Limits to Growth in Uncertain Environments

Barnabé Ledoux,
David Lacoste
Laboratoire Gulliver - EPSCI
barnabe.ledoux@polytechnique.edu

Silvia Montagnani
iRisk - University of Lille
C3S - University of Frankfurt
silvia.montagnani.etu@univ-lille.fr

Background

Fluctuating environments impose a fundamental **trade-off between growth and survival**, affecting both ecological and economic systems. Neoclassical economic models often assume unlimited exponential growth, based on the premise of environmental stability and sustained technological progress. However, real-world growth processes unfold under conditions of inherent stochasticity and uncertainty. In biological systems, species employ diverse survival strategies, including **bet-hedging through phenotypic diversification, dormancy** (such as desert plants' seeds and fungal spores waiting out unfavorable seasons), and **adaptive sensing**, to buffer against environmental unpredictability. Financial systems and ecosystems alike can experience **tipping points** where **a seemingly minor perturbation triggers a catastrophic shift to a less favorable state**. For example, the Wall Street crash of 1929 or the 2008 credit crisis mirrors ecological regime shifts. Mechanisms that dampen small fluctuations (for instance, aggressive risk management that creates an illusion of stability) may paradoxically increase the risk of **a full-scale collapse** [1].

Motivations

By extending **Kelly's gambling model** [2], we draw on the analogy between **ecological survival strategies** and **investment strategies** in uncertain environments to:

Explore **insights from biological adaptation strategies** for sustainable socioeconomic transitions.

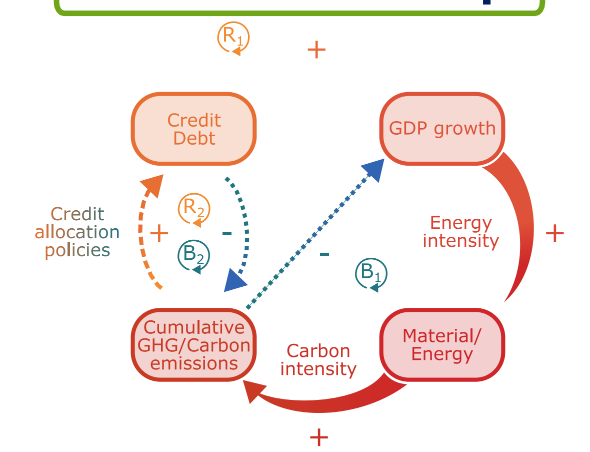
➡

Model debt-fueled growth as a stochastic process and the growth/risk trade-off.

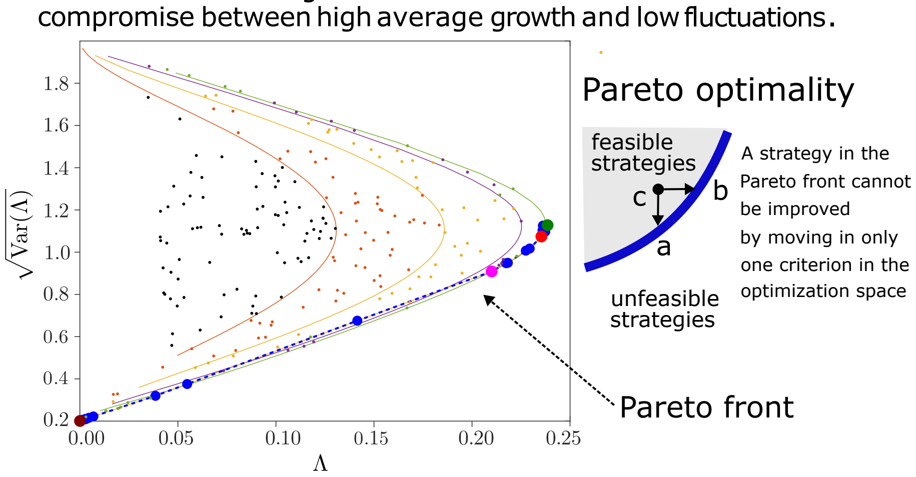
➡

Quantify the **risk of collapse** due to debt.

Credit Carbon Loop



Fundamental trade-off between growth and risk in uncertain environments [3]: strategies on the Pareto front achieve the best compromise between high average growth and low fluctuations.



Growth/Risk Trade-Off

Here, we consider **a simple model of stochastic phenotypic switching between two phenotypes**, where organisms (such as bacteria) grow in two randomly alternating environments. Each phenotype is better adapted to one of these environments. Analysing the trade-off between the average growth rate and its variance, we uncover a "no risk, no gain" principle encapsulated in a **Pareto front**. The shape of this front suggests that **a slight reduction in the maximum growth rate can significantly lower risky fluctuations.** Moreover, the interplay between growth rate and fluctuations is crucial in determining **extinction probability**, which **may increase with higher growth rates under certain conditions**.

Analogies

Biological system		Financial system
Environmental Uncertainty	⟷	Investment Risk
Phenotype Switching	⟷	Portfolio Diversification
Growth Rate	⟷	Capital Return
Survival probability	⟷	Bankruptcy Risk

Debt-Dependent Growth as a Financial Risk

Allowing leveraged bets dramatically increases potential growth and the risk of ruin. In simulations of the extended Kelly's model, **an agent who takes an initial loan to boost investment can achieve faster capital growth than an unleveraged Kelly gambler, but with a significant probability of bankruptcy.** The graph on the right illustrates a growth–survival trade-off: leveraging debt accelerates growth but significantly increases the likelihood of financial collapse. In other words, **maximum-growth strategies are not maximum-survival strategies in uncertain environments**.

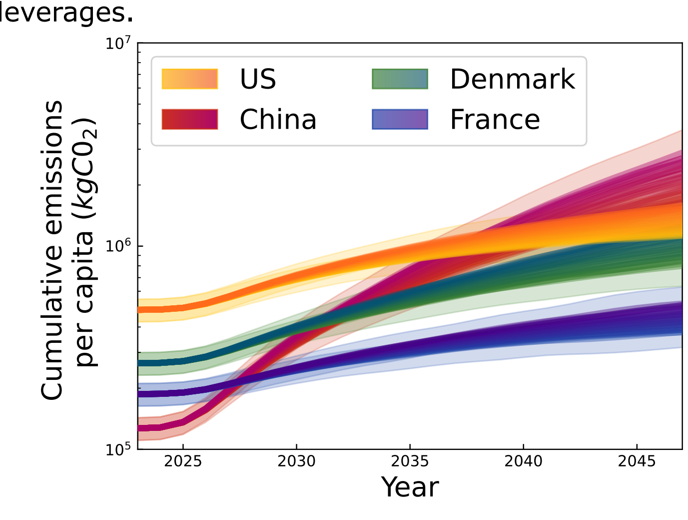
Capital Evolution with Borrowing

- C_τ be the capital at time τ,
- B_0 be the initial loan,
- ρ be the interest rate,
- t_p be the payback time τ,

Thus, for $\tau \geq t_p$:

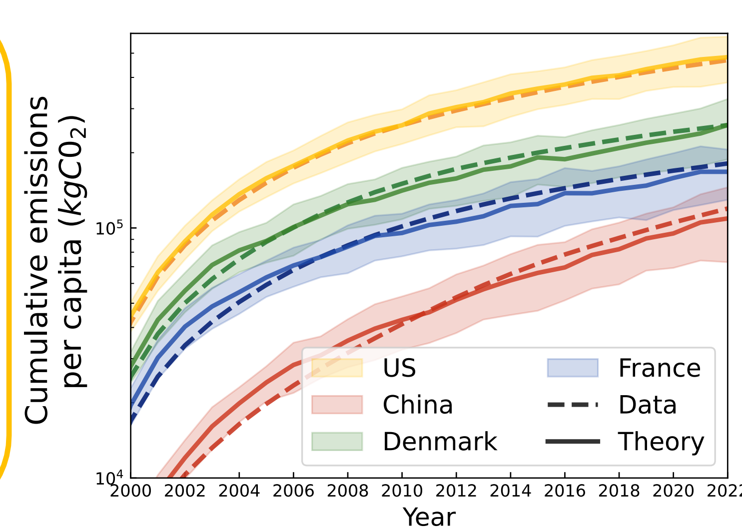
$$C_\tau = B_0 \left(\prod_{\tau' \leq t_p} \frac{b_{x,\tau'}}{r_{x,\tau'}} - \rho^{t_p} \right) \prod_{t_p \leq \tau' \leq \tau} \frac{b_{x,\tau'}}{r_{x,\tau'}}$$

Predicted emissions based on carbon intensity and consumption habits for different countries, with different leverages.



Conclusions & Implications

Debt-driven growth entails a fundamental **trade-off between capital accumulation and survival.** In this stochastic extension of the Kelly model with borrowing, the survival probability is **non-linear with payback time**: early repayment reduces risk at high interest rates, while delayed repayment enhances growth under low interest rates but with **greater volatility and increased bankruptcy risk**. The system shows hysteresis with path-dependent dynamics and **asymmetric recovery**. This mirrors biological systems, where, in some cases, sacrificing a small amount of growth can increase the probability of survival. This analogy underscores the pressing need to **<u>shift from maximising growth to maximising persistence</u> for long-term sustainability** [4]. Lastly, climate mitigation strategies focused only on efficiency or technology miss **a critical feedback loop, the financial mechanisms sustaining growth themselves drive cumulative emissions upward**.



This graph compares **the observed cumulative CO_2 emissions per capita** in the United States (1990–2020) with the **prediction of our debt-augmented growth model**, which extends the **Kaya identity**. GDP is not an exogenous path; it is a function of financial leverage. The model shows that even as **carbon intensity declines (I), emissions (ε) continue to rise** because **GDP growth is amplified by borrowing.** The close match between data and theory suggests that **<u>debt-fueled expansion structurally undermines decoupling and net-zero targets.</u>**

[1] May, R. M., Levin, S. A., & Sugihara, G. (2008). Ecology for bankers. Nature, 451(7181), 893-894.
[2] A. Despons, L. Peliti, and D. Lacoste, "Adaptive strategies in Kelly's horse races model," vol. 2022, no. 9, p. 093405.
[3] Dinis, L., Unterberger, J., & Lacoste, D. (2020). Phase transitions in optimal betting strategies. *Europhysics Letters*, *131*(6), 60005.
[4] Lenton, T. M., & Scheffer, M. (2024). Spread of the cycles: a feedback perspective on the Anthropocene. *Philosophical Transactions of the Royal Society.*