Unit 2.3 Complexity: How are the dynamics of nature-society systems shaped by their complexity and the non-linearities, multiple regimes and tipping points that emerge from it?

Nature-society interactions constitute not only *adaptive* systems, as discussed in the previous unit, but *complex* adaptive systems. Three fundamental attributes of nature-society systems have been shown to make them *complex* adaptive systems rather than just *adaptive* ones (the back story for these assertions is provided in the Levin et al 2013 paper listed below under "Digging Deeper…."):

- **persistent heterogeneity** (individuality, diversity) of their basic elements [e.g. fishing towns and mining towns are and remain distinctive nature-society systems rather than being generic and interchangeable ones];
- **local interactions** (relationships) among those heterogeneous elements that are local or context specific [e.g. neighboring fishing towns interact differently with one another depending on whether they compete for coastal lobsters or oceanic swordfish];
- **autonomous selection** processes that enhance some elements (but not others) based on the outcome of the local interactions [e.g. fishing towns that learn to harvest sustainably will (one hopes) prosper by attracting more investment and retaining more young fishers than those that don't, and wither].

These attributes of complex adaptive nature-society systems give rise to an array of far-from-equilibrium dynamics that are fundamentally important for the pursuit of sustainability, including:

- **non-linear responses** to interventions, which are in play whenever repetitions of the same action (cause) do not always produce the same result (effect) [e.g. Push a book sideways across a table by snipping it with your finger. Each snip moves the book by about the same amount until its position reaches the edge of the table, at which point the same snip has a very different result. Mathematically, y=mx is a linear system because the "effect" on y of a change in the "cause" x is always the same regardless of the initial value of x. Whereas y=mx^2 (i.e. x raised to the power of 2) is a nonlinear system because the effect on y of a given change in x depends on the initial value of x].
- **Regimes** are particular sets of dominant relationships, feedbacks, or other "rules of the game" (both natural and social) that give rise to characteristic dynamics of development pathways [e.g., fossil-fuel energy regimes, intensive agriculture regimes] in nature-society systems. Characteristic of regimes is that within them, small perturbations—whether caused by chance, internal dynamics, or outside disturbances—encounter feedbacks that tend to push the system back toward its earlier state or to lock in the development pathway. Separating neighboring regimes are thresholds (also called "tipping points")...
- **Thresholds or tipping points** seem to turn up everywhere in nature-society systems. We'll explore formal definitions of "tipping points" in the readings. But your intuition is probably about right if you think of "tipping points" as "points of no return" beyond which system dynamics get quickly and irretrievably very different: YouTube segments that go from a few shares to viral, taking a curve too fast on a mountain road, bursting a speculation bubble, melting the Greenland Ice Cap, etc. We care about tipping points because they undermine our ability to seek sustainable development by just trial and error feedback or, as a famous political science paper puts it, by "muddling through."

<u>**To prepare for this Unit, please:**</u>

a) **Read:** Matson, P., Clark, W. C., & Andersson, K. (2016). *Pursuing Sustainability: A Guide to the Science and Practice*. Princeton University Press. Read Ch. 3 "Dynamics of social-environmental systems," pp. 63 (start with "Complexity") – pg. 70 (stopping at the heading "Evaluating complex systems").

b) **Experiment**: Conduct the paper-folding experiment in non-linear systems described in Clark, W. C., & Harley, A. G. (2025). *Non-linear behavior in paper folding*. Harvard University. (Unpublished MS, available in Course Library).

c) **Explore:** Clark, W. C., & Harley, A. G. (2025). *NetLogo Guide for Sustainable Development Course*. Harvard University. (Unpublished ms, available in the Course Library). For this Unit, reread Section 1 and explore Section 3 "Netlogo fire model."
With this material, we continue our use of simple models to develop an appreciation of how complex and often unexpected system dynamics can arise from very simple system structures. This fire model captures common elements of the spread of disease, rumors or innovations.

Study Questions to help you get the most out of the readings:

I. Explain the result of your paper-folding experiment assigned in (b) above. Is the difficulty of doing a fold the same regardless of how many folds have already been made? Why? In crafting your explanation, consider whether your conclusion would be different if you had used a bigger sheet of paper. (It may help to compare your result with the single sheet of typing paper to the experience of a Myth-Buster group trying the same experiment with a foot-ball-field sized tarp: https://youtu.be/65Qzc3_NtGs?si=bIaHy4FsfrAnSyzo ; 4 min). What nature-society interactions display relationships like those found in the paper-folding experiment?

II. Use the NetLogo fire model described in (c) above to explore how the thresholds arise in complex systems, and to get a feel for their implications for adaptive management. In particular, how does initial forest density relate to the % of the forest that burns? Is the relationship linear (a unit change in density always results in the same amount of change in the % of the forest that burns) or does it exhibit discontinuities or tipping points? Why? What are the implications for management? Would it make sense to design different strategies for managing a low density forest "regime" and a high density one? What other nature-society interactions display relationships like those found in the simple fire model?

III. Think back to the system dynamics of the Fishbanks game that you played in Unit 0.2. Describe the role of trial-and-error in your management of that complex adaptive system, with special attention to your goal, the trial of your action intended to achieve the goal, the measurement of the actual impact of your action, your assessment of what worked vs. what turned out to be an error, and what adaptation you adopted for the next round of play. What were the successes of your approach to adaptive management? Where and why did it fall short. How could modeling the system help to improve your trial and error management?

Digging deeper (optional materials for further exploring frontiers in the pursuit of sustainability):

d) **Read**: Levin, S., Xepapadeas, T., Crépin, A.-S., Norberg, J., de Zeeuw, A., Folke, C., Hughes, T., & Arrow, K. (2013). Social-ecological systems as complex adaptive systems: Modeling and policy implications. *Environment and Development Economics*, *18*(2), 111–132.
This paper lays out the fundamentals and practical implications of its title.

e) **Read:** Biggs, R., Peterson, G. D., & Rocha, J. C. (2018). The Regime Shifts Database: A framework for analyzing regime shifts in social-ecological systems. *Ecology and Society*, *23*(3), 9–9. https://doi.org/10.5751/ES-10264-230309
This paper introduces the 'Regime Shifts Database', an open-access database that synthesizes information on regime shifts in nature-society across a wide range of scales.

f) **Read:** Steffen, W., Rockström, J., Richardson, K., Lenton, T. M., Folke, C., Liverman, D., Summerhayes, C. P., Barnosky, A. D., Cornell, S. E., Crucifix, M., Donges, J. F., Fetzer, I., Lade, S. J., Scheffer, M., Winkelmann, R., & Schellnhuber, H. J. (2018). Trajectories of the Earth System in the Anthropocene. *Proceedings of the National Academy of Sciences*, *115*(33), 8252–8259. https://doi.org/10.1073/pnas.1810141115
This paper takes the concept of tipping points to environmental systems operating at global scale, examining how human activities may push the climate into "no-analog" regimes beyond the experience of civilization. The tipping point figure is worth careful study.

g) **Read:** Barrett, C. B., Travis, A. J., & Dasgupta, P. (2011). On biodiversity conservation and poverty traps. *Proceedings of the National Academy of Sciences*, *108*(34), 13907–13912. https://doi.org/10.1073/pnas.1011521108

This paper reminds us that "tipping points" are not necessarily bad by emphasizing the goal of helping impoverished societies to cross a tipping point beyond which lies an escape from poverty traps into a regime of potentially self-reinforcing growth in well-being.