System Sustainability

Federico M Pulselli, University of Siena, Siena, Italy

Sustainability

Sustainability is a word that is used—sometimes overused—in many fields to indicate many things. Sometimes it refers to the environmental sphere and sometimes it has to do with the human sphere, considering its social, economic, financial and political aspects at macro and micro levels. It is therefore difficult to arrive at a univocal definition of the concept, although a strong scientific basis for it can be found in the literature that has evolved in the last 30–40 years.

Nature is the quintessence of sustainability; a translation of the concept for humans would define a virtuous path for evolution of the human system. Sustainability is important for humans and their actions for many reasons, not least the survival of our species. Learning from nature can enable us to translate its winning strategies into virtuous behavior and avoid mistakes and risks for the future.

The first step to characterize sustainability consists in the identification of its biophysical foundations as necessary condition to limit the elusive aspects of the concept (Pulselli *et al.*, 2008).

Time

If we look at a pianist, we see that he plays a chord by striking keys on the piano. When he removes his hands from the keys, the chord dies. If the pianist presses a special pedal, a mechanism enables the chord to continue to vibrate even after the fingers have been removed. The pedal maintains the notes for a while and its name is "sustain." Time is therefore intrinsic to the meaning of sustainability. Something that exists or survives in time is sustainable. This essence of the term "sustainability" and the adjective "sustainable" is important to avoid misuse. It also characterizes the difference between the expressions "carrying capacity" and "sustainable development" because the verb "to carry" means to hold, contain or support something, whereas "to sustain" means to maintain in time. So if we consider time as a crucial element of sustainability it means that we view the dynamics of ecosystems and human activity not as a simple sequence of changes of state and modifications, but as evolution. This helps clarify which actions are virtuous and which should be avoided in order to maintain a system indefinitely in time.

Biophysical Limits

Nature has been surviving for about 4 billion years, during which time biological evolution proceeded through winning strategies under the inevitable condition of limited resources. Nature diversifies: biodiversity is a strong general attribute for survival. Nature exploits the most abundant and reliable energy source, solar energy, finding ways of using it to feed vital mechanisms. Nature optimizes resources and disposes of wastes and degraded energy (e.g., by closure of cycles and dissipation of heat into space). Nature has not only been successful in surviving in time but also in thriving and flourishing within geobiophysical constraints (Jørgensen *et al.*, 2015). Human activities, which are always fed by resource extraction and consumption and generate flows of degraded energy and matter, should be consistent with the finite and constrained ability of the planet to regenerate resources and absorb wastes.

Relations

Thermodynamics gives us the tools to understand these constraints. For instance, its fundamental laws define the limits to overall availability and our capacity to exploit energy: the law of conservation of energy (first law of thermodynamics) states that energy cannot be created or destroyed, and the law of energy dissipation (second law of thermodynamics) states that every activity or conversion degrades energy to heat which is unable to do work. Biological systems are open systems (they exchange matter and energy with their environment) that involve extremely ordered structures and evolve in the direction of increasing order by processing the flow of energy and resources they capture from the environment. They discharge their wastes as degraded energy (heat) and matter (e.g., emissions, pollutants). A continuous process of transformations, cycles and feedbacks demonstrates the importance of relationships for living systems and the dependence of these systems on the context in which they live. This is valid for a cell, a tree, a human being, an ecosystem, but also for a city, a production process, an urban or regional system. All these systems survive by exploiting flows of energy and matter, releasing wastes, emissions and heat into their surroundings (see, among others, Schrödinger, 1944; Prigogine, 1954; Tiezzi, 2003).

Time, biophysical limits and relations are three cornerstones of the concept of sustainability. A system or project cannot be called sustainable if it does not rest on these foundations: it must be durable, it must develop within the limits imposed by natural

 doi:10.1016/B978-0-12-409548-9.10610-4

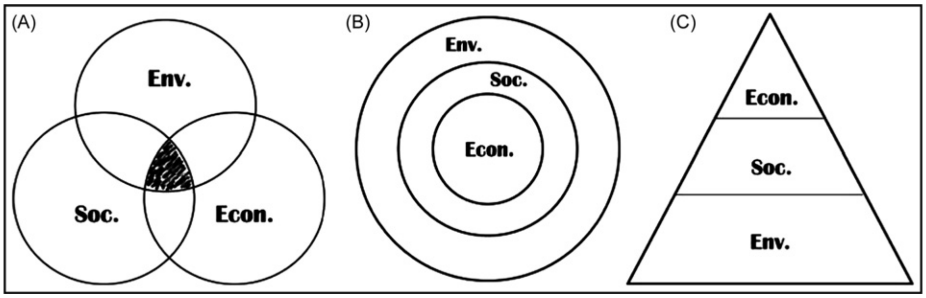

Fig. 1 Representations of sustainability. The usual representation of sustainability shows the *different (A–C)* contributions and interactions between the environmental (Env.), social (Soc.) and economic (Econ.) spheres of human life.

laws (such as the laws of thermodynamics) and it must maintain relationships with other systems and the surrounding environment. Without considering these pillars, the use of the word sustainable is misleading, inappropriate, or even false.

Representing Sustainability

Human development involves three spheres: economic, social and environmental. According to Barbier (1987), sustainable development is defined by simultaneous interaction of the three intersecting spheres. The intersection is where sustainable development can occur, suggesting that converging goals from the different spheres must be achieved together (**Fig. 1**A). This view, however, places the three circles on the same level, and excluding their intersection, it considers the ecological, social and economic elements of sustainability to be interchangeable or substitutable (which amounts to the condition of weak sustainability). An alternative interpretation is that of concentric circles, which implies an environmental basis for the social sphere that contains the economic expression of society (**Fig. 1**B). Another view depicts sustainability as a pyramid, highlighting the relative sizes of the three spheres (**Fig. 1**C). These rather conventional ways of representing the concept of sustainability underline the need for an organic view of human presence and activity on the planet. Study of the relationship between the human species and the Earth system is urgently needed. Researchers have been proposing ideas in this field for several decades, highlighting the risk and consequences of reaching or passing critical points or thresholds. This was one of the aims of the well-known and influential report entitled "The Limits to Growth" (Meadows *et al.*, 1972), which took an organic, comprehensive and global view of the planet.

System Sustainability

The basic concept of system is expressed by the well-known adage of systems science: "the whole is greater than the sum of its parts." This can be explained by the fact that a system, namely "things that stay together," consists of components that cooperate with each other, giving rise to emerging novelties and new properties. For instance, a human being has a body made of 10^{14} cells. Every cell has biochemical, metabolic and anabolic characteristics and properties determined by genetic and environmental conditions but they do not explain the characteristics and properties of the organism as a whole (knowledge, feelings, emotions, pain, etc.). Similarly, an ecosystem is composed of organisms linked in a complex cooperative synergistic relationship that results in properties like adaptation, evolution, self-organization, resistance, flexibility and ultimately beauty (Jørgensen *et al.*, 2015).

According to Jørgensen (2012), "systems with emerging properties cannot be described by listing the components and their properties, but it is necessary to capture, understand and describe the emerging system properties." A fundamental overview of general systems theory was proposed by Von Bertalanffy (1969). Since then many authors have investigated the question which is relevant to our life on the planet and especially sustainability. In a comprehensive survey of the systems approach, Capra (1996) suggested that the essential properties of an organism or living system are properties of the whole system, which no single component has per se. These properties emerge from interactions and relations among the parts of the system. There have been major advances and novelties in many areas of systems science. Ecology, for example, is an area permeated by the systems view. According to Capra, if we consider the world as an integrated system rather than a series of separate components, we take a holistic or even ecological view in keeping with the term "ecological," namely something characterized by relations among its parts and included in a larger context. One fundamental contribution to the advancement of ecology was by Eugene Odum. In a major paper, he emphasized the role of ecology as a discipline that connects and advanced various ideas about the concept of sustainability: "[…] cell level science will contribute very little to the well-being or survival of human civilization if our understanding of supraindividual levels of organization is so inadequate that we can find no solutions to population over-growth, social disorder, pollution, and other forms of societal and environmental cancer. […] It is in the properties of the large-scale, integrated system that hold solutions to most of the long-range problems of society" (Odum, 1977). The paper is actually a precursor of sustainability science because it also traces the link between ecology on the one hand, and social sciences, technology, politics and economics on the other. Jørgensen (2012) subsequently published a textbook on Systems Ecology that deals with thermodynamics- and biochemistry-based foundations, ecological laws, ecosystem properties and ultimately environmental management. He stresses the need for a holistic view to problem solving and touches on the progressive emergence of meta-disciplines, particularly ecological modeling and ecological engineering, that tend to unify different approaches. Another interesting example of adoption of a systems approach can be found in systems chemistry, that is "the study of complex systems, or networks, of molecules [to] investigate how interactions between members propagate through networks allowing complex behavior to emerge" (Nitschke, 2009).

The concept of sustainability can only be considered from a systemic viewpoint. The study of human sustainable development is concerned with relations between the individual and collective expressions of humankind and the multiplicity of contexts in which the human action develops. The context can be physical, environmental, social, economic, political, institutional, urban, legal and so forth. Pulselli *et al.* (2016) derive at least three key points from this: (a) the organic picture of reality (i.e., what should be sustainable?) requires a transdisciplinary approach in order to encompass the many dimensions of the context in which we live; (b) the purpose (i.e., why should we be sustainable?) is to create and maintain the conditions for durably living better and in harmony with nature and other individuals; and (c) the critical assessment of how we can reach these conditions (i.e., how can we be sustainable?) demands new frameworks in which to evaluate progress toward the desired change. Sustainability therefore connotes a system within its context. By adapting a statement from Jørgensen (2012), originally referring to ecosystems, we can say that if we can understand how ecosystems (as well as human systems) work as systems, we will be able to develop an ecosystem (as well as sustainability) theory that can be used to predict the effects on an ecosystem (as well as a human system) of well-defined changes of forcing function.

Various approaches and methodologies have been developed in recent years to implement a systemic view. Regarding system sustainability, attempts have been made to identify, categorize, quantify and manage the relationships between human life and activity and the context(s) in which they develop, with particular emphasis on environmental context.

An important approach is that of ecosystem service (ES) identification and evaluation. Ecosystem services are the portion of ecosystem functions that directly or indirectly contributes to human welfare. Ecosystem functions occur independently of humans, however humans exploit the existence of ecosystems and their dynamics. These services are usually classified in four categories: provisioning services (e.g., food, water, timber, fiber), regulating services (regarding climate, floods, disease, wastes, water quality etc.), cultural services (that provide recreational, esthetic and spiritual benefits) and supporting services (e.g., soil formation, photosynthesis, nutrient cycling) (see MA, 2005, and the corresponding entry in this encyclopedia). The benefits people obtain from these ecological services can be assessed in economic terms, and the results are surprising. As Costanza *et al.* (1997) demonstrated, at global level, nature provides humans with more resources, and more efficiently, than does world economic infrastructure (which is designed to do just that). Assessment of ecosystem services is therefore a way to estimate and express the importance of ecological dynamics for human life and its sustainability.

Sustainability research has always paid great attention to the determination of thresholds. These are measured or estimated levels of an entity or parameter, beyond which conditions may change unexpectedly, unpredictably and/or irreversibly. An important approach to human activity thresholds at global level is the so-called planetary boundaries framework that aims to identify a safe global operating space for the survival and prosperity of humanity (see Rockström *et al.*, 2009, and the corresponding entry in this encyclopedia). The approach measures selected control variables to determine the risk of dangerous consequences for human well-being in nine Earth processes: climate change, biogeochemical flows, biodiversity loss, land system changes, ocean acidification, stratospheric ozone depletion, freshwater use, atmospheric aerosol loading and chemical pollution. Research in this field is demonstrating that the first four processes involve risk factors for humanity. A major aspect of this approach is the concept of the Earth as an integrated system to be considered, preserved and managed as a whole. The approach is also inspiring research in other fields, such as legislation. For example, a multidisciplinary group of researchers are promoting a systemic legal framework applicable to the Earth as a whole, with a set of assessment and regulatory tools that can be condensed into a safe operating space treaty (SOS Treaty). The treaty is proposed as a new global guideline for legal framework researchers because the Earth is still formally an unidentified legal object (Magalhães *et al.*, 2016).

A further system sustainability approach is the so-called food-energy-water nexus. Used in many studies by various organizations (e.g., the Food and Agriculture Organization of the United Nations, FAO), it offers a way to first identify and then solve problems that a large portion of the world population is facing. By combining different fields of investigation and action it confirms the importance of seeing the world in which we live as a set of cooperative interrelated units and systems. In this case, study of the three sectors—food, energy and water—, to which the climatic system is often added, helps us recognize the many links between them and the fact that problems in one may trigger serious crises in the others. The three-sided approach highlights the main conditions for achieving essential tasks, such as poverty reduction, human well-being and sustainable development at global level, that depend on the context in which human development occurs.

The Sustainable Development Goals, promoted by the United Nations in 2015, are an enlargement of this view. Countries adopted these goals "to end poverty, protect the planet, and ensure prosperity for all as part of a new sustainable development agenda. Each goal has specific targets to be achieved by 2030" (for an overview, see UN, 2015). The set of goals is so wide that it offers an encompassing vision of the human condition on the planet. It includes the following 17 items: no poverty, zero hunger, good health and well-being, quality education, gender equality, clean water and sanitation, affordable and clean energy, decent work and economic growth, industry, innovation and infrastructure, reduced inequalities, sustainable cities and communities, responsible consumption and production, climate action, life below water, life on land, peace, justice and strong institutions and

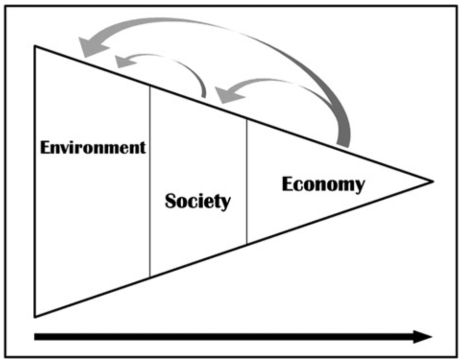

Fig. 2 A less usual representation of sustainability with a more logical/consequential series of stages ordered from left to right.

partnerships for the goals. Again all these aspects are linked and the set works as a system. The challenge is that the purpose of system sustainability is only achieved if the goals are largely achieved together at the same time.

Problems do not observe disciplinary or geographical boundaries but arise almost everywhere, in many ways and with different dimensions and scales. The approaches outlined above can help solve these problems by adopting a systemic view that facilitates understanding of the connections between different components of a given system and identification of emerging properties and problems of the system.

Less Usual Representation of Sustainability and a Possible Interpretative Framework

The scientific community recognizes the environmental, social and economic spheres as components of the concept of sustainability. However, we have seen that they cannot be considered interchangeable.

Fig. 1C shows the relationships between the three spheres of sustainability in the form of a pyramid: the base of the pyramid represents natural assets, crucial inputs into the system; the middle section represents society with its organization and structure, and can be viewed as the state of the system; the point of the pyramid is the real economy that produces the system's output. The pyramid can be considered an evolution of the concentric-circles representation (Fig. 1B) that also combines the environmental, social and economic spheres.

Pulselli *et al.* (2015) proposed a slightly different version of this three-stage approach in order to represent sustainability and facilitate investigation. This less usual representation of sustainability rotates the pyramid 90 degree clockwise to capture the succession of the stages (Fig. 2) from left to right. "A flow of material and energy inputs generated by the available stock of Natural Capital feeds (is captured by) the system. These resources are necessary for the elements of the system (i.e., society and its organizational units) to operate (act, live, survive); the level of organization of the society influences the degree of utility/satisfaction derived from processing/using/consuming resources. An organized society is supposed to be able to achieve better economic results, providing outputs from its productive processes" (Pulselli *et al.*, 2015).

This version of the scheme aims to represent the physical, relational and thermodynamic order (environment-society-economy) of the succession of stages. It offers a more logical/consequential approach to combining and evaluating different indicators, starting from the economy's dependence on societal organization and environmental resources and including feedback produced by the socioeconomic system.

A general systemic approach emerging from this new version of the sustainability scheme could be the Input-State-Output (I-S-O) framework, useful for assessing system sustainability. In Sustainability section, we saw that living biological systems (including human-driven ones like cities and production processes) are fed by a continuous flow of energy and matter that is processed internally (e.g., self-organization) to give useful outputs (in terms of services, feedback flows, products, etc.). These vital evolutionary steps are therefore simplified by this linear but organic scheme (Fig. 3) that also helps select suitable methods and tools for quantifying phenomena. Here different combinations of indicators can be used to count inputs of energy and matter into a system, describe organizational state and quantify outputs. The I-S-O framework orientates the use of well-defined triads of systems indicators representing links between the three spheres of sustainability. This process, consisting of a succession of stages in a series, must be viewed as the integrated way in which the system works. Nevertheless, identifying the three stages makes it possible to select corresponding indicators and compose multidimensional data, often expressed in different units, without losing information. Indeed, the framework can be investigated using a diagram with three axes representing the input, state and output indicators, and the information gained by different indicators is not lost in final aggregations. This framework represents relationships between indicators and helps classify the systems in question in terms of their sustainability.

The choice of indicators is crucial for implementing this method. If we consider the correspondence between the I-S-O scheme and the environmental-social-economic spheres of sustainability, we can use physical measures for input, social indicators for state and economic parameters for output. Thus the triads are composed of groups of indicators/measures representative of each dimension: measures of resource flows (such as ecological footprint, emergy flow, gross emission of CO_2 equivalent, or more

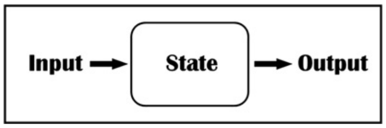

Fig. 3 The Input-State-Output (I-S-O) framework.

generically, energy, matter and pollutant flows) to represent the environmental contribution to the system; measures representative of the state or health of a society or its inequality level (such as employment level or an index of income distribution); economic measures representative of output (such as GDP or value added, or the welfare/happiness of a population).

Each triad gives different information, depending on the indicators chosen. The point representing combination of the three indicator values can be identified in the 3D space enclosed by the three axes. Every system can therefore be identified by a point on the three-axis diagram and its position can be discussed in a static way, determining, for example, the main components that characterize the results obtained (environmental, social or economic), or in a dynamic way, when a time series of indicators is available, signaling development trajectories for that system.

According to the authors, "this application is a rational solution for the study of system sustainability, because it incorporates consistency with traditional sectors proposed in sustainability research and is feasible because it is limited to small number of (already available) data. [The proposal also] maintains the informative capacity of every aspect of system behavior, but it also provides a synthetic picture of the reality. […] This new way of considering these fundamental aspects of our life can be the basis for assessment of long term system sustainability and helps identify the contradictions, hypocrisies, and nonsustainable nature of many of our current behaviors" (Pulselli *et al.*, 2015).

Conclusion

System sustainability designates a condition that characterizes a given system. A system is sustainable if it has durable prospects with respect to constraints and preserves relations. Sustainability is a property of the whole system with all its elements, actors, connections and properties. The concept of sustainability applies especially to human systems, for which a multidimensional/systemic approach makes it possible to consider man-driven systems and actions within their context and limits. Humanity is continuously faced with major problems regarding the health of the planet and ecosystems as life supporting systems, relationships between nations and populations, and ultimately the survival of the species. Improving our capacity to measure/observe the world in which we live and widening the set of investigation tools in this field are urgent tasks. Instruments that enable holistic understanding of the environmental, social and economic view of human life are the most suitable for achieving sustainable systems. In particular, we need investigation and management tools for the environmental and social sphere that complement the primacy of the economic dimension. We have seen that systemic approaches, methods, interpretation proposals and solutions proposed in the last 30 years aim to make the multidimensionality of our world more explicit. To conclude this survey, it is worth mentioning two books which are fundamental references for a systemic view of sustainability. The first is "A prosperous way down" (Odum and Odum, 2001), an innovative contribution that anticipated more modern tendencies like the so-called degrowth movements and the EU Beyond GDP initiative. The importance of the book lies in the fact that it associates relevant aspects of natural and physical phenomena and energy-based dynamics with economic, social, political and demographic problems. The second is "Flourishing within limits to growth. Following nature's way" (Jørgensen *et al.*, 2015): inspired by "Limits to growth" (Meadows *et al.*, 1972), it acknowledges the existence of constraints and limits, but stresses that like ecosystems, human systems must find a way to flourish while observing these limits, seeking wealth but preserving the environment and quality of life.

See also: Human Ecology and Sustainability: Emergy and Sustainability; Ecological Footprint; Ecological Economics 1

References

Barbier, E., 1987. The concept of sustainable economic development. Environmental Conservation 14, 101–110.
Capra, F., 1996. The web of life. New York: Anchor Books.
Costanza, R., d'Arge, R., de Groot, R., *et al.*, 1997. The value of the world's ecosystem services and natural capital. Nature 387, 253–260.
Jørgensen, S.E., 2012. Introduction to systems ecology. Boca Raton, FL: CRC Press, Taylor & Francis Group.
Jørgensen, S.E., Fath, B.D., Nielsen, S.N., *et al.*, 2015. Flourishing within limits to growth. Following nature's way. Florence, KY: Earthscan from Routledge, Taylor & Francis Group.
MA, 2005. Millennium ecosystem assessment. Washington DC: Island Press.
Magalhães, P., Steffen, W., Bosselmann, K., Aragão, A., Soromenho-Marques, V. (Eds.), 2016. SOS treaty. The safe operating space treaty: A new approach to managing our use of the Earth system. Newcastle, UK: Cambridge Scholars Publishing.
Meadows, D.H., Meadows, D.L., Randers, J., Behrens, W.W., 1972. The limits to growth. New York: Universe Books.
Nitschke, J.R., 2009. Systems chemistry: Molecular networks come of age. Nature 462, 736–738.
Odum, E.P., 1977. The emergence of ecology as a new integrative discipline. Science 195, 1289–1293.

Odum, H.T., Odum, E.C., 2001. A prosperous way down. Principles and policies. Boulder, USA: University Press of Colorado.
Prigogine, I., 1954. Introduction to thermodynamics of irreversible processes. Springfield, USA: C.C. Thomas.
Pulselli, F.M., Bastianoni, S., Marchettini, N., Tiezzi, E., 2008. The road to sustainability: GDP and future generations. Southampton, UK: WIT Press.
Pulselli, F.M., Coscieme, L., Neri, L., *et al*., 2015. The world economy in a cube: A more rational structural representation of sustainability. Global Environmental Change 35, 41–51.
Pulselli, F.M., Moreno Pires, S., Galli, A., 2016. The need for an integrated assessment framework to account for humanity's pressure on the earth system. In: Magalhães, P., Steffen, W., Bosselmann, K., Aragão, A., Soromenho-Marques, V. (Eds.), SOS Treaty. The safe operating space treaty: A new approach to managing our use of the Earth system. Newcastle, UK: Cambridge Scholars Publishing.
Rockström, J., Steffen, W., Noone, K., *et al*., 2009. A safe operating space for humanity. Nature 461, 472–475.
Schrödinger, E., 1944. What is life? Cambridge, UK: Cambridge University Press.
Tiezzi, E., 2003. The essence of time. Southampton UK: Wit Press.
UN, 2015. Sustainable development goals. Available at: http://www.un.org/sustainabledevelopment/sustainable-development-goals/
Von Bertalanffy, L., 1969. General system theory. Foundations, development, applications. New York: George Brazillier.