Unit 2.2 Stocks and flows: How do these fundamental properties of nature-society interactions shape their dynamics as adaptive systems?

Part I of the course introduced stocks of resources as the fundamental determinants of sustainable development, and some of the flows through which those stocks are depleted or enhanced by human activity. We began Part II of the course in the previous Unit, arguing that stocks, flows and feedbacks among them are fundamental components of any system, and that seeing them as such can help to understand the dynamics of the nature-society systems that are central to sustainable development. In this Unit, we explore those concepts more deeply, emphasizing:

- How **stock-flow relationships** can produce counterintuitive results that if not properly understood can lead to debilitating management blunders;
- How **feedback loops** cause changes in one stock (part or component) of the system (e.g., building a levee on a river) to cause changes in flows (e.g. reduce flooding of adjacent farmland) that affect other properties of the system (e.g. the incentives for people to settle in the newly protected flood plain) and may eventually loop back to influence that initial stock itself (e.g. building more or higher levees to protect the new settlements);
- How feedbacks allow nature-society interactions to function as ***adaptive*** **systems** in which departures from desired or expected development pathways can be responded to in hopes of achieving various goals (e.g. the levee example above, in which both levee planners and floodplain settlers adapt);
- How systems exhibit **emergent properties** that are more than the sum of their component parts and cannot be understood, much less adaptively managed, without careful analysis of underlying stocks, flows and (adaptive) feedbacks (e.g. the unexpected emergence of a better protected but also more heavily built up and thus potentially vulnerable floodplain as a consequence of initial efforts to protect a few farmers).

The principal means for connecting these concepts to system dynamics is through models. These can be mathematical but need not be: the key is that models unambiguously specify what elements are included in an analysis and how they relate to one another. We've already seen one example of such models for understanding system dynamics in the Fishbanks simulation explored at the beginning of the course, in which fishers attempted to adapt their fleets to changing conditions of the fishery. In this Unit we will further explore models as a means for understanding system dynamics through hands-on work using the multi-agent programmable modeling environment "NetLogo" to address the challenge of climate change.

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

a) **Read**: Matson, P. A., Clark, W. C., & Andersson, K. P. (2016). *Pursuing sustainability: A guide to the science and practice*. Princeton University Press. https://pursuing-sustainability.stanford.edu/ . Continue with Ch. 3 "Dynamics of social-environmental systems," pp. 57–63 (stop at the heading "Complexity…." there).

b) **Read**: Sterman, J. (2002). *System Dynamics: Systems Thinking and Modeling for a Complex World* [Working Paper]. Massachusetts Institute of Technology. Engineering Systems Division. https://dspace.mit.edu/handle/1721.1/102741

c) **Explore:** Clark, W. C., & Harley, A. G. (2025). *NetLogo Guide for Sustainable Development Course*. Harvard University. (Unpublished ms, available in the Course Library). Explore Sections 1 "Basic access" and 2 "NetLogo stocks and flows model."

d) **Read**: Iler, S., & Clark, W. (2025). *NetLogo: Exploring Stocks and Flows for Climate Change*. Harvard University. 1 pg. (Unpublished ms, available in the Course Library).

Study Questions to help you get the most out of this unit:

I. Run the NetLogo "Stocks and Flows model" along the lines introduced in (d) above. For the model run in which you come closest to achieving your goal, write down answers to the following questions, which are also posed under the section "Things to notice and things to do" in the "Model Info" drop down of the "Stocks and Flows model" accessed through reading 'd' above:
   a) In which year did you first stabilize the amount of atmospheric carbon?
   b) How much carbon was in the atmosphere when it stabilized? (Your answer should have units of Gt C.)
   c) What was the annual emissions of carbon in the year that you achieved stabilization of the amount of atmospheric carbon? (Your answer should have units of GtC/y.)
   d) In a sentence or two, describe the shapes of your final graphs of "Atmospheric Carbon" and "Emitted by Society" and their relation to one another.
   e) In a few sentences, describe to someone just starting this exercise the strategy you devised that came closest to achieving your goal.

II. What makes it hard to adaptively manage emission flows as a means of achieving the goal of keeping carbon stocks in the atmosphere below a given threshold? Given what you have learned in using the model, what would you recommend to decision makers in the real world about how they should design a schedule of changes in the flow of emissions that would help to achieve the goal of limiting carbon stocks in the atmosphere while minimizing disruptions to the energy system? What pitfalls would the modeling exercise suggest that you should warn them about as likely to make it harder for them to achieve their goals?

III. All models are simplifications of the real world. What simplifications made in the NetLogo climate model might lead you to draw conclusions from it that are seriously at odds with how dynamics in the real world play out? How do you think the real-world dynamics are likely to differ from those of the model? Are the most problematic simplifications about stocks, flows, feedbacks, adaptation or something else? Why?

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

e) Continue to browse the two classic primers in general systems thinking and modeling originally listed in the "Digging Deeper" section of Unit 2.1:
   - Meadows, D. H. (2008). *Thinking in systems: A primer*. Chelsea Green Publishing.
   - Sterman, J. (2000). *Business dynamics: Systems thinking and modeling for a complex world*. Irwin/McGraw-Hill.

f) The NetLogo modeling environment introduced in this unit is much more thoroughly developed in: Wilensky, U., & Rand, W. (2015). *An introduction to agent-based modeling: Modeling natural, social, and engineered complex systems with NetLogo*. The MIT press. https://www.intro-to-abm.com/ (https://www.intro-to-abm.com/).

g) These two papers are referred to in the reading 'd' above, and can be explored for more details on the argument summarized there:
   - Sterman, J. D. (2002). All models are wrong: Reflections on becoming a systems scientist. *System Dynamics Review*, *18*(4), 501–531. https://doi.org/10.1002/sdr.261
   - Sweeney, L. B., & Sterman, J. D. (2000). Bathtub dynamics: Initial results of a systems thinking inventory. *System Dynamics Review*, *16*(4), 249–286. https://doi.org/10.1002/sdr.198