Linkages of Sustainability

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An Introduction

Thomas E. Graedel and Ester van der Voet

The Components of Sustainability

Sustainability is often approached from the standpoint of understanding the problems faced by humanity as it considers the possibility of sustainability. Several years ago, Schellnhuber et al. (2004) identified what were called "switch and choke elements in the Earth system" and illustrated a "vulnerability framework." A "Hilbertian program for Earth system science" was presented to help frame the discussion (Clark et al. 2004), but this was not regarded as a recipe for sustainability. That program, or set of questions, focuses on needed increases in knowledge of the Earth system. However, only one or two of the twenty-three questions address the other half of the sustainability challenge: that of quantifying the present and future needs of a sustainable world, quantifying the limitations to response that the Earth system defines, and understanding how to use that information to encourage specific actions and approaches along the path to sustainability.

Nonetheless, most of the topics related to addressing sustainability have been treated in detail, if in isolation, by the scholarly community. The human appropriation of Earth's supply of freshwater, for example, has been discussed by Postel et al. (1996). Similarly, the limits to energy, and the ways in which energy in the future may be supplied, were the subject of a five-year effort led by Nakićenović et al. (1998). Mineral resources have been treated, again in isolation, by Tilton (2003). Other research could be cited, but the central message is that the investigations in one topical area related to sustainability do not generally take into account the limitations posed by interacting areas. Engineers like to talk of their profession as one that is centered on "designing under constraint" and optimizing a design while recognizing a suite of simultaneous limitations. For the Earth system, including but not limited to its human aspects, the constraints are numerous and varied, but it is still the integrated behavior that we wish to optimize, not selected individual components.

A challenge in addressing some of these questions in detail involves not only the flows of resources into and from use, but also information on stocks, rates, and trade-offs. The available data are not consistent: the stocks of some resources, those yet untapped and those currently employed, are rather well established, while for others there remains a level of uncertainty that is often substantial. In an ideal situation, resource levels would be known, their changes monitored, and the approaches to the limits of the resource could then be quantified. Consider Figure 1.1a, which could apply, for example, to a seven-day space flight. The stock is known, the use rate is known, future use can be estimated, and the end of the flight established. So long as total projected use does not exceed the stock, adequate sustainability is maintained.

Consider now Figure 1.1b, the "Spaceship Earth" version of the diagram. Here the stock is not so well quantified. The general magnitude is known, certainly, but the exact amount is a complex function of economics, technology, and policy (e.g., oil supply and its variation with price, new extraction technologies, and environmental constraints). This means that stock is no longer a fixed value, but that its amount may have the potential to be altered. Rates of use can be varied as well, as demonstrated so graphically in the scenarios of the Intergovernmental Panel on Climate Change (IPCC 2008a) for future climate change, not to mention changes in commuter transportation with changes in fuel prices. Nonetheless, the starting point for consideration remains the same: How well can we quantify the factors that form the foundation for any consideration about the sustainability over time of Earth's resources?

A major complicating factor in this assessment is that Earth's resources cannot be considered one at a time; there are interdependencies and potential conflicts that must be accounted for as well. A textbook example is water, an essential resource for human life and nature. We use water for drinking, working, and cooking, but it is also required to produce food and to enable industrial

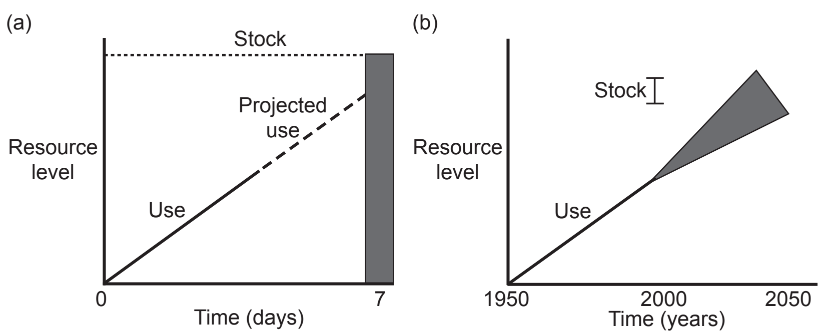

Figure 1.1 Use of a resource and the degree to which it approaches the available stock (a) during a seven-day period in which all parameters are well known and (b) for a time period of a century in which the stock and rate of use are imperfectly known.

processes. More water could be supplied by desalinizing seawater, but this, in turn, is a very energy-intensive process. Is our energy supply adequate to support such a major new use? The problem thus becomes one of optimizing multiple parameters, of deciding what is possible. This cannot be achieved without doing the best job we can of putting numbers and ranges on key individual resources related to sustainability; comprehending the potential of the resources in isolation is not enough.

The Challenge of Systems

Understanding how best to move along the road toward sustainability, as contrasted with understanding the levels and types of unsustainability, is an issue that has not yet been addressed in detail. Sustainability is a systems problem, one that defies typical piecemeal approaches such as: Will there be enough ore in the ground for technological needs? Will there be enough water for human needs? How can we preserve biodiversity? Can global agriculture be made sustainable? These are all important questions, but they do not address comprehensive systems issues, neither do they provide a clear overarching path for moving forward, partly because many of these issues are strongly linked to each other.

It may help to picture the challenge of sustainability as shown in Figure 1.2, where the physical necessities of sustainability are shown as squares and the needs as ovals. It is clear that a near-complete linkage exists among all of the necessities and all the needs, yet tradition and specialization encourage a focus on a selected oval and all the squares, or a selected square and all the ovals.

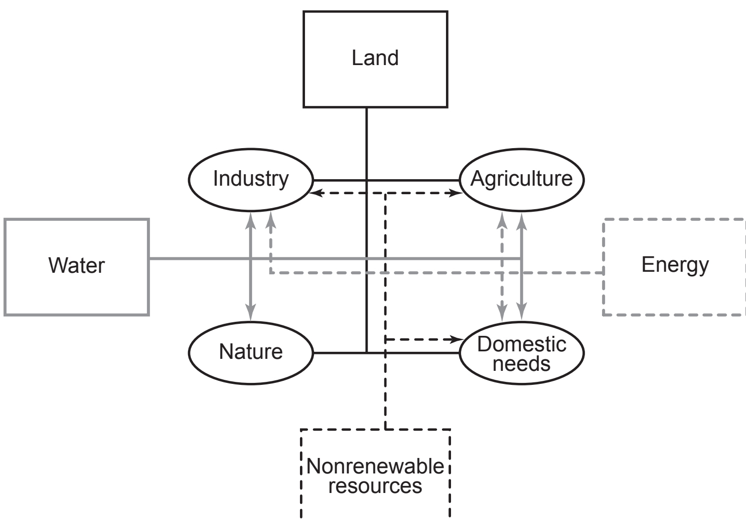

Figure 1.2 The links among the needs for and limits of sustainability.

Can we devise an approach that addresses them all as a system, to provide the basis for constructing a coherent package of actions that optimize the system, not the system's parts?

Emergent Behavior

A feature of natural systems that frequently confounds analysts is that of emergent behavior, in which even a detailed knowledge of one level of a system is insufficient to predict behavior at a different level. An obvious example is the beating heart. At its lowest level, the heart consists of cells, of course, which can be described extensively from physical and chemical perspectives. Little at the cell level suggests electrical activity that leads to rhythmicity at higher levels, however. Rather, rhythmicity of the whole heart arises as a consequence of the electrical properties of numerous intracellular gap junctions, and as modified by the three-dimensional architecture and structure of the organ itself (Noble 2002); it is a property, unanticipated at the cellular level, that suddenly emerges at the level of the organ.

Ecological ecosystems demonstrate emergent behavior as well, behavior in which a system may flip from one metastable state to another (Kay 2002). A common example is shallow lakes, often known to be bi-stable (Figure 1.3): if low in nutrients, the water is generally clear; if high in nutrients, it is generally turbid. The transition is not gradual, however, but rapid once a bifurcation point is crossed. This behavior is related to the biological communities involved. Some nutrient conditions favor algae feeders that reduce turbidity, whereas others favor bottom feeders which increase it. The turbidity, and especially the unanticipated flip from one state to another, results both from the general conditions of the system (e.g., temperature, water depth) as well as from the particular types and number of organisms that comprise it and whose

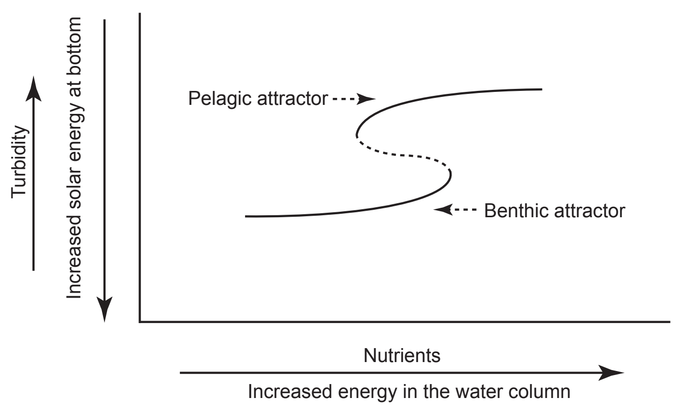

Figure 1.3 The bi-stability pattern in a shallow lake. Adapted from Scheffer et al. (1993); courtesy of J. J. Kay.

populations evolve with it (van Nes et al. 2007). That is, the lake is a component of, and subject to, higher-level components, as suggested on the left side of Figure 1.4.

Emergent behavior is also a feature of human systems. Consider the example of cellular telephony. This complex technology was developed in the 1980s and 1990s. The fixed-location base stations that were originally needed were few, and the telephones expensive and briefcase-sized. Cell phone use and the infrastructure that supported it were largely predictable, and users were anticipated to be a modest number of physicians, traveling salespeople, and others not having convenient access to a landline phone. Around the year 2000, improved technology made cell phones much smaller and much cheaper. Parents began to buy cell phones for their children, as well as for themselves. Suddenly it became possible to call anyone from anywhere. Demand skyrocketed, especially in developing countries where the technology made it possible to avoid installing landline phones almost completely. As a result, an entirely new pattern of social behavior emerged, unpredicted and certainly unplanned.

The cell phone story is relevant here because sustainability ultimately involves humans, resources, energy, and the environment. The production of hundreds of millions of cell phones demands an incredible diversity and quantity of materials for optimum functionality. At one point in their rapid evolution, tantalum came into short supply, and the mineral coltan was mined in Africa by crude technological means to fill the supply gap, doing significant environmental damage in the process. The worldwide cell phone network is now trying to address a new emergent behavior: the recovery of precious metals from discarded cell phones through primitive "backyard" technologies. This social–technological activity did not exist when cell phones were few; however, as they became abundant, the recycling networks flipped into a new and unanticipated state.

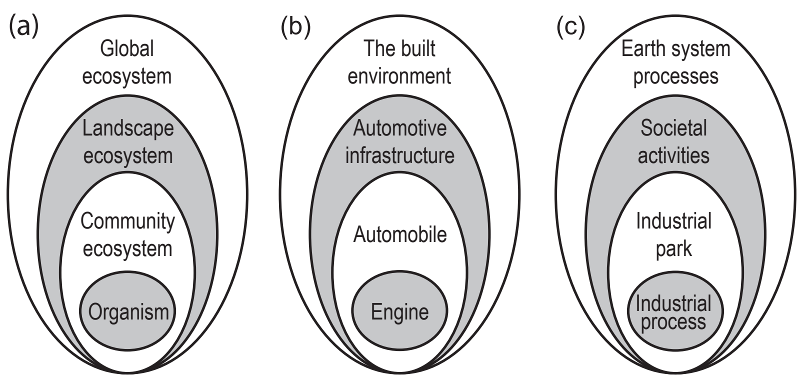

Figure 1.4 Examples of complex systems: (a) classical multilevel natural system; (b) technological system based on stocks of material in use; (c) technological–environmental system based on flows of materials and energy.

The adaptive cycle provides considerable perspective on the interpretation of human–natural systems as they undergo evolution and transition. Consider the industrial ecosystem of Barceloneta, Puerto Rico, described more fully by Ashton (2008). This system underwent a major shock in the 1940s and 1950s, when sugar industry exports declined markedly, as did the use of the land for agriculture. From the mid-1950s through 1970, a shift toward manufacturing-based industry resulted in a rejuvenation of the island's economy and a substantial increase in the island's energy infrastructure, the latter based almost entirely on imported fossil fuels. Over the following twenty years, pharmaceutical industries were added, and the industrial system began to exploit Puerto Rico's limited freshwater resources. Currently (2009), manufacturing is contracting, perhaps signifying the beginning of a new collapse of the cycle. It is clear that this story involves interlocking issues regarding the short- and longer-term sustainability of industry, water, energy, agriculture, land use, social behavior, governmental policy, and environmental implications. It is equally clear that the issues were addressed in isolation, with less than optimal long-term consequences for a number of them.

Aiming at the Right Target

The automotive system, at the center of Figure 1.4, exemplifies many of the challenges of sustainability. Even a cursory evaluation of the automotive system indicates that attention is being focused on the wrong target, thus illustrating the fundamental truth: a strictly technological solution is unlikely to mitigate fully a problem that is culturally influenced. Engineering improvements of the vehicle—its energy use, emissions, recyclability, and so forth, on which much attention has been lavished—have been truly spectacular. Nonetheless, and contrary to the usual understanding, the greatest attention (so far as the system is concerned) should probably be directed to the highest levels: the infrastructure technologies and the social structure. Consider the energy and environmental impacts that result from just two of the major system components required by the use of automobiles. First, construction and maintenance of the "built" infrastructure—the roads and highways, the bridges and tunnels, the garages and parking lots—involve huge environmental impacts. Second, energy required to build and maintain that infrastructure, the natural areas that are perturbed or destroyed in the process, the amount of materials demanded—from aggregate to fill to asphalt—are all required by and are attributable to the automobile culture. In addition, a primary customer for the petroleum sector and its refining, blending, and distribution components—and, therefore, causative agent for much of its environmental impacts—is the automobile. Efforts are being made by a few leading infrastructure and energy production firms to reduce their environmental impacts, but these technological and management advances, desirable as they are, cannot in themselves begin to compensate for the increased demand generated by the cultural patterns of automobile use.

The final and most fundamental effect of the automobile may be in the geographical patterns of population distribution for which it has been a primary impetus. Particularly in lightly populated and highly developed countries, such as Canada and Australia, the automobile has resulted in a diffuse pattern of residential and business development that is otherwise unsustainable. Lack of sufficient population density along potential mass transit corridors makes public transportation uneconomic within many such areas, even where absolute population density would seem to augur otherwise (e.g., in the densely populated suburban New Jersey in the United States). This transportation infrastructure pattern, once established, is highly resistant to change in the short term, if for no other reason than the fact that residences and commercial buildings last for decades.

Integrating Science and Society

Perceptions of sustainability instinctively turn to physical parameters, as is largely the case in this volume. Most of the contributions relate primarily to one or another of four types of resources: land, nonrenewable resources, water, and energy. Among the obvious questions related to each of these is: "Will we have enough?" This question, however, is not solely about supply (a largely physical parameter); it also involves demand (a largely sociological factor).

Demand rears its head most vigorously in urban areas, especially in urban areas that are undergoing rapid development. New cities in China and India are obvious examples, but anticipated advances in wealth and urbanization throughout the developing world will mimic enhanced Chinese and Indian demand. It has been well established that urban residents use higher per-capita levels of many resources of all kinds than do rural dwellers (e.g., van Beers and Graedel 2007; Bloom et al. 2008). Urban people live in smaller dwellings and use energy more efficiently. The spatial compactness renders recycling more efficient and resource reuse more likely. However, cities are also "point sources" of pollution, which often overwhelm the assimilative capacities of adjacent ecosystems.

Whatever the level of demand for resources, it will largely be dictated by the choices made by individuals and influenced by the institutions of which they are a part. In this volume, insufficient attention is paid to these human driving forces, in large part because they are less quantifiable and more difficult to incorporate into the more quantitative views of sustainability. This approach should not be interpreted as lack of relevance of these social science-related topics, but rather that their inclusion is so challenging. Ultimately, the social and physical sciences must become full partners in the study (and perhaps the implementation) of actions related to sustainability. We recognize this challenge, but only hint at how it should be met.

The Utility of an Integrated Understanding

Can modern technology feed a world of nine billion people or thereabouts in 2050? Yes it can, if the agricultural sector is provided with sufficient land, energy, water, advanced technology equipment, and a suitable regulatory structure.

Can sufficient energy be supplied to serve the needs of nine billion people or thereabouts in 2050? Yes it can, if the energy sector is provided with sufficient land, water, advanced technology equipment, and a suitable regulatory structure.

Can sufficient water be supplied to serve the needs of nine billion people or thereabouts in 2050? Yes it can, if the water sector is provided with sufficient energy and advanced technology equipment.

Can the nonrenewable resource sector supply the materials needed by the advanced technology sector in meeting the needs of nine billion people or thereabouts in 2050? Yes it can, if the sector is provided with sufficient land access, energy, water, and a suitable regulatory structure.

Can these important, overlapping needs be addressed in a quantitative, systemic way so as to move the planet in the direction of long-term sustainability? This is the crucial question and focal subject of the chapters that follow.

It is of interest to note that the existence of at least a first attempt at an integrated quantification will provide information that is highly relevant to recent efforts to establish national materials accounts (e.g., NRC 2004; OECD 2004). These accounts, now in existence in a number of countries in a preliminary form, assume a new level of importance when their contents are placed in perspective with the progress needed to achieve or approach sustainability and to consider how they might monitor such progress. In at least a preliminary fashion, we have explored throughout this Forum the linkages among the individual, important components, and we posit in this volume how they might perhaps be optimized as an integrated system. It is one of the major challenges of our existence as a species, and for the sustainability of the planet as we know it. Surely nothing could be more worth exploring.