Inducing global sustainability in a network of unstable socio-ecological systems

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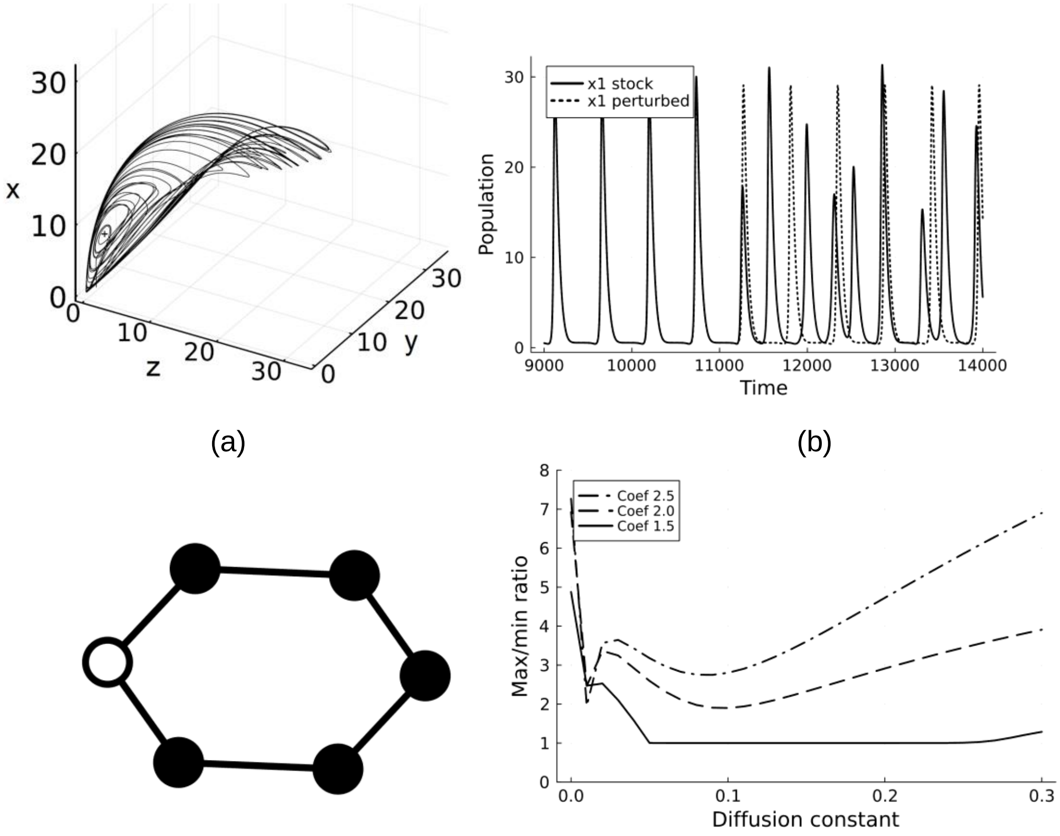
Socio-ecological systems are facing a multitude of problems related to the sustainable use of natural resources. Thus, developing tools for understanding and managing such complex systems is more crucial than ever to avoid ecosystem or social collapse [1]. In this work we explore the dynamics of networks of socio-ecological systems by means of numerical simulation and investigate the conditions when collapse occurs or is averted, and overall sustainability can be achieved. More specifically, we propose a simplified model of a socio-ecological system that accounts for population, resources, and wealth, with a quadratic population contribution in the resource extraction term. The quadratic interaction term is meant to represent the cooperative effects in the population (via self-interaction) working towards extracting resources and producing goods.

Analysis of the dynamics shows that systems with an extraction rate α below a critical threshold α_c will reach a steady state. If the extraction rate is above the critical value α_c, then a supercritical Hopf bifurcation leads to the appearance of a limit cycle. The oscillations are typically large enough that they approach the origin, so all variables are periodically at almost zero value (i.e., the system collapses). Hence, systems with a low extraction rate of natural resources that reach a steady state are called sustainable, whereas systems with a high extraction rate, that oscillate with large amplitude, are considered unsustainable.

The model is then generalized to multiple interacting systems with chaotic dynamics emerging for small non-uniformities in interaction matrix. The chaotic behavior is described with the usual numerical techniques, making use of the phase portrait, Poincare map and calculating the largest Lyapunov exponent. Certain choices of interaction matrix lead to the synchronization of the systems in the network. In this case the dimensionality of the problem reduces from 3N (where N is the number of nodes in the network) to 3, and chaotic attractor can be represented, see Fig. 1(a). The divergence of two initial conditions with a small difference between them can be seen in Fig. 1(b).

Another network extension introduces diffusion in the population variable, which can be seen as a type of migration under population pressure. We show that diffusion can stabilize networks of sustainable and unsustainable societies, and then interconnection could be a way of increase resilience in global system. In the ring network in Fig. 3(a) the white nodes are sustainable, and the black ones are not. If $\alpha/\alpha_c = 1.5$ for the black nodes, then there is a range for the higher values of the diffusion constant where the max/min population ratio is 1, see Fig. 3(d). This indicates that there is no limit cycle and all the populations in the network reach a fixed point. If α/α_c is increased then oscillations do appear, with ratio between the maximum and minimum total population of 2 to 3. Other topologies have been investigated with similar results.



(a) (b)

(c) (d)

Fig. 1. (a) Chaotic attractor for the synchronized system with N = 3 subsystems. (b) Divergent trajectories for small difference in initial conditions. (c) Ring topology with sustainable (white) and unsustainable (black) nodes. (c) Ratio of maximum and minimum total population on the network when parameters (extraction rate, diffusion const) are varied.

In addition to the above mathematical considerations, we also present a novel interpretation of the dynamics. As mentioned, systems reaching a steady state can be considered sustainable, but analyzing the evolution of marginal costs and benefits we can also conclude they behave rationally (in an economic sense). On the other hand, systems where large amplitude limit cycles appear have marginal costs that exceed the marginal benefits, to the point where all net benefits are lost. Thus, these systems can be said to behave irrationally.

The present work aims to contribute to a “Global Systems Science” which previous work has advocated for [2]. Overall, the multi-systems model gives a timescale of predictability (500-1000 years) for socio-ecological dynamics comparable to results from other work [3], while indicating that the emergent dynamics of networks of interacting complex socio-ecological systems over the long term is likely chaotic and hence unpredictable.

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