DISS. ETH NO. XX

Eco-evolutionary processes in ecological and economic systems

Confronting dynamical models and data

A thesis submitted to attain the degree of
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presented by

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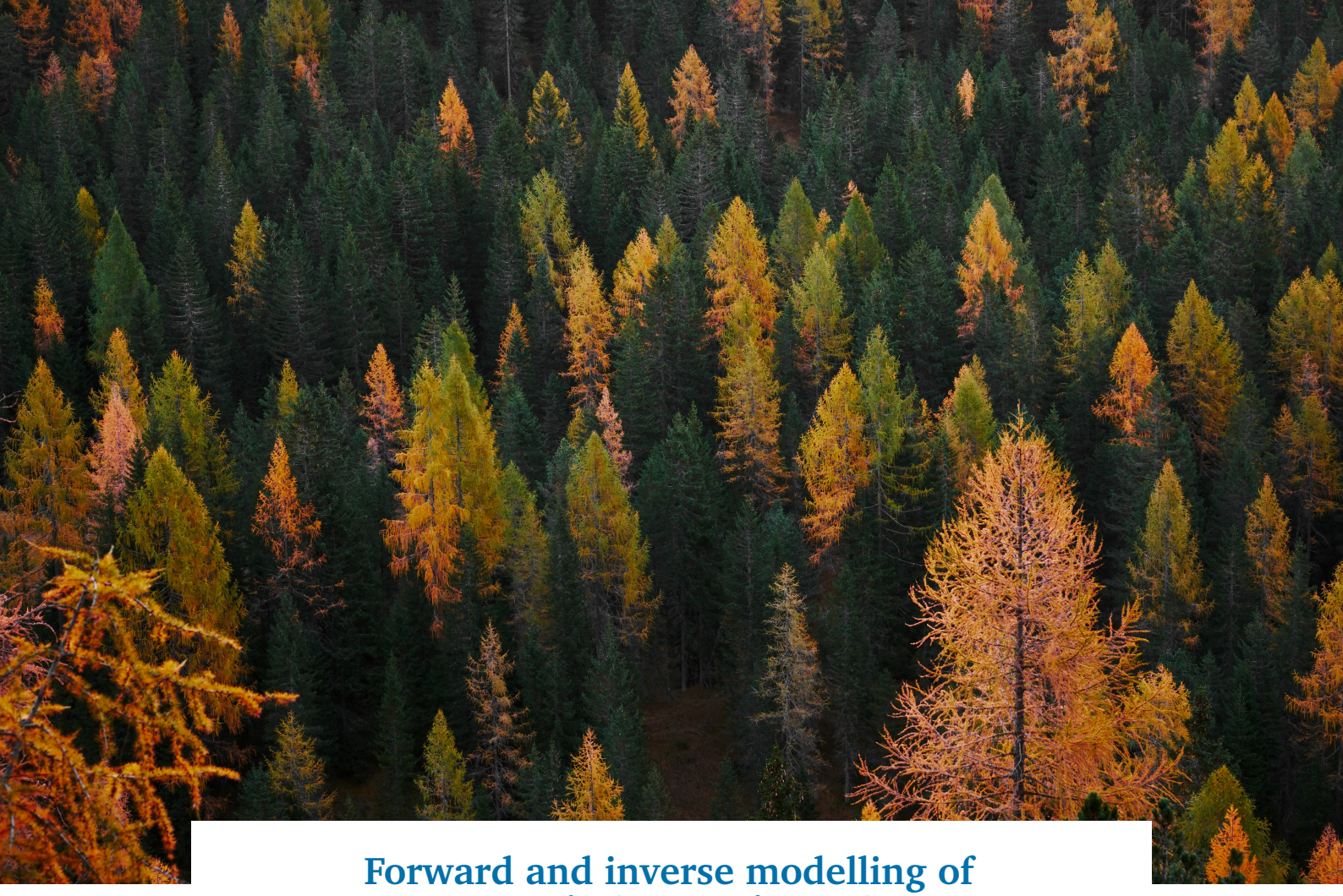
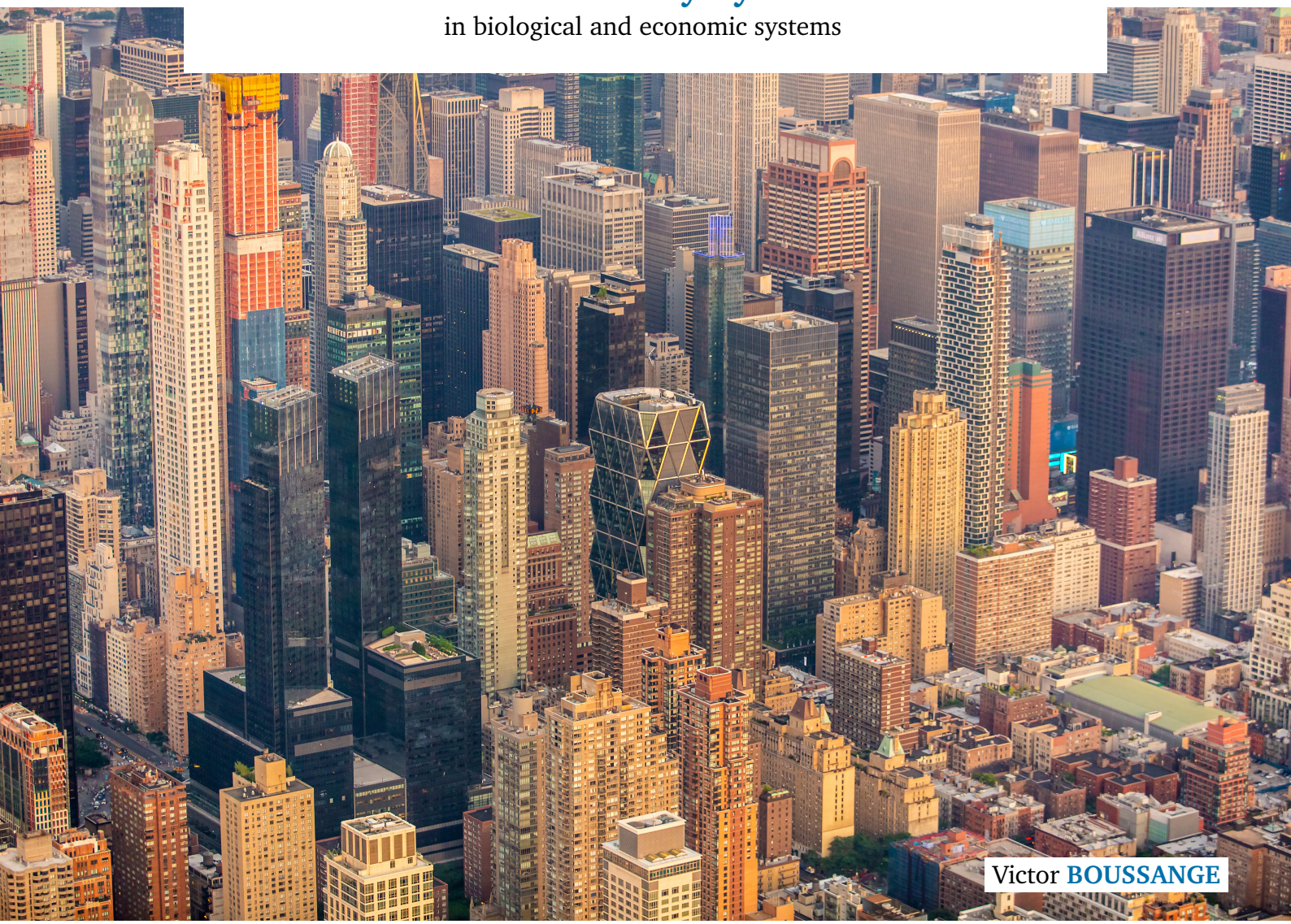
2022



Forward and inverse modelling of eco-evolutionary dynamics

in biological and economic systems



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Forward and inverse modelling of eco-evolutionary dynamics in biological and economic systems

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Summary

Ecological and economic systems are complex adaptive systems (CAS): they are systems that are composed of many entities with heterogeneous characteristics, which interact and experience selection processes. Those processes act at the entity level, but are key in determining the macroscopic behaviour at the system level, a feature that make those systems unique. For instance, the diversity of species within an ecosystem results from a hierarchy of processes acting at different scales of time and space, comprising the variations experienced by single organisms, their interactions, and selection pressure acting upon populations. Analogously, economic growth at the level of a country is greatly affected by its ensemble of economic actors, their interactions, and the selection pressure they experience. Despite the complexity of the processes driving their dynamics, regularities at the macroscopic level emerge in ecological and economic systems. This is the case of large-scale spatial patterns of biodiversity and differences in economic growth across countries, calling for a mechanistic understanding of the essential mechanisms that generate them.

Recently, a considerable interest has grown up around the interplay between ecological processes, the processes that regulate interactions between organisms, and evolutionary processes, the change of the characteristics of biological populations over time, to explain current biodiversity patterns. Analogous economic processes have been proposed to explain differences in economic growth across nations. Nonetheless, a quantitative investigation of their importance is missing. Determining how those patterns can emerge from eco-evolutionary processes is required to improve our current understanding. This project delivers new quantitative insights following a unique approach that combines dynamical eco-evolutionary models and empirical data.

Simulations of eco-evolutionary models and their integration with empirical data pose several methodological challenges that we adress in the first part of this project. Entities in CAS have distinct quantitative attributes that determine their fitness in a given environment. Accounting for the variety of these characteristics leads to models with a high dimensionality, associated to a large if not prohibitive computational cost preventing its simulation. In particular, partial differential equation (PDE) models, which can encode eco-evolutionary processes acting upon entities defined

by many characteristics, are cursed by their dimensionality. To this aim, we develop machine learning algorithms that break down the curse of dimensionality. Such algorithms rely on neural networks to approximate the solution to PDE models. An other difficulty consists in confronting eco-evolutionary models outputs to data, since those models cannot be manipulated with standard statistical techniques. We apply methods commonly employed in the training of neural networks, together with model selection techniques, to infer fundamental mechanisms that might have generated the patterns under investigation. Altogether, the methods permit efficient model simulations and their integration with empirical data, allowing to deliver quantitative answers to the motivated research questions.

In the second part, we make use of the above techniques to study eco-evolutionary models and to test them against data, to explore hypotheses on the fundamental mechanisms that drive patterns of biodiversity and economic growth. From one hand, we explore how eco-evolutionary processes, in combination with complex landscape topologies, can explain patterns of species diversity. To this aim, we develop and analyse an eco-evolutionary model on spatial graphs, to understand how the combination of eco-evolutionary processes and spatial structure might have shaped biodiversity patterns that are found in complex landscapes such as mountain regions.

On the other hand, we investigate how eco-evolutionary processes can provide new insights in the understanding of economic dynamics. We proceed by developing a simple eco-evolutionary model which explanatory power we test against long time series that proxy the dynamics of the size of economic sectors.

Overall, this project delivers quantitative insights on how the interplay between ecological and evolutionary processes is shaping the features of the world that surrounds us.

Résumé

- Same as above, but in french

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1 Curriculum vitae

CV

2

Personal Information

Residence	Zürich, Switzerland
E-mail	bvictor@ethz.ch
Website	vboussange.github.io
Github	github.com/vboussange
Age	Born 1995 (age 27)
Citizenship	France citizen

Personal skills

Languages	English (fluent)
	French (native)
	Spanish (B2)
	German (B1)
Programming languages	Julia
	Python
	C++
	Java
	Matlab
	R
	Bash
	VBA
Sports	Ski mountaineering
	Alpinism
	Rock climbing
	Enduro mountainbiking
	Surfing

Alpine CV [vboussange.github.io/pages/alpine_cv/]

Education

10.2022 – 09.2018 **Ph.D in Environmental Sciences,** Swiss Federal Institute for Forest, Snow and Landscape (WSL | Swiss Federal Institute of Technology Zurich, ETH), Switzerland
Forward and inverse modelling of eco-evolutionary processes. Under the guidance of Prof. Dr. Loïc Pellissier.

06.2017 – 09.2016 **Full year academic exchange,** University of New South Wales (UNSW Sydney), Australia

06.2017 – 02.2017 **Master thesis in theoretical geomechanics,** UNSW Sydney | CSIRO, Australia
Numerical continuation and bifurcation analysis for unconventional geomechanics. Under the guidance of Dr. Thomas Poulet.

08.2018 – 09.2013 **M.S. in Energy and Environmental Engineering,** Institut National Des Sciences Appliquées de Lyon (INSA Lyon), France
Three-year undergraduate engineering course in Energy and Environmental Systems, focused on Advanced Energy Systems and Efficiency.

08.2018 – 09.2013 **B.S. in Mathematics and Physics,** Institut National Des Sciences Appliquées de Lyon (INSA Lyon), France
Ranking : 21/650 students.

Professional appointments

08.2018 – 03.2018 **R&D intern,** Compagnie National du Rhône (CNR), France
Development of an Energy Management System based on various optimisation techniques for optimal production of renewable resources. Applications to EU sponsored projects: Jupiter1000 (power-to-gas), Move in pure (vehicle-to-grid), Marie-Galante island (micro-grid)

Publications

Peer-reviewed

1. **Boussange, V.** & Pellissier, L., *Eco-evolutionary model on spatial graphs reveals how habitat structure affects phenotypic differentiation*. Commun Biol 5, 668 (2022). [bioRxiv]

Preprints

1. **Boussange, V.**, Vilimelis-Aceituno, P., Pellissier, L., *Mini-batching ecological data to improve ecosystem models with machine learning* [bioRxiv] (2022), 46 pages. In review.

2. **Boussange, V.**, Becker, S., Jentzen, A., Kuckuck, B., Pellissier, L., *Deep learning approximations for non-local nonlinear PDEs with Neumann boundary conditions*. [arXiv] (2022), 59 pages. Revision requested from Partial Differential Equations and Applications.

Proceedings

1. Poulet, T., Alevizos, S., Veveakis, M., **Boussange, V.**, Regenauer-Lieb, K., *Episodic mineralising fluid injection through chemical shear zones*, ASEG Extended Abstracts (2018), 5 pages.

In preparation

1. **Boussange, V.**, Sornette, D., Lischke, H., Pellissier, L., *Analogous forces to ecological interactions, dispersal and mutations shape the dynamics of economic activities*.

Talks

07.2022 **Speaker,** HighDimPDE.jl: A Julia package for solving high-dimensional PDEs, JuliaCon2022, online. youtube.com/watch?v=4sXqGhhknT4

06.2022 **Speaker,** Interpretable machine learning for forecasting dynamical processes in ecosystems, World Biodiversity Forum, Davos, Switzerland.

06.2022 **Invited speaker,** Investigating empirical patterns of biodiversity with mechanistic eco-evolutionary models, Seminar at the Theoretical Ecology and Evolution group, Universität Bern.

11.2021 **Invited speaker,** Numerical approximations of solutions of highly dimensional, non-local nonlinear PDEs, StAMBio seminar, St Andrews, UK.

10.2021 **Speaker,** Graph topology and habitat assortativity drive phenotypic differentiation in an eco-evolutionary model, Conference on Complex Systems, Lyon, France.

10.2021 **Speaker,** Using graph-based metrics to assess the effect of landscape topography on diversification, ECBC, Amsterdam, Netherlands.

09.2021 **Speaker,** Solving non-local nonlinear Partial Differential Equations in high dimensions with HighDimPDE.jl, International Conference on Computational Methods in Systems Biology, Bordeaux, France.

04.2021 **Speaker,** Responses of neutral and adaptive diversity to complex geographic population structure, Mathematical Population Dynamics, Ecology and Evolution, CIRM Marseille, France.

Softwares

2022 **MiniBatchInference.jl** Julia
github.com/vboussange/MiniBatchInference.jl
A Julia package for maximum likelihood estimation and model selection of strongly nonlinear dynamical models.

2021 **HighDimPDE.jl** Julia
github.com/vboussange/HighDimPDE.jl
A Julia package that breaks down the curse of dimensionality in solving non local, non linear PDEs.

2021 **EvoId.jl** Julia
2019 github.com/vboussange/EvoId.jl

Evolutionary individual based modelling, mathematically grounded.

2018 **OptiVPP** Python, GAMS
confidential
Energy Management System for Virtual Power Plants.

Open source software contributions

SciML
DiffEqFlux.jl
CUDA.jl
Flux.jl
LightGraphs.jl

Teaching and supervision

12.2020 – 09.2020 **701-3001-00L Environmental Systems Data Science,** ETH Zürich, D-USYS, Switzerland

06.2020 – 04.2020 **262-0100-00L Lab rotation,** ETH Zürich, D-BSSE, Switzerland

12.2020 – 09.2020 **Taste of research internship,** Polytech Nice-Sophia, France

Reviews

2022 **Journal of Open Source Software**
2019 **Journal of Theoretical Biology**

Colophon

This thesis was typeset with LaTeX 2$_\varepsilon$. It uses the *Clean Thesis* style developed by Ricardo Langner. The design of the *Clean Thesis* style is inspired by user guide documents from Apple Inc.

Download the *Clean Thesis* style at `http://cleanthesis.der-ric.de/`.