Jožef Stefan Institute

UNIVERSITY OF CAMBRIDGE

Modelling the collapse of complex societies

Sabin Roman

Work on collapse

Ecological Economics
Volume 132, February 2017, Pages 264-278

Analysis

Coupled Societies are More Robust Against Collapse: A Hypothetical Look at Easter Island

Sabin Roman [a, b], Seth Bullock [c], Markus Brede [a, b]

Ecological Economics
Volume 146, April 2018, Pages 312-324

Analysis

The Dynamics of Human–Environment Interactions in the Collapse of the Classic Maya

Sabin Roman [a, b], Erika Palmer [c], Markus Brede [a, b]

Cliodynamics: The Journal of Quantitative History and Cultural Evolution

The Growth and Decline of the Western Roman Empire: Quantifying the Dynamics of Army Size, Territory, and Coinage

Sabin Roman[1,2], Erika Palmer[3]
[1] *Centre for the Study of Existential Risk, University of Cambridge*
[2] *Romanian Institute of Science and Technology*
[3] *Ruralis—Institute for Rural and Regional Research*

Heliyon
Volume 7, Issue 6, June 2021, e07293

Research article

Historical dynamics of the Chinese dynasties

Sabin Roman

My articles on societal dynamics and collapse.

My field: Societal collapse and cliodynamics

Clio, the muse of history (Berlin)

- Interest in topic since late 1700s (Gibbon and Malthus)

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- Real progress?
- Mathematical modelling is rare
- Data scarce and sparse
- Apparent intractability

The first scientific success

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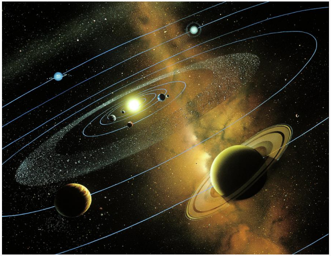
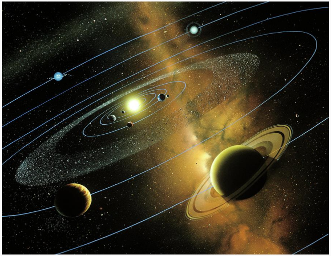


Kepler’s laws of planetary motion, published in Astronomia Nova

The first scientific success



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Gravity is the dominant force over large spatial scales (solar system).

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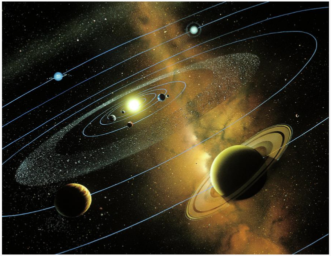
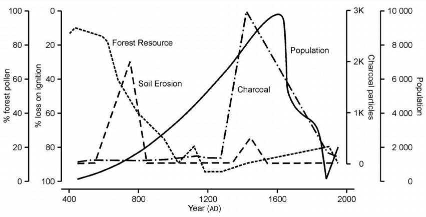


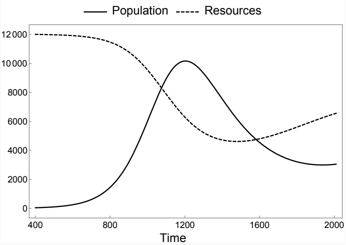
Kepler's laws of planetary motion, published in Astronomia Nova

Gravity is the dominant force over large spatial scales (solar system).
What is the equivalent of "gravity" in terms of social forces that persist over long temporal scales?

The first model in the literature



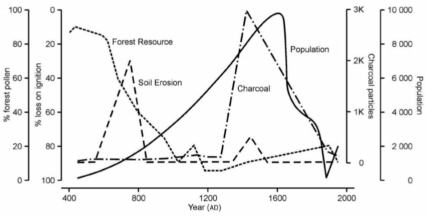
Archaeological record



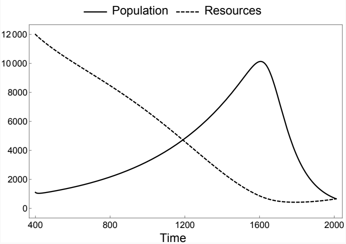
Brander and Taylor (1998) results

Economic model gives a poor fit.

Easter Island improvement



Archaeological record



Roman et al. (2017) results

Ecological model with same parametrization as economic model.

Easter Island model

Interpretation

- x is the population
- y is the resources, e.g., trees, fish
- z is the wealth e.g. food stocks, housing, tools

Equations

$$\dot{x} = \left(b - de^{-z/(\rho x)}\right) x$$
$$\dot{y} = ry\left(1 - \frac{y}{K}\right) - \boldsymbol{\alpha} xy$$
$$\dot{z} = \boldsymbol{\alpha} xy - sx\left(1 - e^{-z/(\rho x)}\right) - cz$$

Roman, S., Bullock, S., & Brede, M. (2017). Coupled societies are more robust against collapse: A hypothetical look at Easter Island. Ecological Economics, 132, 264-278.

Modelling criteria

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- Robustness
- Diversity / flexibility
- Reproducible, ease of communication

Maya Civilisation model

The dynamical model we propose is given by

$$\begin{aligned}
\dot{x}_s &= [(1-\tau)+\tau p_s]\beta n x - \beta n^{-\delta} x_s + \sigma[(1-\theta(n))x_b - \theta(n)x_s] \\
\dot{x}_i &= \tau p_i \beta n x - \beta n^{-\delta} x_i \\
\dot{x}_b &= -\beta n^{-\delta} x_b - \sigma[(1-\theta(n))x_b - \theta(n)x_s] \\
\dot{y} &= w_t r y(1 - y/(w_t K)) - s d n x \\
\dot{z} &= b x_b - m z
\end{aligned}$$

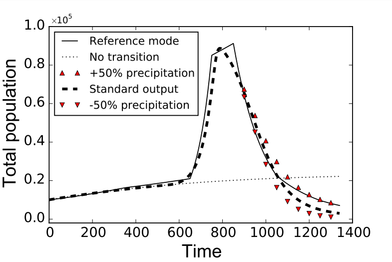
where x_s, x_i, x_b are specialisations, y resources, z infrastructure, and x, n, and $\theta(n)$ are given by:

$$x = x_s + x_i + x_b \qquad n = w_t \frac{x_s + \alpha x_i}{x_s + x_i + x_b}(1 - e^{-y/(w_t c K)})$$

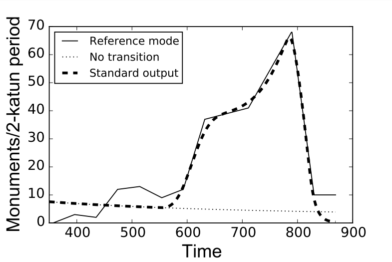
$$\theta(n) = \frac{1}{1 + e^{-2k(n-n_b)}}$$

Roman, S., Palmer, E., & Brede, M. (2018). The dynamics of human–environment interactions in the collapse of the Classic Maya. Ecological Economics, 146, 312-324.

Maya civilisation results



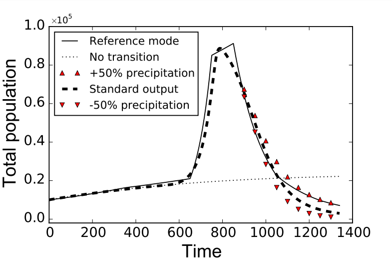
Population fit



Monuments fit

Lowland Maya results (Roman et al., 2018)

Maya civilisation results



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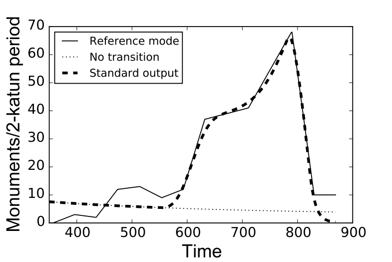


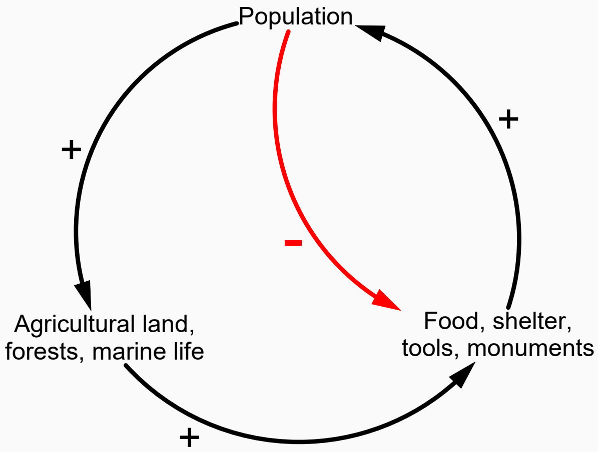
Monuments fit

Lowland Maya results (Roman et al., 2018)

Joseph Tainter, world leading expert on collapse:
We need more model building of this calibre.

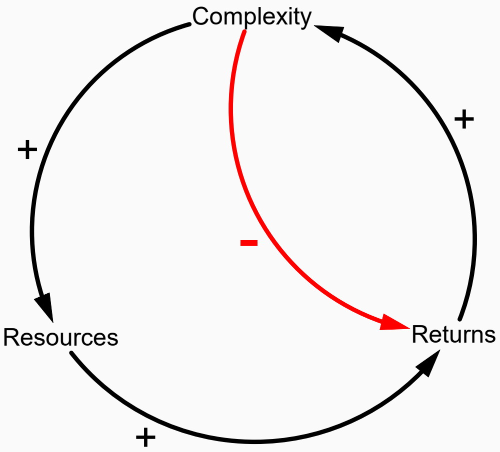
Tainter, Joseph. "Modelling the mysterious Maya." Nature Sustainability 1.2 (2018): 79-80.

The feedback mechanisms



Common feedback mechanism

General mechanism



Diminishing returns to investment in complexity

Another instance: The Roman Empire

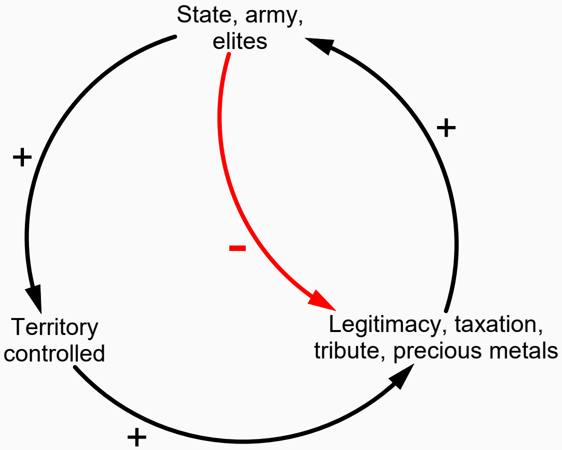
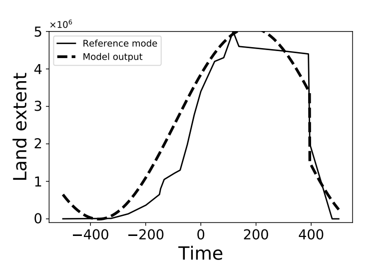
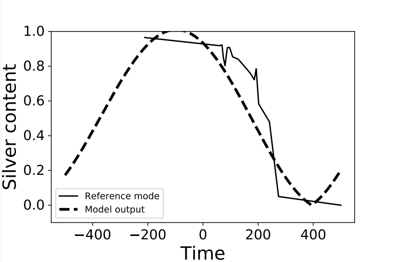


Diagram for the Roman Empire

Fitting the historical record



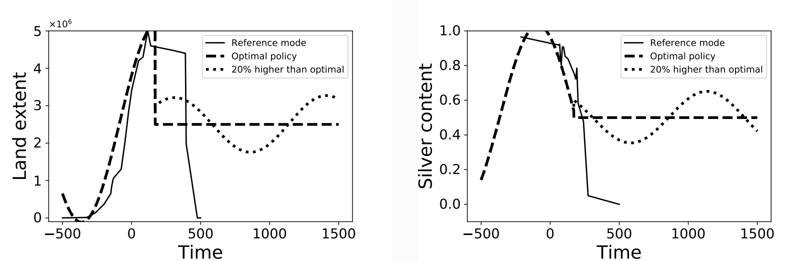
Territorial evolution



Coin debasement

Results from Roman and Palmer (2019).

Saving the empire



Cutting army, territory and fixing coin purity.

Separation of time scales

Dynamics	Time scale (years)
Biological evolution, tool making, climate effects (e.g., ice ages)	100,000

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Individual plans, fiscal reporting, celebrations	1

Simplest instance of feedback mechanisms

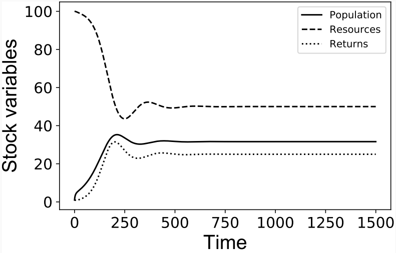
$$\dot{x} = b\frac{z}{x} - dx$$

$$\dot{y} = ry\left(1 - \frac{y}{K}\right) - \boldsymbol{\alpha} x^2 y$$

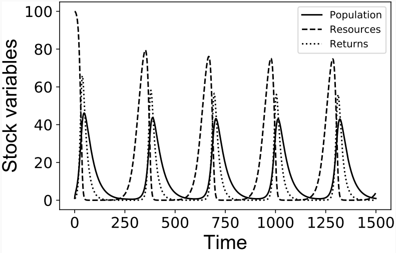
$$\dot{z} = \boldsymbol{\alpha} x^2 y - cz$$

Model for population, resources and returns.

Model dynamics



Stable fixed point



Limit cycle

Critical parameter value given by:

$$\alpha_c = \frac{2cd + (c+2d)^2}{4Kb}\left(1 + \sqrt{1 + \frac{8rcd(c+2d)}{[2cd + (c+2d)^2]^2}}\right)$$

Extractive network structure

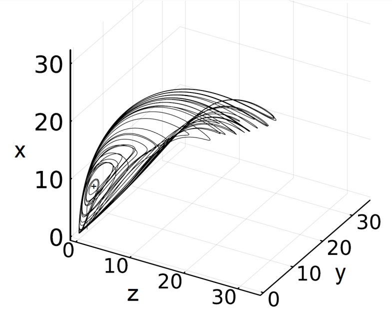
$$\dot{x}_i = b\frac{z_i}{x_i} - dx_i$$

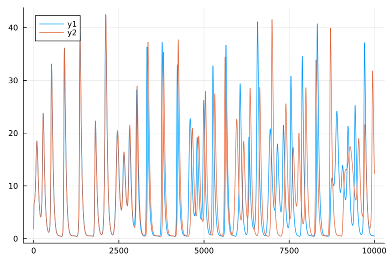
$$\dot{y}_i = ry_i\left(1 - \frac{y_i}{K}\right) - \alpha_i x_i y_i \sum_{j=1}^{N} x_j A_{ij}$$

$$\dot{z}_i = \alpha_i x_i y_i \sum_{j=1}^{N} x_j A_{ij} - cz_i$$

Interaction between regions is given by adjacency matrix A.

Chaos and synchronization





$$A = \begin{bmatrix} 1+\delta & 1 & 1 \\ 1 & 1+\delta & 1 \\ 1 & 1 & 1+\delta \end{bmatrix}$$

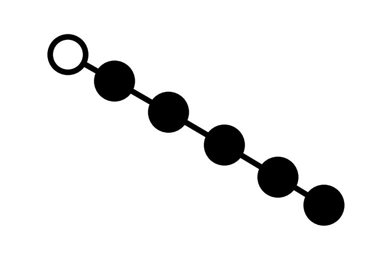
Dynamics is chaotic and synchronized on a 3-dimensional manifold. Lyapunov exponent $\simeq 3.6 \times 10^{-3}$ (close to upper limit). Inverse is $\simeq 280$ years, compatible with lifespan of empires.

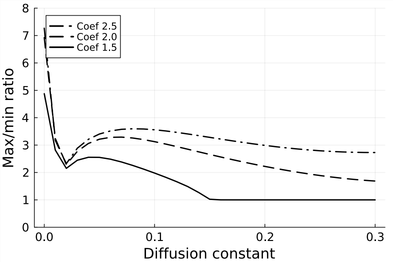
Diffusive network structure

$$\dot{x}_i = b\frac{z_i}{x_i} - dx_i - \sigma \sum_{j=1}^{N} x_j B_{ij}$$
$$\dot{y}_i = ry_i\left(1 - \frac{y_i}{K}\right) - \alpha_i x_i^2 y_i$$
$$\dot{z}_i = \alpha_i x_i^2 y_i - cz_i$$

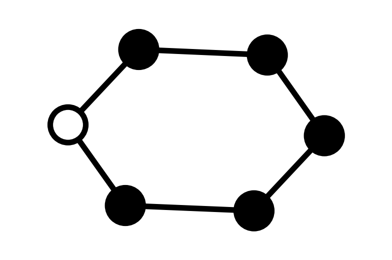
Where σ is the diffusion constant and B is the network Laplacian.

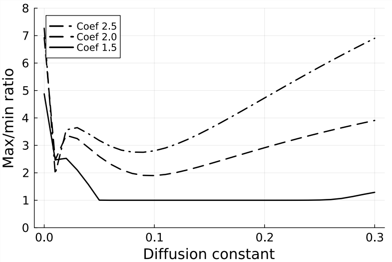
Inducing sustainability I



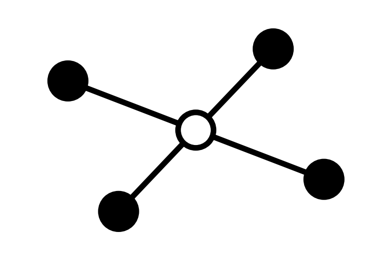


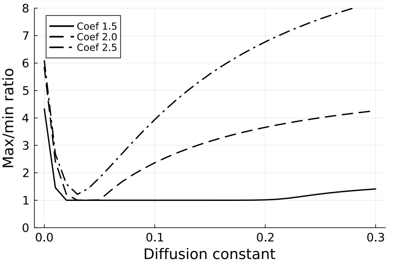
Inducing sustainability II



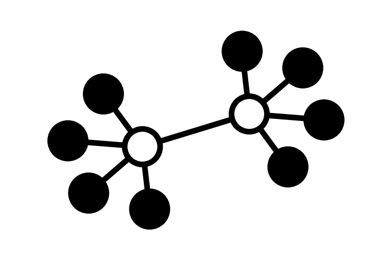


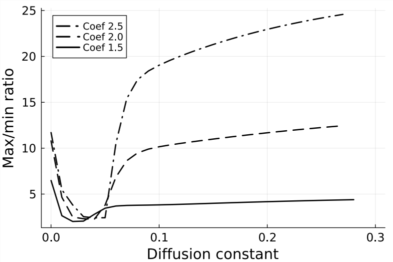
Inducing sustainability III





Inducing sustainability IV





References

Dynamic and game theoretic modelling of societal growth, structure and collapse

Roman, Sabin (2018) Dynamic and game theoretic modelling of societal growth, structure and collapse. *University of Southampton, Doctoral Thesis*, 136pp.

Record type: **Thesis (Doctoral)**

University of Southampton

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Abstract

The dynamics and structure of societies have long been a puzzle to archaeologists, historians and social scientists in general. In particular, increases in social inequality and the possibility of societal collapse are two deeply distressing prospects for any society. In this three paper thesis we provide two contributions to the literature of

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RESEARCH ARTICLE

Global history, the emergence of chaos and inducing sustainability in networks of socio-ecological systems

Sabin Roman, Francesco Bertolotti

Published: November 16, 2023 • https://doi.org/10.1371/journal.pone.0293391

Article | Authors | Metrics | Comments | Media Coverage | Peer Review

Abstract
Introduction
Background
Model specification

Abstract

In this study, we propose a simplified model of a socio-environmental system that accounts for population, resources, and wealth, with a quadratic population contribution in the resource extraction term. Given its structure, an analytical treatment of attractors and bifurcations is possible. In particular, a Hopf bifurcation from a stable fixed point to a limit cycle emerges

Long-term Feedback Mechanisms Underlying Societal Growth and Collapse

26 Pages • Posted: 25 Oct 2023 • Last revised: 27 Nov 2023

SSRN

Sabin Roman
Centre for the Study of Existential Risk

Date Written: October 2, 2023

Abstract

In this work we address some common methodological pitfalls in understanding societal collapse and propose a framework to remediate them. With this goal we reformulate and extend Tainter's theory of societal

2. Theories and Models: Understanding and Predicting Societal Collapse

Sabin Roman (author)

Chapter of: *The Era of Global Risk: An Introduction to Existential Risk Studies* (pp. 27–54)

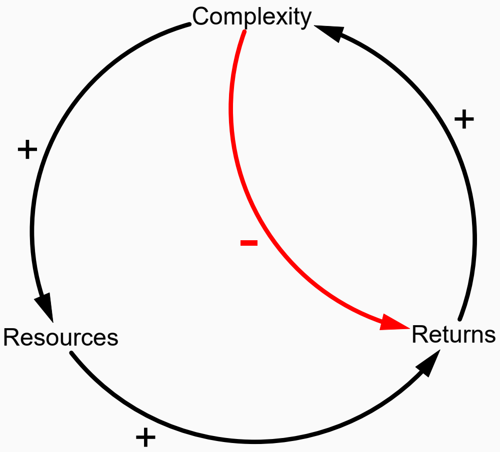
READ ONLINE | DOWNLOAD

Why do societies collapse? This chapter offers approaches to understanding which quantitative and qualitative models of societal dynamics can predict societal collapse and which exogenous and endogenous factors contribute to it.

The big picture papers.

Thank you!

Main lesson 1: Qualitative



Diminishing returns to investment in complexity

Main lesson 2: Quantitative

Building a modelling dictionary:

- $x(1-x)$ logistic growth
- xy mass action term
- $b - de^{-z/(\rho x)}$ effect of wealth on birth rates
- $w_t sd(x_s + \alpha x_i)\exp\left(\frac{-y}{w_t cK}\right)$ agricultural production
- $\sigma[(1-\theta(n))x_b - \theta(n)x_s]$ changing between specializations
- $\frac{z_1}{p_1 z_2} - 1$ effect of debasement on army and land

Main lesson 3: Quintessential

Inequality, migration, natality, agricultural practices, the military doctrine, religion, trade, bureaucracy, natural disasters, resource depletion, political incentives, biological predispositions, economic policy, relations with neighbours, ruler's character ...

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For N concepts we have $N!$ permutations of their importance (aka theories). $N = 14$ we get 87 billion possible theories. Which one is "right"?

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Time scale separation helps.