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Sustainability factors in dynamical systems modeling: Simulating the non-linear aspects of multiple equilibria

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ABSTRACT

What is sustainability? Sustainability is a concept that can be defined in many ways depending upon a society's perception of current material needs and the actual material needs of future generations. Much of our ability to achieve sustainability entails developing indicators and measurements that will guide us to this goal. This paper suggests that we can strengthen the prediction of sustainability indicators by adopting a "multiple equilibria" approach for a more effective decision-making process in various sectors of the economy, in ecosystem protection, or in political arenas. There is an emerging need for further development of predictive mathematical models of system sustainability over economic growth models for sustainable resource measurement and management. The objective of this paper is to use computer modeling and differential equations to simulate the "multiple equilibria" of a 3 variable real world system. In our study, we tested the theoretical validity of "multiple equilibria" sustainability modeling through simulated measurements of precipitation and nitrogen runoff into a hypothetical lake. As a quantitative tool to model, the "multiple equilibria" techniques can have tremendous predictive power for business leaders, political decision makers, and environmental scientists, and assist in better management of ecological, economic, and material resources in short-term and long-term end-use scenarios.

1. Introduction: why sustainability is important

Biophysical sustainability is the process of balancing resource stocks and flows within a dynamical system over time. Sustainability is a universal necessity, because, in the natural world, an ecosystem thrives on the symbiotic interaction of numerous individual organisms and communities of organisms that depend on each other biologically and ecologically. Thus, an ecosystem dynamically strives to be in equilibrium but often finds itself far from equilibrium in real world scenarios. But a system's equilibrium can be constrained by its input availability and its output absorbance capabilities. According to Fath (2015), "... meeting Input–Output requirements are necessary but not sufficient conditions for sustainability. For ecosystems, the input constrains are fundamentally energy and matter flows that manifest themselves in terms of solar radiation, global carbon cycle, rate of nitrogen cycling, rate of hydrological cycle, etc. The ability of the environment to accept the system output is constrained by the rate of decomposition, the rate of accumulation of unwanted by-products, and the synergistic couplings that allow material reuse. The adjacent system receiving output must be a lower gradient than the system generating them [making it] necessary for the continual renewal of the configurations that emerge out of these flow gradients" (p. 14). So, internal dynamics in the ecosystem are just as important as external dynamics.

Over time, natural systems either remain sustainable, if they are stable and resilient, or they become unsustainable, if they are fragile or fail to adapt to the dynamics of change. A fragile ecosystem is likely to be an unstable ecosystem due to limited resources or weak symbiotic integrations in the system. If there is an overshoot of population thresholds with persistent nitrogen deficiencies or resource disruptions, fragile system populations will begin to die off and affected species drift toward extinction. When a system is stable and/or resilient it has a capacity to withstand external stress and disturbances, and can quickly recover from systemic shock and return to its original state or an approximate state of functionality.

Lambin (2007) suggests, [an] ecosystem's degree of resilience is often a better indicator of its "health" than its stability. A stable system is often un-resilient because it has rigidly protected itself

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against minor disturbances, rather than develop mechanisms for flexibly coping with major disturbances. In the language of mathematics, the resilience can be described as branching points or bifurcations since when a dynamical system is disturbed it can naturally rebound for better or worse. As an ecosystem evolves, the ecosystem can be acted upon by disturbances knocking it into two different possible states. If both states are stable then the system is robust enough to recover from these external stresses. If not, then the system is said to be unsustainable. To explain the bifurcation process at the macro-scale, Lambin (2007) uses the example of the vast network of dams and sea walls constructed by industrialized countries to protect urban environments from inundation. But, this process has caused natural soil fertilization to be replaced by sizable amounts of chemical fertilizer. Excessive runoff can pollute waterways or lead to eutrophication (or algal blooms) in the regional water systems that possibly feed the red tides and lead to oceanic dead zones. In addition, when flood waters rise to a height where they can overflow the barriers or they can break. Once these events take place, one must address the tremendous economic, ecological and social costs. The aftermath of Hurricanes Rita, Katrina and Sandy are stark examples of how resilience tradeoffs can have devastating impacts. Under normal circumstances strengthened levees and self-sustaining barrier islands, wetlands, and coastal forests would have acted as buffers against the storm surges minimizing environmental damage and human hardship. Therefore, the notion of sustainability is a strategic endeavor and a vast effort to preserve the human condition.

On a societal level, sustainability involves basic life systems, maintenance of diversity, stability in providing goods and services, basic human needs and intangible human needs and support. To reach these objectives, sustainability managers may rely on spatial factors (household, local, regional, national, global), temporal factors (days, months, years, decades), identification of critical sectors (government, industry, community) or resources (natural, synthetic, energy), identification of the characteristics and sensitivities of groups in society (citizens, consumers, cultures), the recognition, creation and maintenance of required organizational and institutional structures, and the degree of risk acceptable in designing sustainable futures (Garner, 2011). In practice, "sustainability" involves these topical considerations, but sustainability indicators and sustainability measurements are also necessary to set goals and determine a relevant course of action. It is the development of sustainability indicators that establishes a baseline for measurement and provides mechanisms for targeted application of sustainable technologies.

2. The Limits to Growth model

Early research on sustainability used the predictive power of computer modeling to simulate how dynamical systems would behave, and eventually brought attention to the stress on natural resources by growing human populations and the limited carrying capacity of the Earth's ecosystems. In the late 1950s, MIT Professor Jay Forrester established the field of "systems dynamics" by using mathematical modeling to analyze the behavior of complex engineering and social systems. Forrester's computer program was designed to simulate a web of complex systems with interactive feedback loops and non-linear equations (Harvey and Hallett, 1977; Jin et al., 1995).

In 1969, Italian business executive Aurelio Peccei published the book, The Chasm Ahead which predicted that civilization will eventually face limitations to population growth, pollution, materials, and energy. Since these problems were global, Peccei believed that these problems should be studied on a global scale. He decided to form an interdisciplinary team of eminent scientists and international consultants into a futurist think tank called the Club of Rome (Humphrey and Buttel, 1982). Professor Forrester's "systems dynamics" modeling methods used extremely complex mathematical equations that seemed an appropriate tool to study the problems envisioned by Peccei. In 1970, Professor Dennis Meadows and a small team of researchers at Massachusetts Institute of Technology (MIT) joined Forrester who was using his modeling methods to support the Club of Rome's Project on the Predicament of Mankind. This collaboration resulted in the report, The Limits to Growth, two years later.

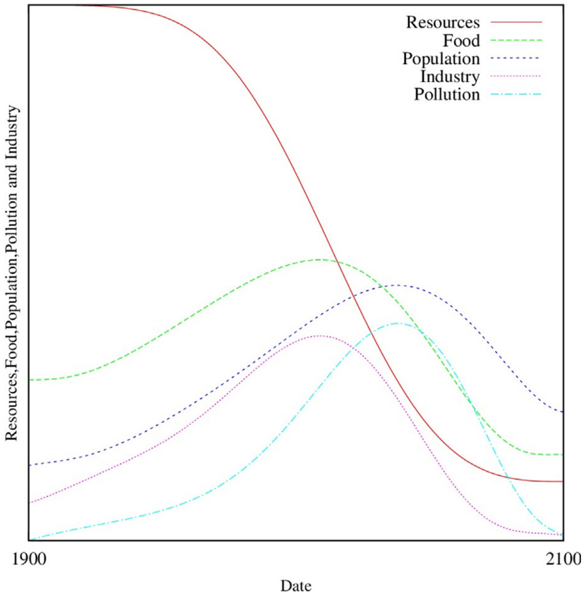

Fig. 1. The standard scenario as reproduced from Meadows, Donella H., Meadows, Dennis L., Randers, Jørgen, and William Behrens III, (1972), Limits to Growth, New York: Universe.

The Limits to Growth report identified the complex web of technical, economic, ecological, social and political problems that all countries face and aggregated them to a global level. The Club of Rome's research team chose five basic quantities whose levels indicated essential components to the state of our world system: population, pollution, natural resources, agricultural capital (or output), and industrial capital (or output). They then established levels and rates of flow along with feedback loops to describe interrelationships among key factors and develop a responsive systems model. Next, the model's mathematical behavior was run through a computer to establish its graphical behavior over the time period 1900–2100 A.D. The computer model produced what was called the World Model Standard Run (Harvey and Hallett, 1977).

According to Meadows et al. (1972), the "standard" world run made no changes in the historical physical, economic and social relationships that governed the development of world systems, so the run plotted the five basic quantities from the years 1900 to 1970. But, the model goes further by using that existing knowledge of current world systems levels to project these operational levels towards the year 2100. The results revealed that if the quantity levels continued to proceed at the current rates, food, industrial output and population would grow exponentially until the rapidly diminishing natural resource base would force a slowdown in industrial growth. While population and pollution will continue to grow for a while after the peak of industrialization, eventually population will start to decline due to increasing death rates once food and medical services decrease as shown in Fig. 1.

Although the "Standard" run was alarming, and perhaps, unrealistic exponential growth, it did take stock of global resource quantities and suggest that there is an opportunity for humans to