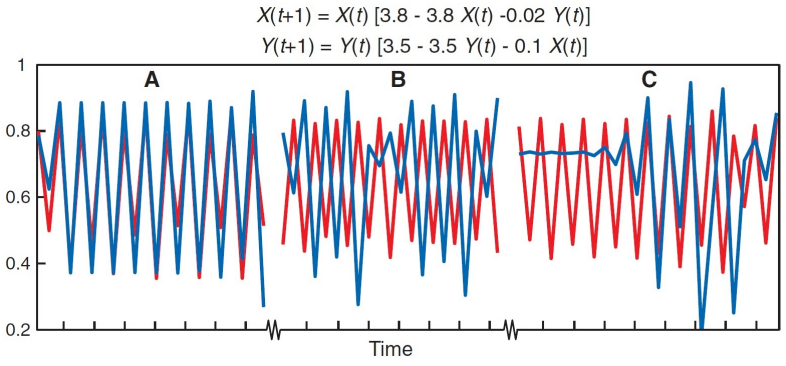
# Sugihara et al. (1990) Philosophical Transactions: Biological Sciences




*Often it is thought that* ***environmental factors are associated with stochastic fluctuations in population density, and biological ones with deterministic regulation****. We revisit these ideas in the light of recent work on chaos and nonlinear systems. We show that* ***completely deterministic regulatory factors can lead to apparently random fluctuations in population density****...*

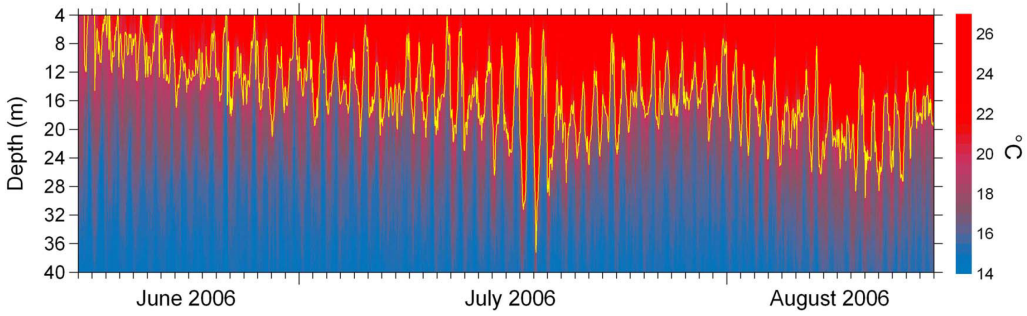
# Sugihara et al. (2012) Science




*Identifying causality in complex systems can be difficult. Contradictions arise in many scientific contexts where* ***variables are positively coupled at some times but at other times appear unrelated*** *or even negatively coupled depending on system state.*

What about marine primary production and noise?

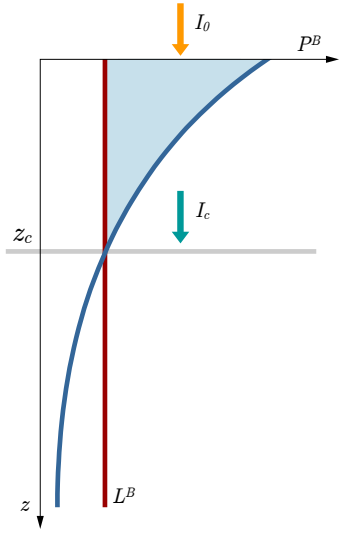
# High frequency observations in the Adriatic Sea (Orlić et al., 2011)



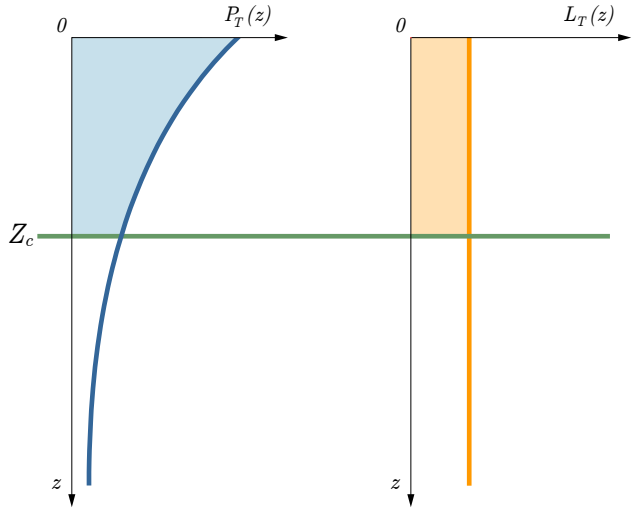

*As for the productivity of coastal waters, the* ***diurnal upwelling may influence the generation of phytoplankton characterized by a near-daily scale*** *and therefore may also influence the generation of zooplankton and nekton at much larger temporal scales.* ***The well-known fact that the larger areas of the islands of Lastovo and Vis are relatively productive ones in the Adriatic*** *supports the proposed mechanism and suggests that these islands represent the natural laboratories in which the generation times of various members of the food web can be studied.*

Let us first observe a simple model without noise!

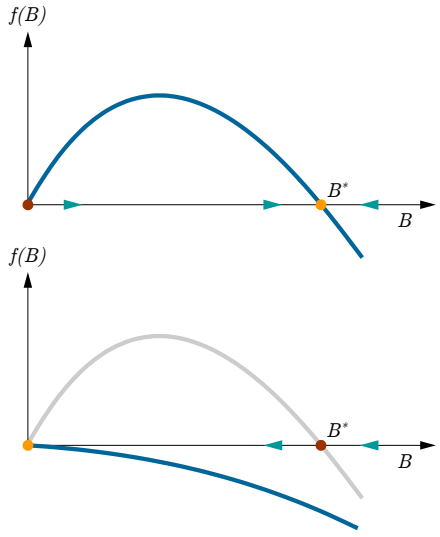
# Photosynthesis in a stratified water column



# The classical Critical Depth Criterion (Sverdrup, 1953)



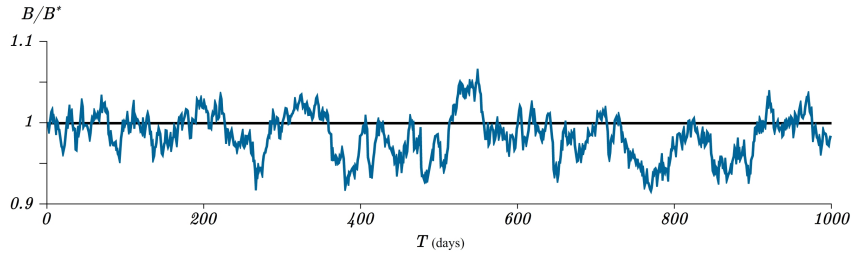
Bio-optical bifurcation (Kovač & Sathyendranath, 2025)



What happens when we add noise to surface irradiance?

$$I_0^m(t) = \langle I_0^m \rangle + \delta I_0^m$$

# Dynamics



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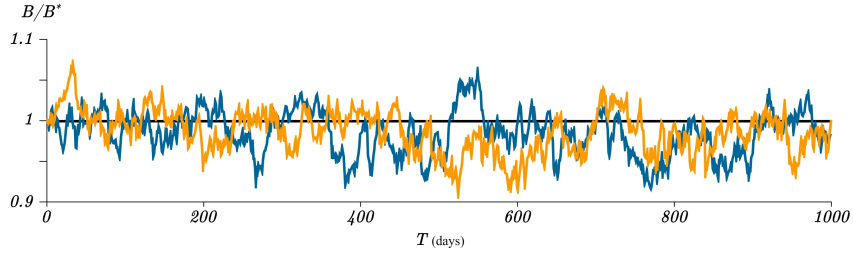

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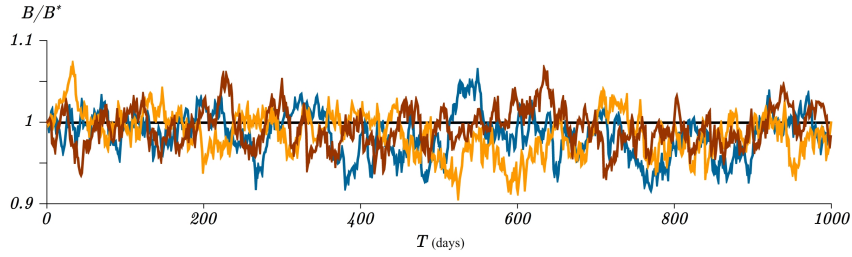
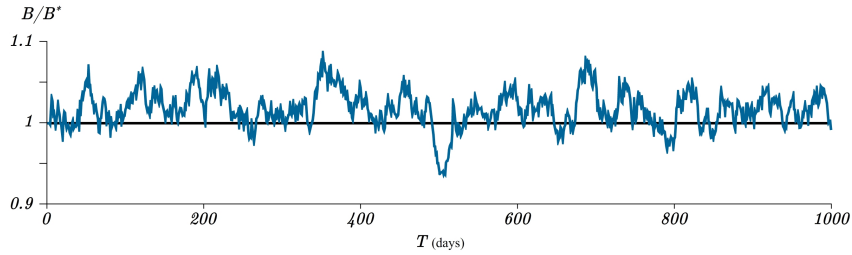



Biomass is suppressed despite having received same total energy!

What happens when we add noise to mixed-layer depth?

$$Z_m(t) = \langle Z_m \rangle + \delta Z_m$$

# Dynamics



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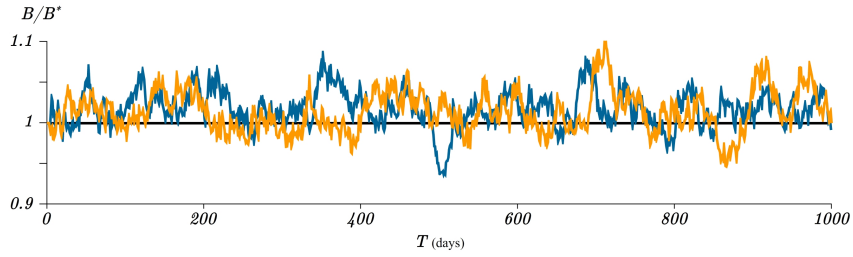

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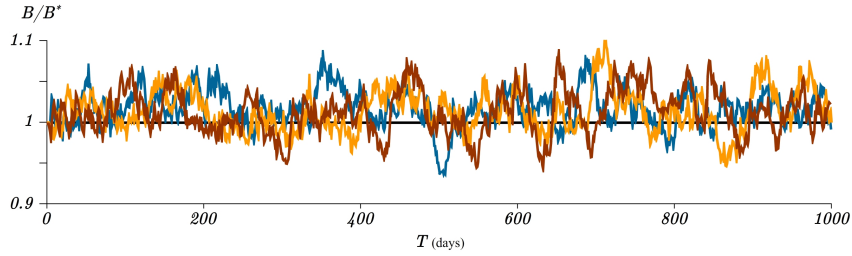



In this case the opposite holds: biomass is increased on average.

# An analogy to illustrate the concept

| FRAGILE | ROBUST | ANTIFRAGILE |
| --- | --- | --- |
| suffers from disorder | stays the same | gains from disorder |

A candidate definition of anti/fragility for primary production

**Marginal production**

$$M_x = \frac{\partial P}{\partial x}$$

**Fragility**

$$F_x = \frac{\partial M_x}{\partial x}$$

$x$ is the controlling variable, such as irradiance, nutrients, mixed layer depth, ...

**Ito's lemma** to model the effect of noise on primary production

If we assume the controlling variable is a stochastic process, for example:

$$\mathrm{d}X = \mu\,\mathrm{d}t + \sigma\,\mathrm{d}W$$

we need to apply **Ito's lemma** to calculate how production changes:

$$\mathrm{d}P^B = \left(\frac{\partial P^B}{\partial t} + \mu\frac{\partial P^B}{\partial x} + \frac{\sigma^2}{2}\frac{\partial^2 P^B}{\partial x^2}\right)dt + \sigma\frac{\partial P^B}{\partial x}\,\mathrm{d}W$$

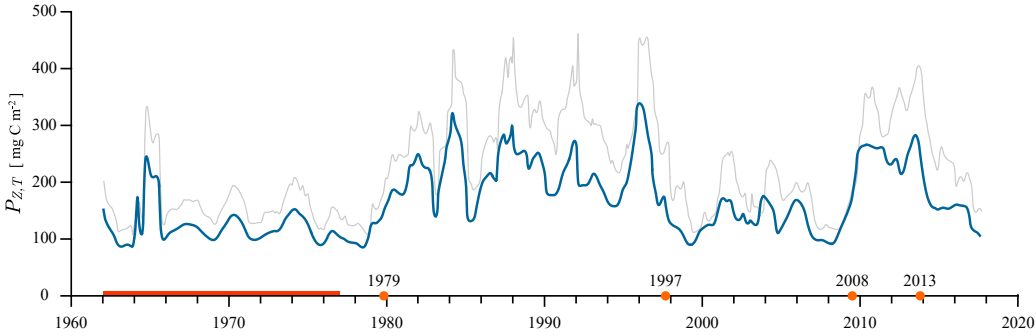
**Ito's lemma** to model the effect of noise on primary production

Using the definitions of **marginal production** and **fragility** we get:

$$\mathrm{d}P^B = \Big(\frac{\partial P^B}{\partial t} + \mu M_x + \frac{\sigma^2}{2} F_x\Big) dt + \sigma M_x \,\mathrm{d}W$$

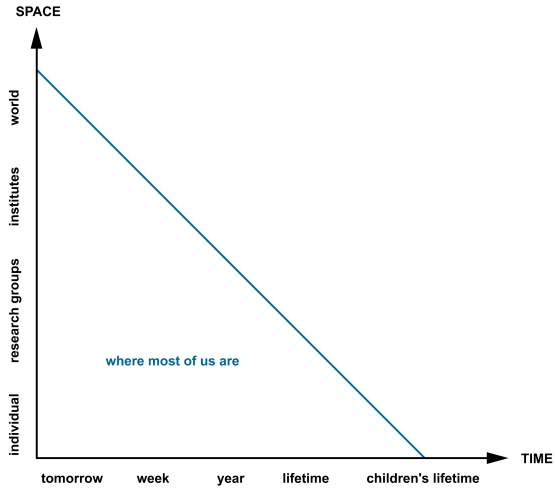
The effect of noise spills over to the deterministic component.

Are we seeing evidence of anti/fragility on longer time scales?




55 year long in situ time series from the Adriatic (Kovač et al., 2018)

How to even think on such long time scales?




Adopted from Limits to growth (1972)

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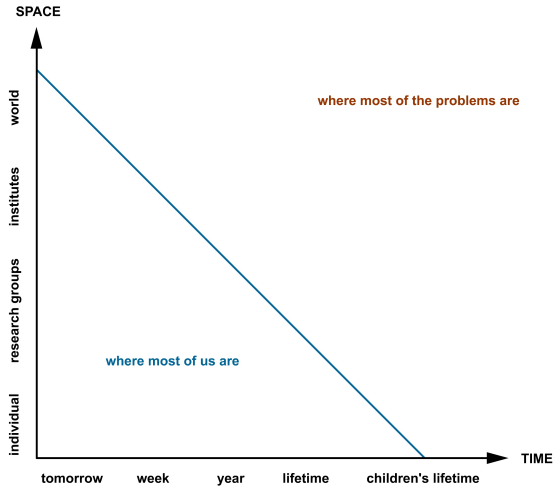


Adopted from Limits to growth (1972)

# Valuation: a hard problem

What would you rather: a tree today or two trees tomorrow?

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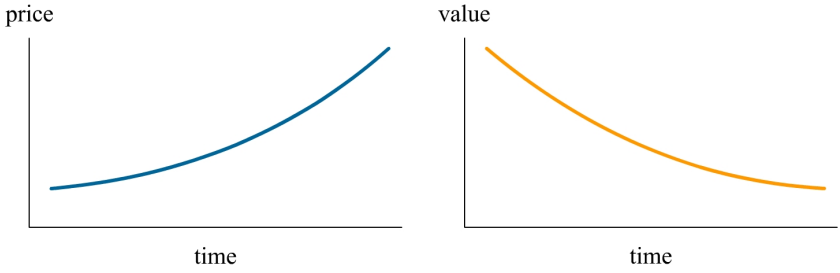
Depends on how fast the trees grow!

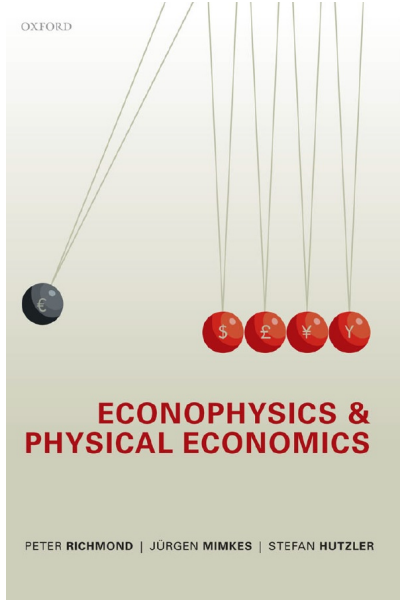
# Discounting



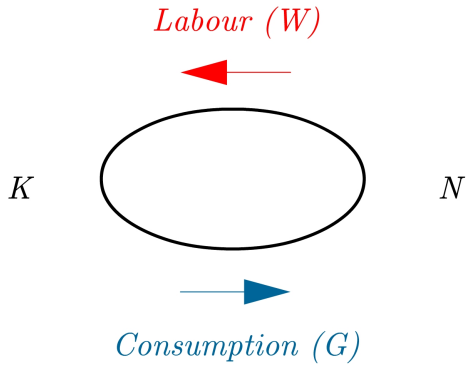

The process of converting value received in the future to value received now.

How to discount primary production?

The source of the problem?



# A model of a closed natural production circuit (Richmond et al., 2013)




Labourers from $N$ households work in the fields (their capital, $K$). In return for their work, $W$, consumer goods, $G$, are brought back from the fields to the households.

Critique: A far too simple description for modern day economy!

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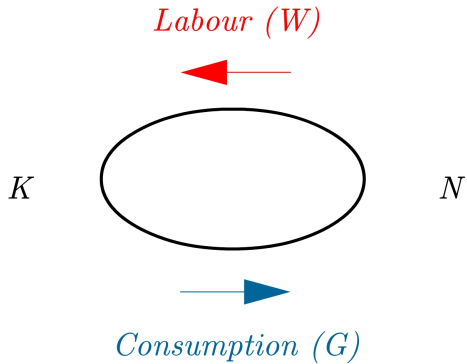
Is it really?!

# A model of a closed natural production circuit




**Ships** from $N$ **harbours** fish on the **sea** (their capital, $K$). In return for their **effort**, $W$, **fish**, $G$, are brought back from the **sea to the harbour**.

Thank you!

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