Sustainable and Unsustainable Growth: Land Erosivity & Long-Run Development

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Introduction

Long-run development

- UGT describes and endogenously reproduces distinctive phases in the process of growth
  - Malthusian Regime
  - Transition Phase
  - Modern Growth Regime
- Framework allows to analyze how various factors map into historic development, transition dates and modern prosperity
- Theory captures the important features of the Malthusian economy: fixed land and diminishing productivity of labor
- However, the theory does not capture important feature of the agricultural world: soil erosion

Soil and Society

- Soil quality is a dynamic variable
- Soils can erode or be replenished naturally and due to human activity
- Important feature of the process of growth:
    - Development of agriculture
    - Growing population
    - Erosion of soil
    - Potential Environmental Catastrophe
- In the most dramatic cases societal collapse can occur:
    - Maya
    - Sumer city-states
    - Easter Island
    - Khmer Empire

This paper

- Extends UGT to account for endogenous dynamics of soil quality
- Studies how endogeneity of soil quality and fundamentals of its dynamics affect:
    - Population and growth in the Malthusian regime
    - Timing of the transition and modern day development
- Takes theoretical predictions to data at a country, ethnicity and cell levels

Theory

Theoretical Model

- Simplified case of UGT in a Malthusian regime
- No investment in human capital
- Positive association between income and fertility
- **Land quality** is dynamic and endogenous
- Model studies development implications of different land quality dynamics characteristics:
    - Erosivity
    - Natural reblinishability

Production

- Total agricultural output of the society in period t is

$$Y_t = (B_t A_t X)^\alpha L_t^{1-\alpha}$$

  - X – fixed amount of land
  - A_t – land quality in t
  - B_t – level of technology in t
  - L_t – population in t

- Total output is split equally between the members of society, so that the percapita income is

$$y_t = Y_t / L_t = (B_t A_t X / L_t)^\alpha$$

Preference and Constraints

- Preference of a representative member of the society are

$$U(c_t, n_t) = \gamma \log n_t + (1-\gamma) \log c_t$$

- Individual maximizes utility by choosing:
    - c_t – consumption
    - n_t – number of children
- Subject to the budget constraint

$$c_t + \tau n_t \leq y_t$$

- We assume that there are no investment in human capital at this stage and cost of child-rearing is simply τ units of income

Individual Choice and Human Population Dynamics

- Individual optimally chooses consumption and fertility:
  - $c_t = (1-\gamma)y_t = (1-\gamma)(B_tA_tX/L_t)^\alpha$
  - $n_t = \gamma/\tau y_t = \gamma/\tau(B_tA_tX/L_t)^\alpha$
- Human population evolves as follows

$$\begin{aligned} L_{t+1} &= n_t L_t \\ &= \gamma/\tau(B_tA_tX)^\alpha L_t^{1-\alpha} \\ &= \phi(L_t, A_t, B_t) \end{aligned}$$

- For convince assume $\gamma/\tau = 1$ and $X = 1$

Land Quality Dynamics

- Land quality dynamics reflect several regularities:
  - Land can naturally replenish its quality up to a certain level
  - Land quality is diminished by a human activity
  - The speed of quality replenishment and erosion differs spatially
- A simple dynamical equation is chosen to reflect all these

$$
\begin{aligned}
A_{t+1} &= A_t + \rho(\bar{A} - A_t) - \mu L_t \\
&= \psi(L_t, A_t; \rho, \mu)
\end{aligned}
$$

  - Without humans land quality tends to $\bar{A} > 0$ – saturation level
  - If the quality is below that it replenishes with a speed $\rho \in (0; 1)$
  - Humans deduct from land quality at a $\mu > 0$ rate
  - The more humans there are, the greater the erosion

Dynamical System

- The joint evolution of human population and land quality is given by a two-dimensional dynamical system

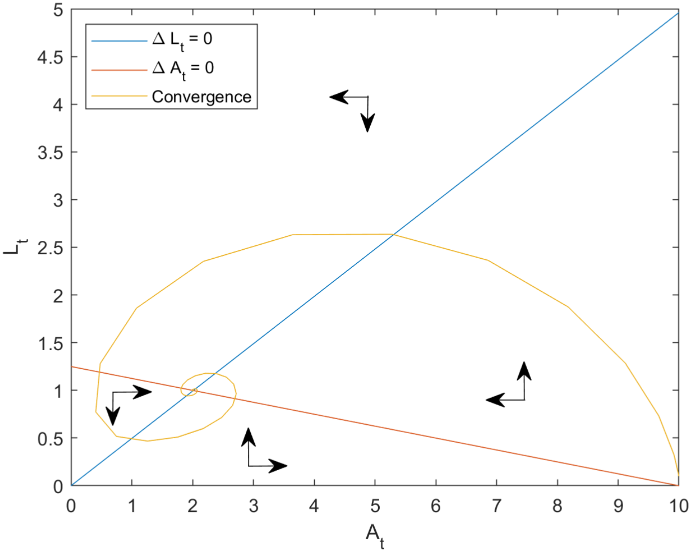
$$\begin{cases} L_{t+1} = (B_t A_t)^{\alpha} L_t^{1-\alpha} \\ \\ A_{t+1} = A_t + \rho(\bar{A} - A_t) - \mu L_t \end{cases}$$

- For now assume no endogenous growth of technology

$$B_t = B \quad \forall t$$

- The dynamics and the steady state of the system are affected by:
    - Replenishment rate – ρ
    - Erosion rate – μ
    - Technology level – B

Phase Diagram



Steady State

- The system is characterized by two distinct steady states:
  - No humans steady state

$$\begin{cases} L = 0 \\ A = \bar{A} \end{cases}$$

  - Non-trivial steady state

$$\begin{cases} L^* = \bar{A}\left(\mu/\rho + 1/B\right)^{-1} \\ \\ A^* = \bar{A}\left(\mu/\rho B + 1\right)^{-1} \end{cases}$$

Steady State Predictions

- Three predictions are important:
    - **Prediction 1:** Population in the steady state is positively related to the replenishment rate:

$$\partial L^* / \partial \rho > 0$$

    - **Prediction 2:** Population in the steady state is negatively related to the erosion rate:

$$\partial L^* / \partial \mu < 0$$

    - **Prediction 3:** Population in the steady state is positively related to the technology level:

$$\partial L^* / \partial B > 0$$

Stability Analysis

- The analysis of the non-trivial steady state stability reviles:
  - (L^*, A^*) steady state is not always stable
  - There are parameter combinations under witch the steady state is unstable, namely:

$$\mu\alpha B + (1-\alpha)(1-\rho) > 1 \tag{1}$$

- In particular, the steady state is unstable if:
  - Erosivity level μ is too **large**
  - Replenishment rate ρ is too **low**
  - Technology level B is too **large**

Introducing Endogenous Growth

- Consider the same model with a possibility of an endogenous technological growth
- Following UGT, assume that greater population density speeds up the technological growth

$$\Delta B_{t+1}/B_t = g(L_t) \quad \text{and} \quad dg(L_t)/dL_t > 0$$

- Following the spirit of UGT, assume that once technology reaches a certain level $\hat{B}$, individual start to invest in human quality and demographic transition takes lace

Dynamic with Endogenous Growth

- There still exists positive association between population and technology (Prediction 3: $\partial L^*/\partial B > 0$)
- Positive loop between L_t and B_t assures endogenous growth to a certain point
- In light of this loop and Predictions 1 and 2 growth is faster:
  - Under high replenishment rate ρ
  - Low erosivity rate μ

Simulation

Unsustainable Growth

- As apparent from the dynamics, as technology grows:
    - Population increases
    - Land quality diminishes
- When B_t is high enough, the system reaches a tipping point where the steady state (L^*, A^*) is unstable
- Namely, from the inequality (1), the system is unstable if:

$$B_t > \bar{B}(\rho, \mu) = \frac{\alpha + (1 - \alpha)\rho}{\mu\alpha}$$

- Once technology surpasses the critical level $\bar{B}$, population can not be sustained on a given land – collapse follows Simulation
- If system reaches a level of technology needed for a demographic transition before that, population stabilizes and collapse is avoided

Dynamics Predictions

- Technological growth is **faster** under **higher** replenishment rate ρ and **lower** erosivity μ
- As a result escape from the Malthusian regime occurs earlier under **higher** replenishment rate ρ and **lower** erosivity μ
- In light of the great divergence argument, this leads to difference in income per capita in a modern regime
- Maximal potentially attainable level of technology , $\bar{B}$, is:
  - **Positively** affected by the replenishment rate: $d\bar{B}/d\rho > 0$
  - **Negatively** affected by the erosion rate: $d\bar{B}/d\mu < 0$
- If replenishment rate ρ is too low or erosivity μ is too high, the collapse may occur earlier than demographic transition:

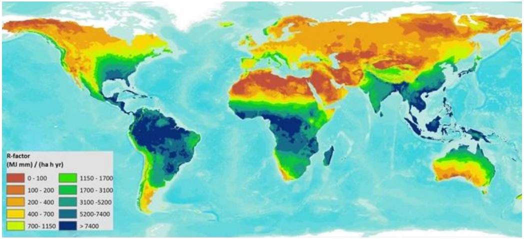
$$\frac{\alpha + (1-\alpha)\rho}{\mu\alpha} < \hat{B}$$

Empirics

Data

- Global Erosivity Map
- 30 arc-seconds
- R-factors
- Based on 3625 precipitation stations
- Based on 60,000 years of rainfall records
- Within the model this can be interpreted as:
    - Lower replenishment rate ρ
    - Higher erosion rate μ

Map



R-factor
(MJ mm) / (ha h yr)
0 - 100
100 - 200
200 - 400
400 - 700
700- 1150
1150 - 1700
1700 - 3100
3100 -5200
5200-7400
> 7400

Ethnic Group Development

	Jurisdictional Hierarchy					Community Size				
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Log [Erosivity]	-0.637***	-0.602***	-0.670***	-0.650***	-0.409***	-1.438***	-1.315***	-1.487***	-1.134***	-1.036***
	(0.0659)	(0.0762)	(0.0748)	(0.0935)	(0.129)	(0.145)	(0.156)	(0.159)	(0.237)	(0.324)
Neolithic Transition Timing		0.150***	0.125***	0.0302	0.0626		0.215***	0.166**	0.0262	0.138
		(0.0364)	(0.0373)	(0.0503)	(0.0535)		(0.0717)	(0.0731)	(0.0885)	(0.0974)
Crop Yield (pre-1500CE) (mean)			0.120***	0.248***	0.230***			0.271***	0.352***	0.320***
			(0.0310)	(0.0338)	(0.0363)			(0.0770)	(0.0835)	(0.0846)
Region FE	No	No	No	Yes	Yes	No	No	No	Yes	Yes
Geographic controls	No	No	No	No	Yes	No	No	No	No	Yes
Observations	1232	944	944	944	943	636	505	505	505	505
R^2	0.203	0.248	0.257	0.356	0.380	0.459	0.499	0.509	0.541	0.578

Note: Outcome variables are taken from Murdock's Ethnographic Atlas (questions 33 and 31 respectively)

Ethnic Group Population Density

	Log Population Density					
	(1)	(2)	(3)	(4)	(5)	(6)
	1 AD	300 AD	600 AD	900 AD	1200 AD	1500 AD
Log [Erosivity]	-0.118***	-0.120***	-0.105***	-0.0989**	-0.106**	-0.0867*
	(0.0313)	(0.0337)	(0.0367)	(0.0419)	(0.0470)	(0.0505)
Neolithic Transition Timing	0.253***	0.253***	0.237***	0.249***	0.262***	0.267***
	(0.0336)	(0.0339)	(0.0340)	(0.0369)	(0.0392)	(0.0399)
Crop Yield (pre-1500CE) (mean)	0.0589***	0.0585***	0.0553***	0.0567**	0.0894***	0.101***
	(0.0185)	(0.0197)	(0.0210)	(0.0230)	(0.0252)	(0.0271)
Region FE	Yes	Yes	Yes	Yes	Yes	Yes
Geographic controls	Yes	Yes	Yes	Yes	Yes	Yes
Observations	1046	1046	1046	1046	1046	1046
R^2	0.570	0.558	0.530	0.519	0.520	0.512

Note: Population Density Data from HYDE database

Dynamic Effect of Erosivity on Population Density: Ethnic Groups

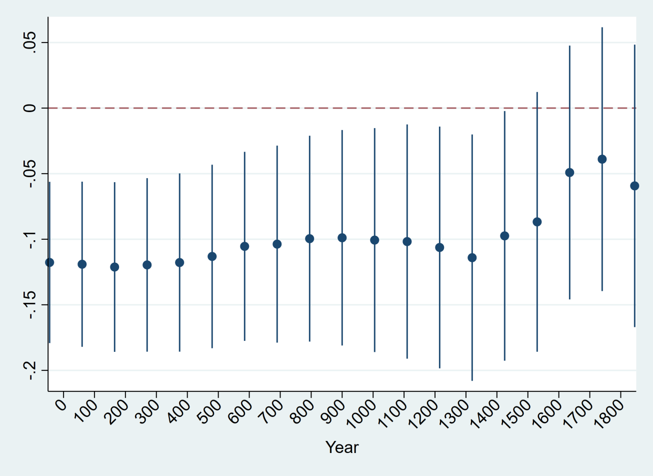


Figure 1: Effect of Erosivity on Population Density

State Complexity (Borcan, Olsson and Putterman; 2018)

	State Complexity Index									
	Overall Avarage					5-Century Windows				
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Log [Erosivity]	-2.629***	-1.984***	-3.180***	-3.611***	-2.137***	-5.055**	-5.379**	-5.083**	-6.811***	-2.704**
	(0.362)	(0.416)	(0.695)	(0.699)	(0.630)	(2.464)	(2.218)	(1.940)	(1.779)	(1.061)
Continent FE	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Geographic controls	No	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Soil controls	No	No	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes
YST	No	No	No	No	Yes	Yes	Yes	Yes	Yes	Yes
Observations	137	137	129	126	122	122	122	122	122	122
R^2	0.241	0.433	0.553	0.580	0.643	0.596	0.532	0.464	0.530	0.465

Note: Columns (6)-(10): 5-century windows, starting from 1500-2000

Country transition dates

	Log FDG transition date				Log Reher transition date			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Log [Erosivity]	0.00514***	0.00343***	0.00405***	0.00290**	0.00304**	0.00246***	0.00307***	0.00337***
	(0.00174)	(0.00112)	(0.00142)	(0.00131)	(0.00121)	(0.000693)	(0.000910)	(0.00101)
Neolithic transition	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Continent FE	No	Yes	Yes	Yes	No	Yes	Yes	Yes
Soil controls	No	No	Yes	Yes	No	No	Yes	Yes
Geographic controls	No	No	No	Yes	No	No	No	Yes
Observations	114	114	105	105	116	116	110	110
R^2	0.134	0.593	0.629	0.638	0.098	0.717	0.739	0.767

Note: Reher dates of transition from Reher (2004), FDG dates of transition from Fernandez-Villaverde, Delventhal & Guner (2019)

Diversity .

Cell-level analysis

	Cells 0.5x0.5				Cells 1x1				Cells 2x2			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
Log [Erosivity]	-0.181***	-0.155***	-0.152***	-0.149***	-0.189***	-0.188***	-0.194***	-0.182***	-0.217***	-0.217***	-0.241***	-0.230***
	(0.00357)	(0.0104)	(0.00633)	(0.0178)	(0.01000)	(0.0100)	(0.00981)	(0.0130)	(0.00987)	(0.00990)	(0.0111)	(0.0213)
Suitability	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Fixed Effects	No	Yes	Yes	Yes	No	Yes	Yes	Yes	No	Yes	Yes	Yes
Geographic controls	No	No	Yes	Yes	No	No	Yes	Yes	No	No	Yes	Yes
Bio controls	No	No	No	Yes	No	No	No	Yes	No	No	No	Yes
Observations	50790	50790	50790	50789	11657	11657	11657	11656	3224	3224	3224	3224
R^2	0.189	0.205	0.222	0.222	0.222	0.222	0.245	0.247	0.226	0.226	0.259	0.260

Note: Outcome variable: Log [1 + Nighttime Luminosity], based on DMSP Operational Linescan System data

Country GDP per capita (2000)

	Log GDP (2000) per capita							
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Log [Erosivity]	-0.332***	-0.408***	-0.425***	-0.330***	-0.387***	-0.481***	-0.452***	-0.372***
	(0.0646)	(0.0688)	(0.0933)	(0.106)	(0.103)	(0.108)	(0.107)	(0.106)
Continent FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Neolithic transition	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Geographic controls	No	No	Yes	Yes	Yes	Yes	Yes	Yes
Soil controls	No	No	No	Yes	Yes	Yes	Yes	Yes
Legal origins	No	No	No	No	Yes	Yes	Yes	Yes
Religion shares	No	No	No	No	No	Yes	Yes	Yes
Ethnic frac.	No	No	No	No	No	No	Yes	Yes
Tropical zones	No	No	No	No	No	No	No	Yes
Observations	139	134	134	130	130	129	129	129
R^2	0.600	0.630	0.637	0.654	0.711	0.757	0.766	0.777

Note: GDP per capita in 2000 is from Penn World Table, version 6.2; fractionalization from Alesina et al (2003); tropical zones is the share of the population living in Koppen-Geiger tropical zones; legal origin dummies and the shares of major world religions from the data set of La Porta et al. (1999).

Country: Controlling for diversity

	Log FDG transition date					Log Reher transition date				
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Log [Erosivity]	0.00514***	0.00343***	0.00405***	0.00294**	0.00309**	0.00304**	0.00246***	0.00307***	0.00337***	0.00374***
	(0.00174)	(0.00112)	(0.00142)	(0.00143)	(0.00147)	(0.00121)	(0.000693)	(0.000910)	(0.00101)	(0.00108)
Continent FE	No	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes
Soil controls	No	No	Yes	Yes	Yes	No	No	Yes	Yes	Yes
Geographic controls	No	No	No	Yes	Yes	No	No	No	Yes	Yes
Diversity	No	No	No	No	Yes	No	No	No	No	Yes
Observations	114	114	105	105	105	116	116	110	110	110
R^2	0.134	0.593	0.629	0.638	0.646	0.098	0.717	0.739	0.767	0.785

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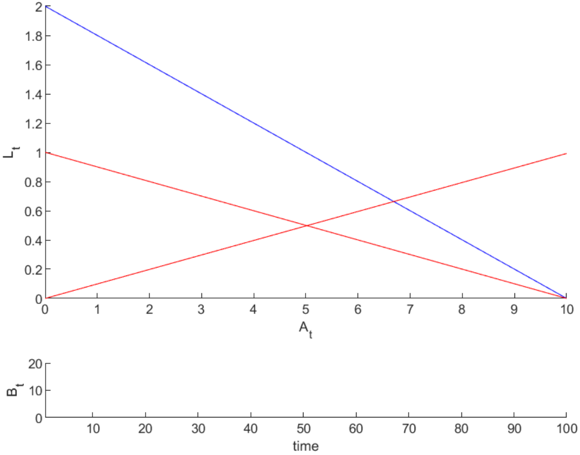
Dynamics with Endogeneous Growth: Simulation



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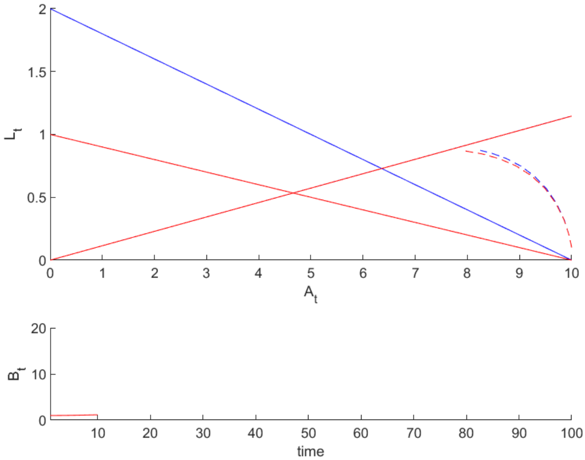

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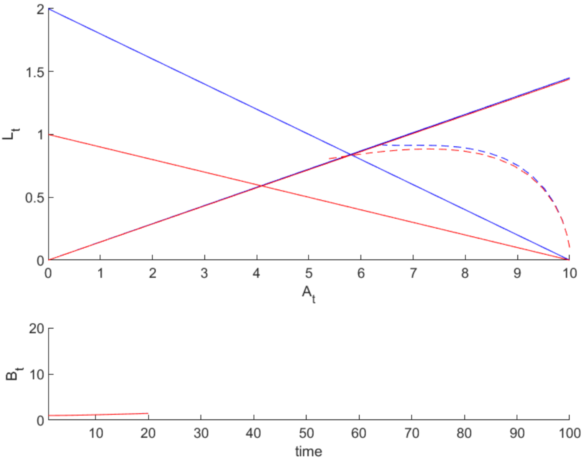

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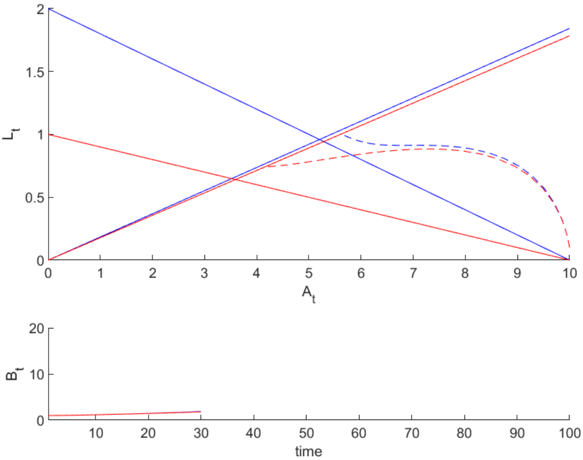

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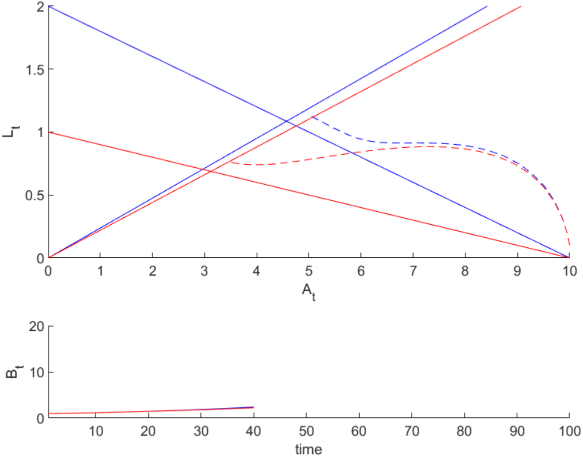

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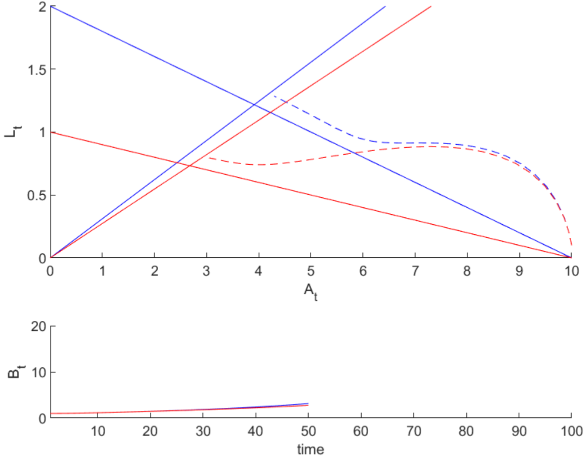

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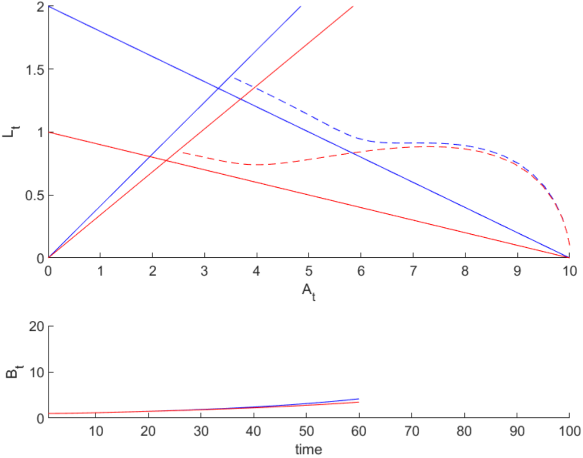

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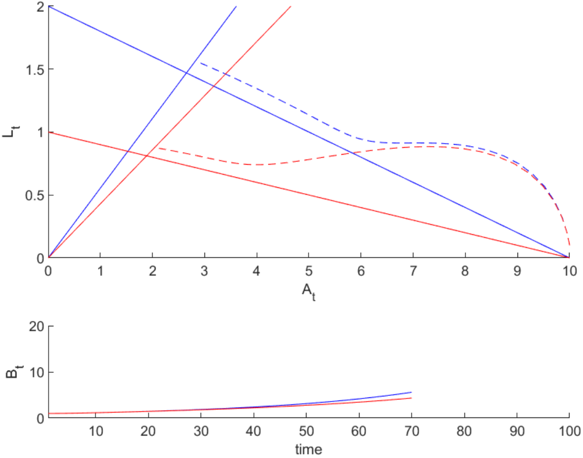

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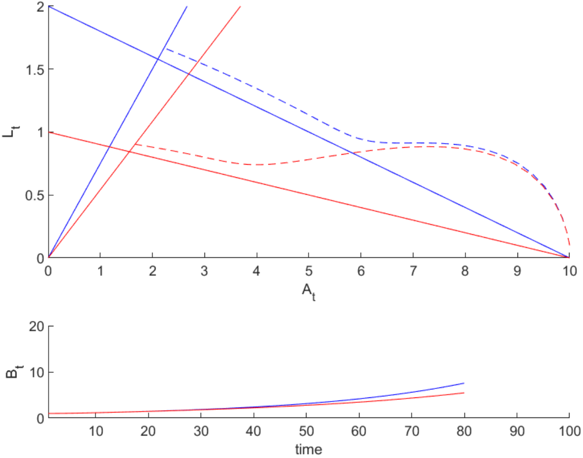

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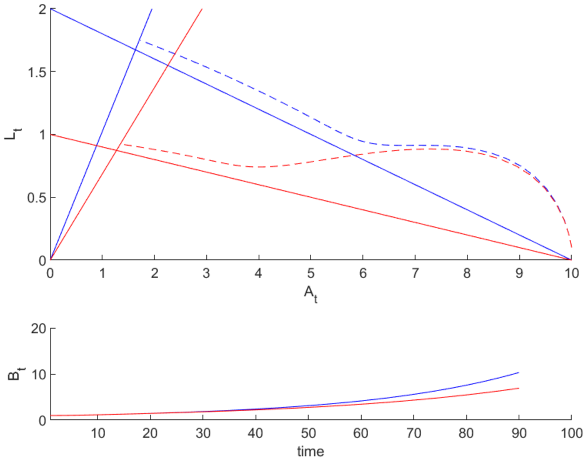

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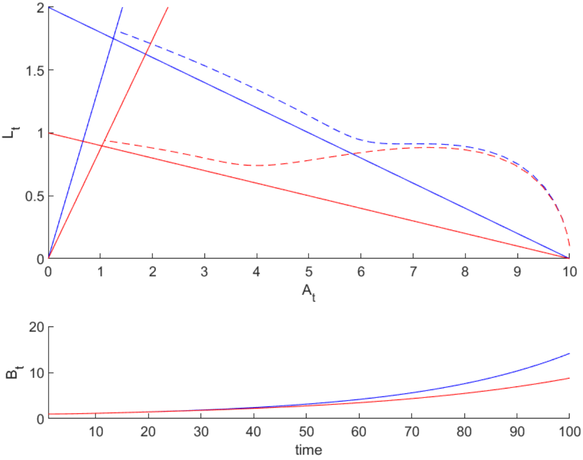

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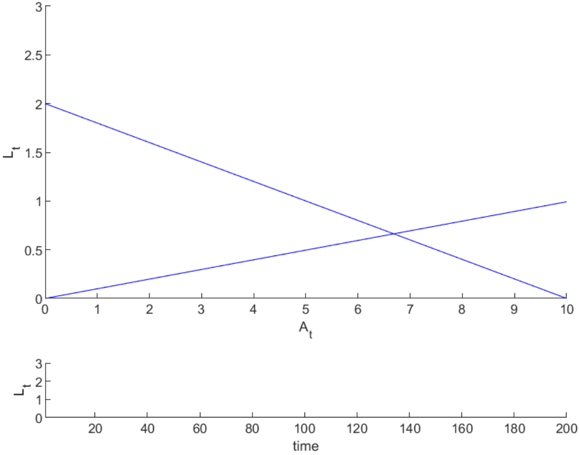
Unsastainable Growth: Simulation



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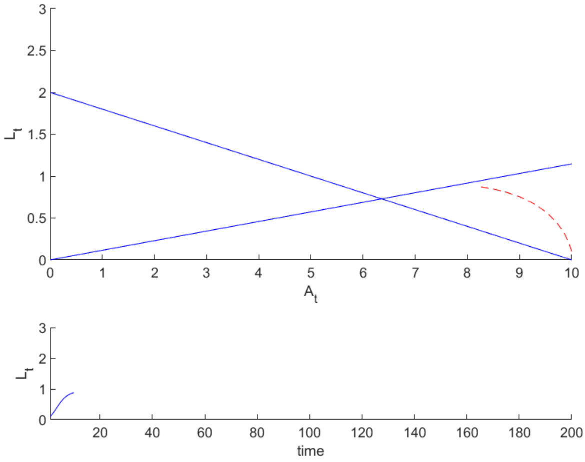

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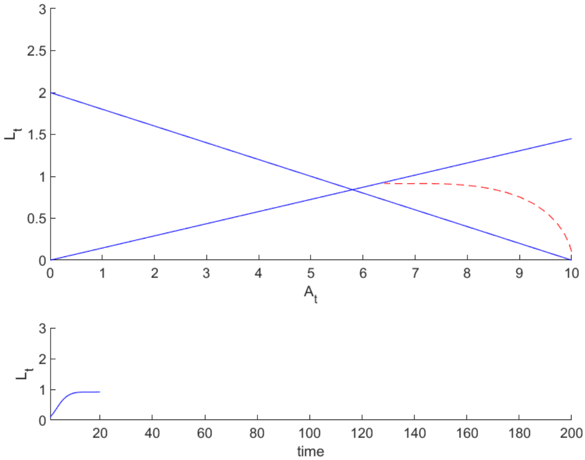

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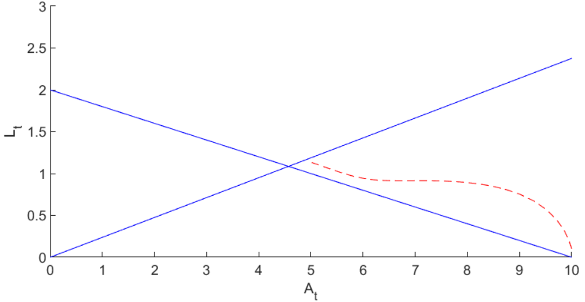

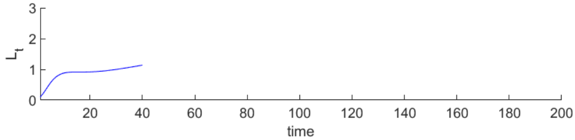

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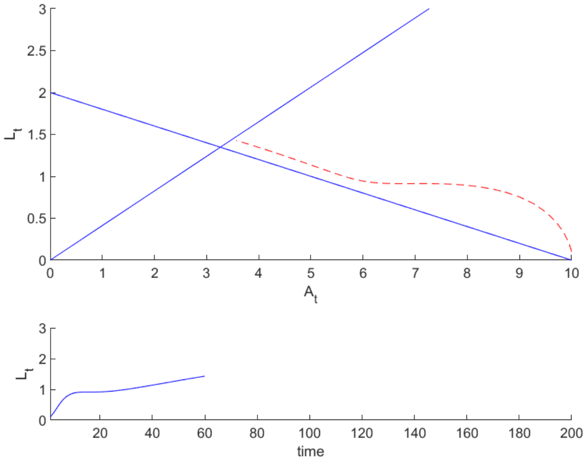

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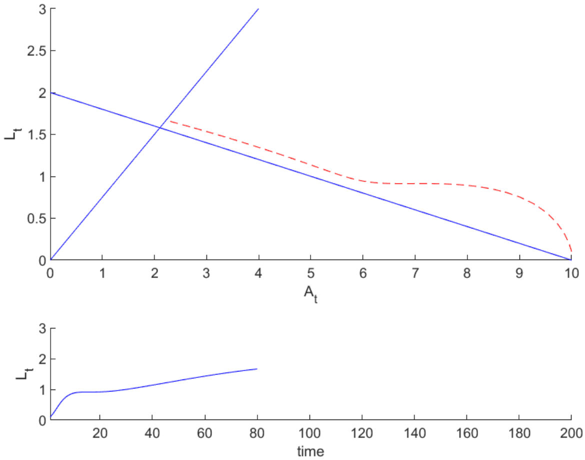

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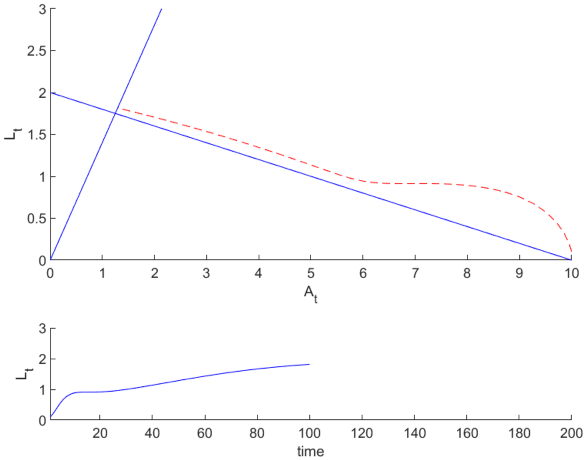

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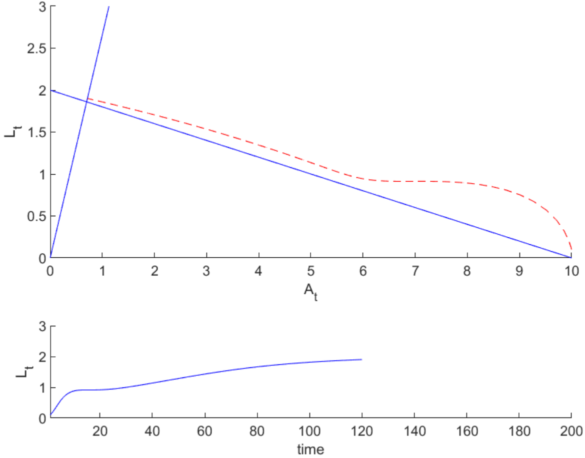
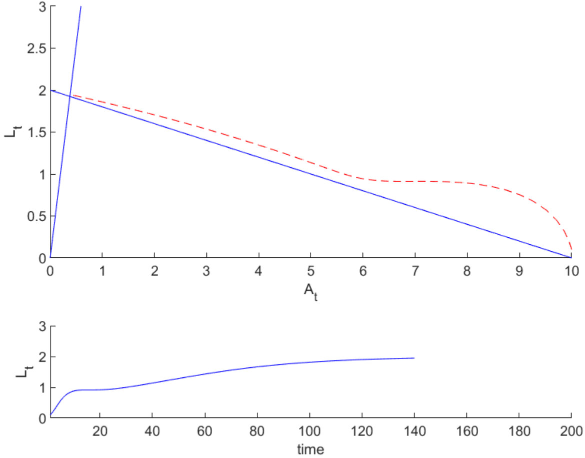
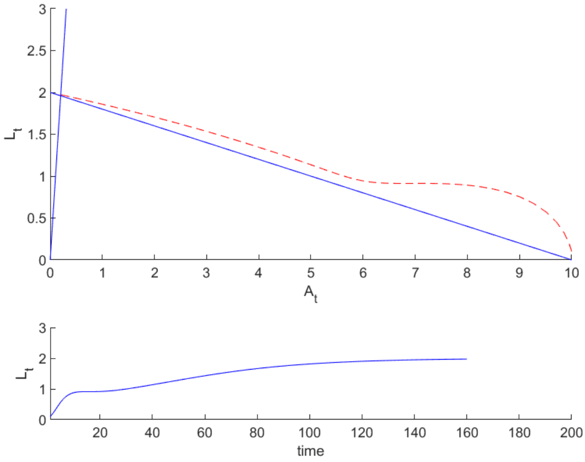


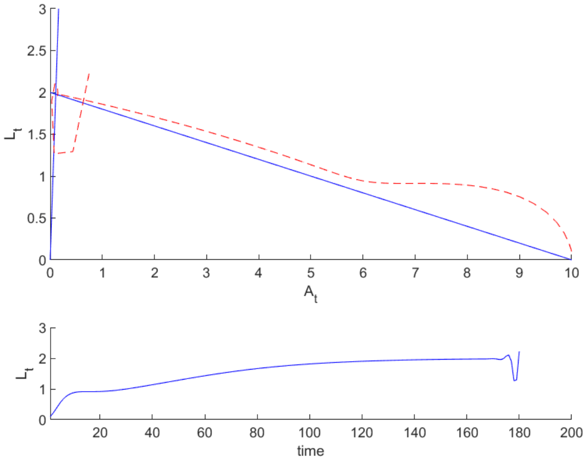
Unsastainable Growth: Simulation



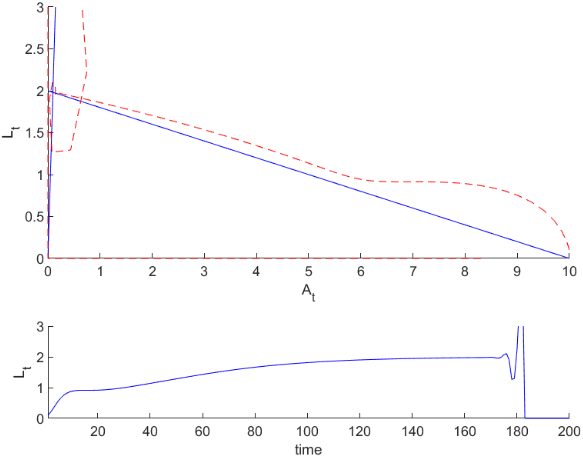
Unsastainable Growth: Simulation



Unsastainable Growth: Simulation



Unsastainable Growth: Simulation



Start Over Back