Complexity and heterogeneity towards sustainability

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Introduction

- The last decades have witnessed the growing influence of **complex system analysis** on physical, biological and social sciences. **Economics** has not remained indifferent.
- The possibility of explaining, in theoretical terms and by means of models, **complex economic phenomena** has been sparking interest.
- The theoretical and analytical tools of complex systems analysis represent a route towards remedying important **weaknesses** in the **traditional representation** and understanding of economic facts.
- There exists **several definitions** of complexity related to, e.g.: complex dynamical systems, computational complexity, complexity in the relationships between individuals, etc.

Economies as Complex Adaptive Systems

Complex **adaptive** economies are characterized by dispersed interaction, no global controller, continual adaptation, and out-of-equilibrium dynamics (Arthur et al., 1997).

- Many **morphologically diverse** parts. Economies consist of a huge number of heterogeneous agents organized in groups and institutional structures.
- Variety of **nonlinear dynamics**. Aggregate behavior cannot simply be derived from the sum of the behaviors of individual components.
- Complex systems maintain themselves **out of equilibrium**.
- Complex systems **adaptively respond** to changes. Their interacting parts adapt by changing their behavior.
- **Irreversible** histories. Each event is the product of individual actions, within a given institutional setting.

Why complexity in economics?

- Because the complexity approach allows to handle and manage the presence of **heterogeneous agents** (agent-based modelling).
- Because of agents' **cognitive limitations** and agents try to formulate decisions in a **boundedly rational** environment.
- Because agents react to the **patterns** they co-create.

Would the system find its way to a conventional equilibrium? Or would it find ever-new patterns, and produce perpetual novelty?

The environmental challenge

- National and international public policy-making have to confront the unprecedented **challenge** of effectively managing the **complex interaction** of economic development, energy systems and environmental change.
- Policy-makers often consider that important **trade-off** exist between improving the sustainability of the economy and adequately supporting economic growth.
- There are four major areas that contribute to **climate policy indecisiveness**: (1) the dynamics of technology adoption and diffusion; (2) macroeconomic impacts of low-carbon policies; (3) interaction between human and environmental systems; and (4) policy implementation and effectiveness.

Why complexity and heterogeneity for sustainability transitions

- **Shortcoming**s of equilibrium and optimisation-based analysis (e.g. it does not consider bounded rationality, agents interactions, path dependence, multiple solutions, etc.)
- A sustainable transition involves socio-technical changes. It is a highly **non-linear** and **self-reinforcing** process that drive expectations, propelled by diverse agents.
- Complexity and **behavioural sciences** provide a suitable analytical framework. An economic transformation towards higher or lower sustainability takes place in direct interaction with the environment and its biogeochemical cycles.
- In models accounting for agents heterogeneity, interactions among technology, society, the macroeconomy and the environment can be simulated, as in models used to simulate the climate.

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Green growth: employment and income impact

- The **Energy-Environment-Economy Macro-Econometric model** (E3ME) is a computer-based model of the worlds economic and energy systems and the environment, originally developed through the European Commission.
- It assesses the interactions between the economy and the environment. As a **global model**, based on the full structure of the economic national accounts, E3ME is capable of producing a broad range of economic indicators.
- E3ME is designed to form annual **projections** up to 2050. As such, E3ME is commonly used to compare scenario projections.

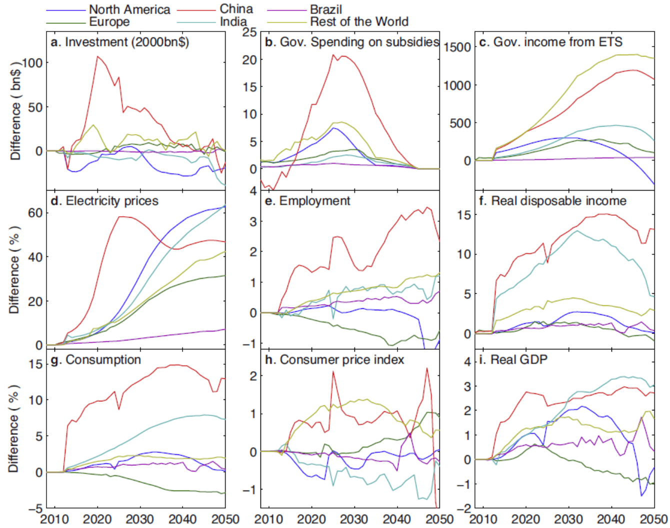

Figure: economic impacts of investment in low-carbon electricity generators (*source Mercure et al., 2015*)

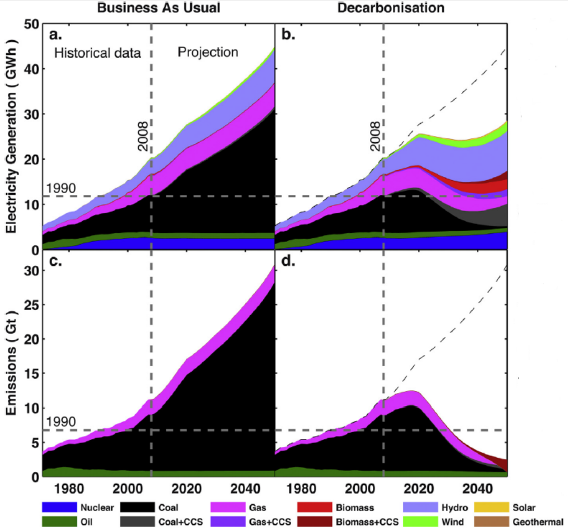

Figure: Example calculation of the environmental impacts of electricity policy instruments (*source Mercure et al., 2015*)

Interacting markets: analytical investigation

- Framework, e.g., of Cavalli et al. (2018, 2022) where a model of a market consisting of real, financial and monetary **interacting sectors** is studied.
- Agents populating the stock market are assumed to be heterogeneous and are updated within an **evolutionary framework**.
- Depending on the expectations structure, **multiplicity** of steady states can arise, consisting in enhanced or depressed levels of income, reflecting the optimistic or pessimistic nature of the agents' beliefs.
- Quasi-periodic dynamics resembling the business cycle fluctuations are also a relevant characteristic. Persistent trajectories provide a representation of how the **propagation of financial instability** may affect the overall pace of the economic activity.

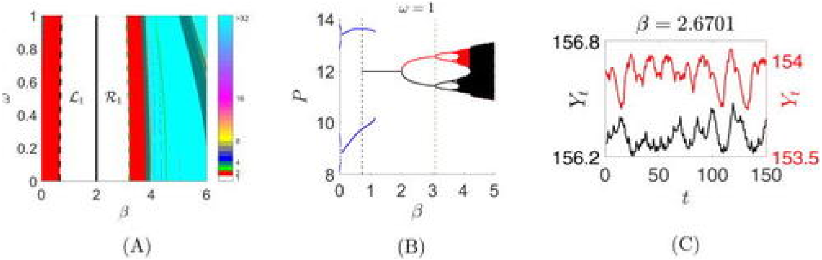

Figure: (a) two-parameters bifurcation diagram; (b) bifurcation diagram on varying the behavioral parameter β; (c) Time series of the national income after the pitchfork bifurcation. (*source Cavalli et al. 2018*)

- A possible and simple extension would be the introduction of an **environmental resource**

$$E_{t+1} = E_t(\bar{E} - E_t) + \eta Y_t$$

where $\bar{E}$ represents the carrying capacity of the environmental resource.

- Another way of introducing the environmental related issue would be to model directly **how agents perceive** environment and climate change. It is important to understand how individuals with opposite attitudes towards climate issues interact.
- Agents can be **biased** and be **supportive** or **against** policies that try to avoid the effect of climate change. They are also allowed to **switch** among their beliefs.

- There are several ways of modelling the fraction of agents adopting a certain **attitude towards different policies** (e.g. Lux (1995), Brock and Hommes (1997)).
- The **transition** from a status to another can be described as

$$p^{+-} = \lambda \exp(\beta\Phi)$$

$$p^{-+} = \lambda \exp(-\beta\Phi)$$

where the parameters λ and β reflect the speed of change and the herd behavior while $\Phi \in [-1, 1]$ is a variable that reflect the **general sentiment** of the population towards environmental issues.

- Alternatively, one can model the transition from a state to another linking her/his decision to the course of the economic activity or of the labour market (e.g. considering the **employment level** e_t)

$$p^{+} = \frac{\exp\left(\beta \frac{e_t - e_{t-1}}{e_{t-1}}\right)}{\exp\left(\beta \frac{e_t - e_{t-1}}{e_{t-1}}\right) + \exp\left(-\beta \frac{e_t - e_{t-1}}{e_{t-1}}\right)}$$

where $\beta > 0$ represents the intensity of choice.

Network approach

- The human society can be viewed as series of **interacting and interrelated** man-made infrastructures and activities that provide a variety of services to the individuals.
- The persistence and future development of human society are constrained by the challenge of making the **transition towards sustainability** possible.
- Human systems are complex entities where multiple users and technologies interact. Therefore, information on multiple attributes must be combined to obtain a systemic view and a clear understanding.
- The issue of sustainability within human systems can thus be studied through the tools of **network analysis**, which is suitable to represent such systems characterized by a high degree of complexity and interactions.

Geospatial Science and the Complex Nature of the Sustainable Development Goals

- The 17 **Sustainable Development Goals** formulated by the United Nations can be visualized as interrelated nodes of a network.
- There is a complex **interrelated nature** of these 17 goals: multiple causes and effects between them, feedback loops and autonomous actors.
- Hence, the consideration of network theory (link analysis potentially) would **optimise prioritisation** among these goals, driving also **decision-making**.
- How would Goal 1 (No Poverty) be achieved without consideration of Goal 3 (Good Health and Well-being) or Goal 4 (Quality Education)?

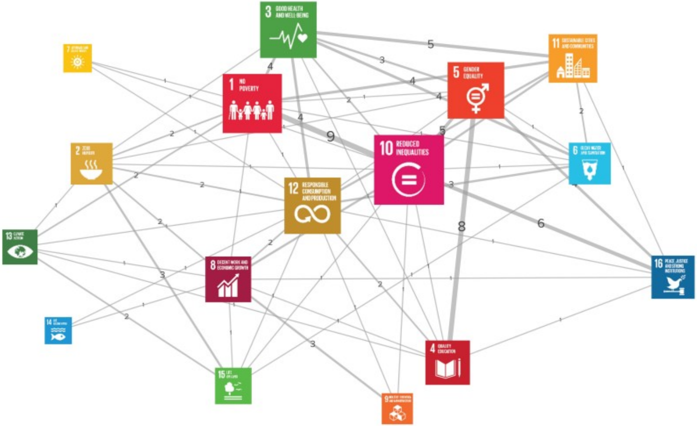

Figure: SDG Network Representation (*Jeff Mohr @kumupowered*)

- The application of **Geospatial Science** in studying complex systems offers far more than the mere analysis and visualisation of static or even basic temporal geographic dynamics.
- Advancement in techniques for the incorporation of these data into agent-based modelling or in network models may result in a significant advance in the understanding of how the 17 goals could be achieved.
- The adoption of **geospatial data** intervenes in several aspects, e.g. optimising the assessment of urban energy performance, aiding the sustainable management of the complex relationship between the built and natural environment, enhancing sustainable design, etc.

Examples: SDG1 - No poverty

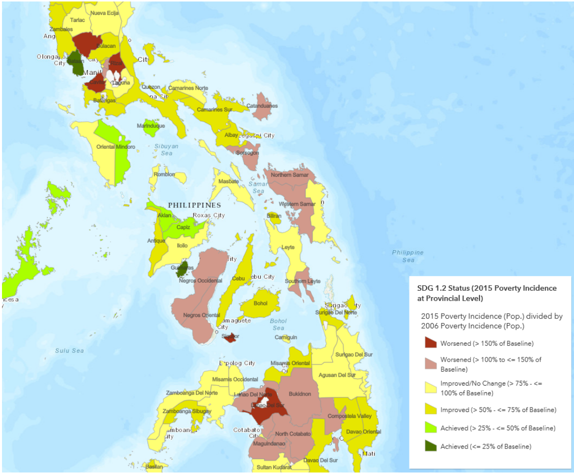

Figure: 2006-2015 Poverty Incidence at Provincial Level (©*Esri, HERE, Garmin, FAO, NOAA, USGS, Philippine Statistics Authority*)

SDG3 - No Hunger

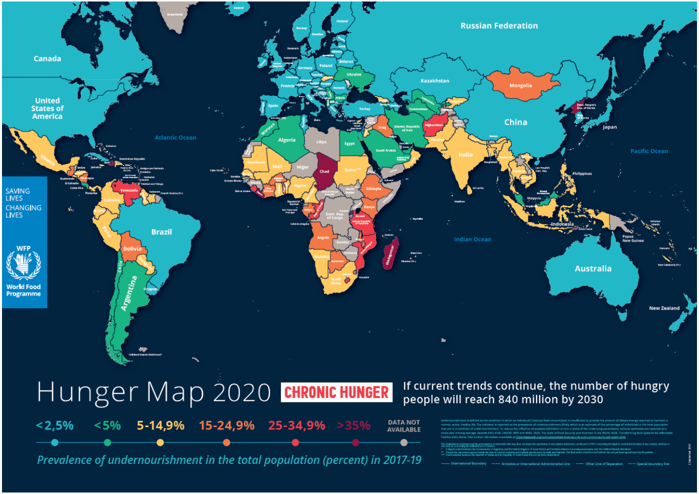

Figure: World Hunger Map 2020 (*Source: World Food Program*)

SDG 11 Sustainable Cities and Communities

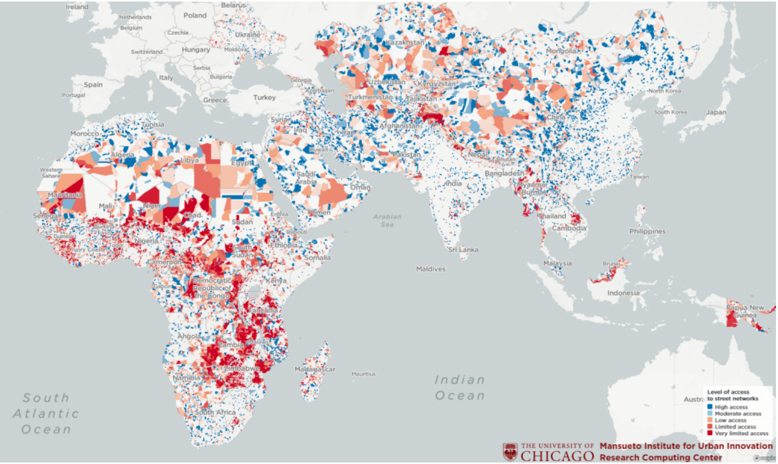

Figure: Million Neighborhoods Map (©*University of Chicago, Openstreetmap, Mapbox*)

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Concluding remarks I

- Equilibrium and optimisation-based models are appropriate to use for normative exploration and identification of desirable future configurations.
- On one hand these models may be appealing because they do not require the empirical knowledge of actual human behaviour.
- On the other hand, they can provide ambiguous information with respect to the achievement of policy goals, due to the lack of causal relationships with human behaviour.
- Instead, producing scenarios that accurately forecast the future course of events as a result of policy choices requires **fine-grained** representations of human behaviour, its diversity and multi-agent interactions.

Concluding remarks II

- Therefore, there is a need of **different modelling techniques**, especially for sustainability-related targets, such as heterogeneous agents models that take into account the above mentioned arguments.
- The outcome of this modelling technique could be the possibility of performing **forecasts**, with an increased attention to known non-linearities and interaction effects.
- Finally, the application and integration of **geospatial data** for modelling dynamical systems (Agent-Based models) and to analyze the **complex networked relationships** among different entities will continue to play a pivotal role in sustainability and climate action.

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