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Sustainability: characteristics and scientific roots

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Abstract Literature about sustainable development is abundant and expanding, and syntheses are therefore increasingly necessary. This paper represents an effort to characterize the main principles behind the concept of sustainability and to identify and describe the scientific approaches at the root of each of those principles. From a scientific point of view, the identification of sustainability principles is possibly more interesting than providing one rigid definition because they are more abstract and conceptual. As a first step, three scientific approaches relevant in the context of sustainability—ecological economics, sustainability transition, and sustainability science—were characterized and synthesized into four sustainability principles. The next step was the identification and description of the scientific approaches at the root of each sustainability principle. All descriptions are based on a literature review. Four sustainability principles were identified: the stressing of biophysical limits that constrain the scale of the human economy; the focus on societal welfare and development; the understanding that each system has its own minimum irreducible needs in order to be viable; and the acknowledgment of system complexity. From an evolutionary perspective, scientific approaches at the root of sustainability progressed from a static view of environmental limits and human impacts to a dynamic and integrative vision of them; from an emphasis on human impacts and availability of natural resources to a more balanced position that puts human and social capital at the center; from a rigid definition of goals to the understanding that the process of transition toward goals is as important as the goals themselves. The four principles of sustainability incorporated in varying degrees a broad range of scientific contributions. Sustainability may, as such, be

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regarded as a step toward consilience, an attempt to bring together scholars from different backgrounds and disciplines in order to create an integrated thesis.

Keywords Sustainable development · Sustainability · Sustainability science · Ecological economics · Scientific development

1 Introduction

The increasing awareness and scale of human impacts on the natural environment have fostered the emergence of the concept of sustainable development. This much debated idea proclaims almost a utopia of a society where human development and nature conservation go hand in hand and no obvious concessions are necessary. Much less has been said, however, about the inevitable tradeoffs between societal development and nature conservation when decisions concerning the allocation of funding and the implementation of policies have to be made.

Brought to international attention by the efforts of the International Union for Conservation of Nature to preserve planetary biodiversity in the eighties, sustainability gained wide popularity after the Brundtland Commission's report "Our Common Future" (World Commission on Environment, Development 1987), whose definition is still the most commonly cited nowadays. Further steps to specify what to sustain and what to develop were made by the United States National Research Council's (NRC) report "Our Common Journey" (National Research Council 1999).

This paper represents an effort to characterize the main principles behind the concept of sustainability and to identify and describe the scientific approaches at the root of each of them. It complements an analysis of the political milestones related to sustainability (Quental et al. 2009). Rather than providing one definition of sustainable development, the preference relied on a more abstract conceptualization of sustainability through the identification of its main traits or principles.

Further methodological details are explained in the next chapter. Chapter 3 describes three scientific approaches accepted as representative of sustainability, as well as four common sustainability principles derived from them. Chapter 4 identifies the scientific approaches at the root of each of these sustainability principles, and Chapter 5 ends up with a discussion about the emergence of sustainability from its root scientific approaches.

2 Methodology

This paper presents several scientific approaches that are relevant to understand the emergence of sustainability as a concept. These approaches vary widely in scope and characteristics. Some of them are long-debated reports that have been acknowledged as fundamental references and sources of paradigm shifts by the scientific community, while others represent disciplines or methodologies embracing core values of sustainability.

As a first step, three scientific approaches accepted as relevant to understand sustainability were characterized. These were ecological economics, sustainability transition, and sustainability science. The analysis of these approaches resulted in the identification of four common sustainability principles that form the backbone of this paper's structure.

The next step was the identification and description of the scientific approaches at the root of each sustainability principle. Like the branches and species in the tree of life, some of the described scientific approaches coexist nowadays and constitute distinct bodies of knowledge.

Throughout the paper, descriptions of scientific approaches are based on a literature review. Most of the papers and books analyzed were identified as highly cited by a bibliometric assessment of the sustainability literature (Quental 2010, unpublished PhD thesis). Nevertheless, as the citation criterion could leave behind important contributions, less cited literature written by renowned authors have also been reviewed when it was strongly linked to the goals of this paper. The bibliometric assessment provided an objective method for literature selection capable of minimizing the degree of subjectivity involved in the process, but the overall choice should be regarded as the ultimate result of careful thought and decision by the authors.

3 Approaches to the concept of sustainability

In order to characterize sustainability, three scientific approaches were accepted as relevant for the purposes of this paper: ecological economics, sustainability transition, and sustainability science. The following sections provide a description of each, and the chapter ends with a set of four common sustainability principles which can be considered the fundamental rationales of the sustainability concept.

3.1 Ecological economics

In reviewing the history of ecological economics, Pearce (2002) traced its origins back to the 50 s when the NGO “Resources for the Future” was established in the United States. Funtowicz (1999) referred to the later eighties, when discontentment with the dominant trends in economics, namely its negligence with respect to ecological constraints, led to the appearance of contesting views. Röpke (2005), in turn, situates the birth of the discipline in 1988, when the International Society for Ecological Economics was established, or in 1989, when the first issue of its journal was published.

Ecological economics has been broadly defined as the science and management of sustainability (Costanza 1991)—even if it is probably too much of an ambition. Ecological economics’ distinctiveness may well be asserted to its scope, which embraces not only the allocation of resources addressed by conventional economics but also distribution of resources and the scale of markets. Together, these issues tackle three fundamental concerns of sustainability: efficiency, justice, and environmental impact (Daly 1996). Ultimately, conventional and ecological economics differ strongly in what Joseph Schumpeter calls the “pre-analytic vision” of the world (Costanza 2003b; Röpke 2005). Whereas the conventional economics considers resources and sinks almost limitless (an “empty world”), ecological economics stresses the limiting quality of natural capital and the impacts resulting from human economy (the “full world”) (Daly 1996; Costanza 2003b; Röpke 2005). Economic scale should consequently be limited by the system’s carrying capacity (Daly 1996).

The treatment given to externalities—impacts on any party not involved in a given economic transaction—is another matter of differentiation. They used to be regarded as “fairly minor and manageable deviations from the optimum” (Pearce 2002), but ecological economists consider externalities a problem of institutional dysfunction in the first place. The problem of the external effects often derives from the insufficiently defined property rights, as Ronald Coase explained in his theorem in 1960. Typical neoclassical mechanisms devised to address this issue—such as the so-called Pigouvian taxes or the tradable pollution permits—are seen as "uncertain" (Pearce 2002). Social welfare, in turn, is understood as a function of several needs or values that must be satisfied independently of each other (Funtowicz 1999). Ecological economists thus regard utilitarian welfare and the choice of discount rates with suspicion.

This brings us to another central issue in ecological economics: the debate about strong or weak sustainability. Conventional economics tends to consider human and built capital largely as substitutes for natural capital, whereas ecological economics emphasizes their complementarity (Goodland 1995; Ayres et al. 1996; Daly 1996; Röpke 2005). Natural capital is seen as a critical resource base, or as an "ultimate mean", on which the whole human ecosystem is dependent (Meadows 1998; Ekins et al. 2003). The destruction of the capital base beyond certain thresholds could result in the collapse of ecosystems and eventually of larger systems. Further development of this idea led to the proposal of the critical natural capital concept, defined as "the natural capital which is responsible for important environmental functions and which cannot be substituted in the provision of these functions by manufactured capital" (Ekins et al. 2003). The level of admitted substitution between natural and man-made capital dictates the strength of sustainability: the stronger it is, the more complementary different forms of capital are considered.

An important application of the ecological economics' principles is that of ecosystem services, i.e., "the conditions and processes through which natural ecosystems, and the species that make them up, sustain and fulfill human life" (Daily 1997). They were extensively studied between 2001 and 2005 by the 1,360 experts involved in the Millennium Ecosystem Assessment (MEA) (see Millennium Ecosystem Assessment 2005 for a synthesis).

As a synthesis, the excellent review of ecological economics' development made by Röpke (2005) is instructive. She summarizes the core beliefs of the discipline as: the idea of the economy embedded in nature and limited in scale by the natural capital sustaining capacity; the need for transdisciplinary work and system thinking in order to correctly analyze socioecological systems; the acknowledgment of uncertainty and ignorance; the concern for how resources and wealth are distributed across society; and the broader set of criteria used in evaluating different development options, which include the intrinsic value of nature (Röpke 2005).

3.2 Sustainability transition

The idea of a transition toward sustainability was consistently argued in a landmark review about sustainable development issued by the Board on Sustainable Development of NRC: "a transition over the early decades of the twenty-first century in which a stabilizing world population comes to meet its needs by moving away from action that degrade the planet's life support systems and living resources, while moving toward those that sustain and restore these systems and resources" (National Research Council 1999, p. 21). In accessing different future scenarios, the Board concluded that such a transition is possible over the next two generations, but "significant advances in basic knowledge, in the social capacity and technological capabilities to utilize it, and in the political will" are required to turn knowledge into action.

The report proposed, in addition, a sustainable development taxonomy arranged into "what is to be sustained" (nature, life support, and community), "for how long", and "what is to be developed" (people, economy, and society) (National Research Council 1999, p. 24). Each of the subitems was further divided into more specific goals, thus strengthening the conceptual foundations of sustainable development and avoiding the usual criticism of an imprecise definition. While this is a significant advance, more challenging questions—about, for instance, how to achieve those goals and what is the precise scale of tolerable human interference on the Earth system—were still left unanswered.

3.3 Sustainability science

The legacy of Francis Bacon and René Descartes translated into great scientific achievements and the beginning of modern science. Scientists split systems into their constituent parts so that interactions between them can be conveniently studied and replicated. This reductionist approach is the basis of the scientific method, but its limitations become apparent when dealing with complex phenomena. Wilson (1998) magnificently verbalized the challenge ahead of science in "Consilience: the unity of knowledge". "Predictive syntheses, the ultimate goal of science, are still in an early stage", he wrote (Wilson 1998, p. 137). How to effectively incorporate information from different disciplines into meaningful theses is of primary importance for sustainable development. It is clear that traditional cause and effect mechanisms do not fit or cannot embrace the complexity of coupled human–environment systems from where the main environmental problems arise.

A new contract between science and society is emerging, and one of its most prominent examples is the 2001 "Amsterdam Declaration", when delegates from more than 100 countries participating in four big international research programs on global environmental change met together (Clark et al. 2004). The resulting research program was named sustainability science and focused on the "dynamic interactions between nature and society, with equal attention to how social change shapes the environment and how environmental change shapes society" (Kates et al. 2001; Clark and Dickson 2003). Other core questions being addressed include as follows: how are long-term trends in environment and development reshaping nature–society interactions in ways relevant to sustainability; what determines the vulnerability or resilience of the nature–society system in particular kinds of places; which systems of incentive structures can most effectively improve social capacity toward more sustainable trajectories; and how can activities of research planning, monitoring, assessment, and decision support be better integrated into systems for adaptive management and societal learning (Kates et al. 2001; Clark et al. 2004).

Sustainability science is considered post-normal, *inter alia*, because of its problem-driven nature, high uncertainty, transdisciplinarity, and openness (Gallopín 2004; Omann 2004). The selection of research priorities is accepted as a societal role and not as a sole responsibility of scientists, since "quality is crucial and refers more to the process than to the product" (Funtowicz 1999, p. 9). Salience, legitimacy, and credibility to the public and particularly to policy makers thus become primary criteria to judge the quality of the research process (e.g., Funtowicz 1999; Cash et al. 2003; Parris and Kates 2003).

International research programs such as the International Geosphere-Biosphere Programme and the International Human Dimensions Programme on Global Environmental Change are already oriented toward a sustainability science approach, which is finding its own way as a distinct scientific field (Kajikawa et al. 2007; Kates et al. 2001). It is worth mentioning the research going on under the Integrated History of People on Earth project. A report summarizing the main human–environment interactions since 10,000 years ago was published by Costanza et al. (2007).

3.4 Common sustainability principles

The approaches presented in the previous sections share many characteristics which could be understood as shaping the core of sustainability. Kidd (1992) already reviewed in the emergence and evolution of sustainability. He described six roots that evolved over time: the ecological/carrying capacity root; the resources/environment root; the biosphere root; the critique of technology root; the no growth/slow growth root; and the eco-development root. Our proposal, however, not only is less concerned with the specific goals of sustainability but also incorporates novel contributions stemming for instance from system's complexity and uncertainty. Four main sustainability principles were identified:

- the limits principle: the human economy is embedded within the ecosphere. As such, the sustainability depends on ensuring that the scale of the human economy is low enough to allow the maintenance of healthy life support systems;
- the means and ends principle: natural resources and economy have an instrumental value in fulfilling the ultimate ends of society. Economic growth is not understood as an end in itself but an instrument that can help achieving higher-order ends such as human well-being and freedom;
- the needs principle: each system, and every human being, has its own minimum needs in order to be viable. These irreducible needs must be satisfied independently and cannot be aggregated;
- the complexity principle: systems exhibit complex behavior, namely through multiple stable equilibria and non-linear behavior, and may even collapse when thresholds are reached.

Keywords from each approach presented in the previous sections were matched to the four sustainability principles as shown in Table 1. In the next chapter, the scientific roots of each of these principles will be sought and described.

4 The scientific roots of sustainability principles

The four principles identified in the previous chapter can be understood as the backbone of current scientific understanding regarding sustainability. In this chapter, the roots of these principles are sought. A variety of scientific approaches are thus described which account for the emergence of sustainability.

4.1 The limits principle

The limits principle recognizes the existence of a set of boundaries representing the dynamic biophysical space of the Earth system within which humanity has evolved and thrived (Rockström et al. 2009). It is accepted *a priori* that the human economy is embedded within the ecosphere and that avoiding the cross of ecosystem thresholds is essential to ensure a sustainable path. Four approaches to this principle are described in this section: Paul Ehrlich's "Population bomb" (Ehrlich 1968); Garret Hardin's "Tragedy of the commons"; thermodynamics; and Club of Rome's "Limits to growth" (Meadows et al. 1972).

Table 1 The four key principles derived from sustainability approaches

Approach	Motto	The limits principle	The means and ends principle	The needs principle	The complexity principle
Ecological economics (1990s–)	The transdisciplinary research about the interactions between human economies and natural ecosystems	Scale Natural capital	Ecosystem services Manufactured capital Human capital Social capital	Institutional capital Incommensurability Equity Efficiency	
Sustainability transition (1999–)	A transition over the early decades of the twenty-first century in which a stabilizing world population comes to meet its needs by moving away from action that degrade the planet's life support systems and living resources, while moving toward those that sustain and restore these systems and resources	To be sustained (nature, life support)	To be developed (economy)	To be sustained (community) To be developed (people, society)	Transition
Sustainability science (2001–)	The dynamic interaction between nature and society, with equal attention to how social change shapes the environment and how environmental change shapes society	Vulnerability	Social learning	Institutions Decision making	Monitoring Transition Resilience

4.1.1 Paul Ehrlich's "population bomb"

The idea of limited planetary resources appeared at least in 1966, when the British economist Kenneth Boulding published "The economics of the coming spaceship Earth". Only 2 years later, American biologist Paul Ehrlich published his most famous and polemic work. In "The population bomb", Ehrlich presented a neo-Malthusian theory claiming that during "the seventies and eighties hundreds of millions of people will starve to death in spite of any crash programs embarked upon now" and assuring that "the battle to feed all of humanity is over" (Ehrlich 1968). These predictions proved to be wrong and have been severely criticized since the book's publication (Selin and Linnér 2005), but they raised awareness to the issue of population growth and to the scarcity of resources available to feed it. Ehrlich failed to take into account the significant increase in agriculture productivity brought about by the green revolution, even if famine and undernourishment are still commonplace nowadays in the developing world.

4.1.2 Garret Hardin's "tragedy of the commons"

In the same year of 1968, Garret Hardin published one of the most cited articles in the sustainable development literature. The "tragedy of the commons" is a metaphor symbolizing the institutional failure of how to manage open access resources such as the atmosphere. The lack of well-defined property rights results in the absence of successful management systems and of enforcement mechanisms, encouraging each agent (farmer, fisher, polluter, etc.) to free ride the resource, eventually leading to its overexploitation.

4.1.3 Thermodynamics

Sustainability thinking has been strongly influenced by thermodynamic concepts, in particular the entropy law. The work of the Romanian economist Nicholas Georgescu-Roegen, namely "The Entropy Law and the Economic Process" (1971), is frequently credited as a source of inspiration and deep thought about the physical conditions that effectively limit the scale of human enterprise (Hammond 2004). Literature about the energetic and thermodynamic implications on a system's viability is vast and complex, but its main implications may be summarized as follows. On a first step, the quality and amount of available energy ("exergy", which can be understood as the opposite of "entropy") constrains the level of complexity attainable by a system according to the maximum empower principle (Falkowski and Tchernov 2004; Odum and Odum 2006) and, hence, its capacity to maintain non-equilibrium dynamics with its environment. That is the case of urban systems, which are considered self-organizing dissipative structures that are dependent on large amounts of high-quality energy coming from the exterior. On the other side, some authors have argued that exergy degradation is inversely correlated with economic efficiency and thus could serve as an indicator of environmental sustainability (Hammond 2004). Odum and Odum (2006) even analyzed the implications to society of several thermodynamic principles, concluding that a "prosperous way down" is necessary if civilization is to progress. Nevertheless, Hammond (2004) argued that relying on thermodynamics for sustainability assessment is an approach grounded in the domain of the metaphor rather than in science. Thermodynamic constrains had a significant influence on ecological economics (Pearce 2002) and, particularly, on the development of the Natural Step conditions in 1989, which constitute a possible way, even if ambiguous, to operationalize sustainability. Four system conditions were first devised by Daly (1990) and later improved by Robèrt et al. (1997): substances from the lithosphere must not systematically increase in the ecosphere; substances produced by society must not systematically increase in the ecosphere; the physical basis for the productivity and diversity of Nature must not be systematically deteriorated; fair and efficient use of resources with respect to meeting human needs.

4.1.4 Club of Rome's "limits to growth"

"Limits to growth", the report prepared by Donella and Dennis Meadows in 1972 for the Club of Rome (a global think tank dealing with international political issues), called the attention of the world to the biophysical limits imposed on economic growth. In examining future scenarios for five variables—technology, population, nutrition, natural resources, and environment—Meadows et al. (1972) claimed that "if the present growth trends in world population, industrialization, pollution, food production, and resource depletion continue unchanged, the limits to growth on this planet will be reached sometime within the next 100 years." Based on the prediction model World3, the authors added that sustainability was still possible to achieve if the population and economical growth ceased (United Nations Environment Programme 2002). The implications of this discourse were far reaching since it challenged basic human assumptions about unrestrained growth (Goodland 1995). As such, the criticisms from opponents were severe and often misinformed. Meadows (2007), in a recent review of his team's work, reaffirmed the main conclusions of "Limits to Growth" and its subsequent updates ("Beyond the Limits" and "Limits to Growth: the 30-year update"). The important conclusion is not about the prediction accuracy, but that humanity faces a problem of growth where resources are limited and thus actions are needed in order to avoid collapse.

4.2 The means and ends principle

The means and ends principle holds that capital and economy should be regarded as instrumental in fulfilling higher-order ends of society, such as human well-being, and not as ends in themselves. In this section, two approaches related to the means and ends principles are described: steady-state economics and Meadows' sustainability pyramid.

4.2.1 Steady-state economics

Contrasting with the conventional economic theories that emphasize throughput growth and considering only labor and man-made capital as limiting production factors, former World Bank economist Herman Daly presented the idea of a steady-state economy (Daly 1973). Building on John Stuart Mill's proposals formulated back in the XIX century and influenced by the thermodynamic constraints described by Georgescu-Roegen (Pearce 2002), Daly struggled for an economic development within Earth's carrying capacity or, as he put it later on, "development without growth" (Daly 1996, p. 69). Growth should be understood as an increase in throughput holding production efficiency constant and development as an increase in services obtained from both higher production efficiency (stock per unit of throughput ratio) and effectiveness (service per unit of stock ratio) holding throughput constant. The very notion of "externalities" was criticized by Daly, who argued that fundamental issues such as the maintenance of life-supporting systems cannot be conveniently addressed as a lateral issue in economics. Since the sources of social welfare are the capital assets of an economy, they must not be depreciated through time. But that is exactly what is happening with the natural capital, rendering it the limiting production factor in the economy. Thus, Daly concluded sustainable development is only possible in a steady-state economy whose scale is sufficiently small so as to allow the proper function of Earth's ecosystems (Daly 1996).

4.2.2 Meadows' sustainability pyramid

In his already cited work, Daly (1973) proposed a simple conceptual framework for sustainability indicators. The pyramid, later improved by Meadows (1998), draws attention to the main socioeconomic components and processes essential to ensure a system's viability. The hierarchical structure portrays a grading from (a) ultimate means at the base (natural capital, or the resources out of which all life and all economic transactions are built and sustained), followed by (b) intermediate means (human and built capital, which define the productive capacity of the economy), then by (c) intermediate ends (human and social capital, or the goals that economies are expected to deliver, such as consumer goods, health, knowledge, leisure, communication and transportation), eventually leading to society's (d) ultimate ends (the *summum bonum* of society: happiness, identity, freedom, fulfillment, etc.).

4.3 The needs principle

The needs principle contends that irreducible system's needs must be satisfied independently and that their aggregation into single measures or units is therefore incorrect. Four approaches are described in this section: Brundtland's report "Our common future" (World Commission on Environment, Development 1987); incommensurable needs; and Sen's "Development as freedom" (Sen 1999).

4.3.1 Brundtland's report "our common future"

The World Commission on Environment and Development (WCED) was set up by the General Assembly of the UN in 1982 as an "independent" group of high-level experts and government officials chaired by the then-Prime Minister of Norway Gro Harlem Brundtland. The commission was asked to formulate a "global agenda for change" and, more specifically, to "propose long-term environmental strategies for achieving sustainable development by the year 2000 and beyond" (World Commission on Environment, Development 1987). The report "Our Common Future", released in 1987 after 3 years of public hearings, is the most cited document in the sustainable development literature (Quental 2010, unpublished PhD thesis). Being able to reconcile the environmental interests of the North with the development needs of the South, the commission effectively joined the world through the catchphrase "sustainable development". The concept, defined as "meeting the needs of the present generation without compromising the ability of future generations to meet their own needs", although stated with a similar meaning as far back as 1979 (as can be checked through a search in Mitchell 2008), became popular only after Brundtland's work (Selin and Linnér 2005). The report explored the factors behind the growing equity gap between the rich and the poor and issued guidance so that sustainable development could be integrated into countries' policies. These ranged from asking for more growth, conserve and enhance the resource base, ensure a sustainable level of population, reorient technology, integrate environmental concerns into decision making, and strengthen international cooperation (World Commission on Environment, Development 1987).

Some of the commission's statements were rather controversial. For instance, the appeal for a sustainable economic growth is at odds, according to Daly (1996), with sustainable development. However, it is important to bear in mind the procedural and political contexts under which the report was prepared, which probably prevented the commission from refining all discrepancies and lead to what Kirkby et al. (1999, p. 9) called "irreconcilable positions". Or it may be that the commission truly believed that the growth limits were only technical, cultural, and social (Kirkby et al. 1999), dismissing the biophysical limits that nowadays seem very present. Brundtland's original call for a "five to tenfold more growth" was rectified and reversed in 1992 by placing population higher on the agenda of sustainability (Goodland 1995, p. 9).

4.3.2 Incommensurable needs

A long debate has been going on regarding how to improve quality of decision-making processes. Several authors argue for a broader set of criteria instead of aggregating different categories into an often misleading single unit (Finco and Nijkamp 2001; Costanza 2003a). There are two main issues at stake: first, the substantial question of whether different criteria (namely, nature conservation and economic prosperity) should, in principle, be aggregated; second, when such aggregation is accepted on ethical or practical grounds, the question of how to carry out a scientifically sound process follows. The latter has been called the "commensurability problem" (Bohringer and Jochem 2007). The influence of social scientists, such as Abraham Maslow and, more recently, Manfred Max-Neef, has swept through the ecological economics and planning fields. They stressed the irreducible character of human needs that an organism requires to thrive (Funtowicz 1999; Lambin 2004). Bossel (1999) has further extended the concept to formulate what he called the "basic orientators" of all systems. Likewise human needs, these orientators (existence, effectiveness, freedom of action, security, adaptability, coexistence) must be satisfied in some extent for a system to be viable, but no clues are given as to draw the borderline between sustainability and unsustainability. Because orientators guide system's response to environmental properties, Bossel reasoned they also act as evolutionary forces. The second question—of how to correctly aggregate different criteria into a single unit—is a promising methodological research field. Aggregated environmental indices are being devised and improved by scientists in spite of the inherent difficulties of such a process and the serious doubts about exactly such indices measure (Parris and Kates 2003). Valuation tools used in multi-criteria and cost-benefit analyses are making progresses in calculating a good's total economic value, which comprises both use and non-use values seldom valued by existing markets. Indices such as the ecological footprint or the human development index use different aggregation methods. This aggregation controversy should not be separated from the conflict between model complexity and measuring capacity. One may have to be compromised in favor of the other. Ultimately, the decision about whether to aggregate depends on the desired goal. Decisions concerning projects with significant impacts should in principle be based on more complex multi-criteria analyses with limited and precisely explained aggregations, so as to capture a more faithful picture of the reality (Funtowicz 1999; Costanza 2003a), instead of relying on narrowly defined and utilitarian views of social welfare such as the aggregate economic growth (Daly 1996; Dasgupta 2001; Pearce 2002; Sneddon et al. 2006). The concept of human needs was somehow replaced by the modern ideology emphasizing human rights (Redclift 2006) and corresponding human values. Freedom, equality, solidarity, tolerance, respect, and shared responsibility were identified by the United Nations Millennium Declaration as the essential values governing international relations in the twenty-first century, but the gap between those values, attitudes, and behaviors needs to be bridged for a sustainability transition to occur (Leiserowitz et al. 2006).

4.3.3 Sen's "development as freedom"

Indian economist and Nobel prize winner Amartya Sen built a robust approach to development economics, reclaiming its original significance of improving people's welfare and stressing its role as a process of expanding people's substantive freedoms. "Development as freedom" (Sen 1999) was built on hundreds of studies covering a multitude of sectors—many of them portraying Indian and Asiatic realities—to provide a deep argument about the foundations of society's progress and development. Adam Smith and other "fathers" of modern economics were repeatedly cited, often to correct commonplace but misleading ideas about them. Several phenomena, such as the Bengal famine of 1943 and the decline in fertility rates, were explained through a combination of social and economic data—a method that is increasingly used to explain complex system behavior, instead of simple cause and effect mechanisms (Costanza et al. 2007). Sen's *capability approach* shed new light on the process of development, which was conceptualized as an expansion of individual capabilities and social opportunities and not as an increase in consumption, health, and education alone. In addition, Sen argued against the existence of a universal list of capabilities that should be promoted. Instead, priorities are value judgments that should be made explicitly and in many cases by a process of public debate (Alkire 2002). An important lesson for the sustainability debate should be derived from Sen's argument: that development issues, too often left on a secondary place, are at the center of sustainable development.

4.4 The complexity and transition principle

The complexity principle asserts that socioecological systems are complex as they can have multiple stable equilibria, are usually strongly interconnected, present non-linear behavior, or collapse when thresholds are reached. This requires scientists to acknowledge a basic ignorance and uncertainty about those systems under research. It is also under the complexity principle that the process of transition becomes sometimes as important as the nature of that change. Two scientific approaches are described: complex social–ecological systems and panarchy, adaptive cycles and resilience.

4.4.1 Complex social–ecological systems

Human ecology approaches were introduced in the 1920s and 1930s in order to study the interactions between society and the environment (Machlis and Force 1997). With the advent of the "great acceleration" (Hibbard et al. 2007) or the "anthropocene" (Crutzen 2002), most environmental problems could only be understood as a result of the interplay between human driving forces and ecosystem dynamics (Gallopín 2002; Scheffer et al. 2002). Social–ecological models combine information from several disciplines and therefore are, in principle, better suited to account for system changes. A number of such frameworks have been proposed (e.g., Machlis and Force 1997; Pickett et al. 1997; Alberti et al. 2003; Piracha and Marcotullio 2003; Haberl et al. 2004; Hjorth and Bagheri 2006;

Ostrom et al. 2007; Young et al. 2007), but their application remains object of research. Elinor Ostrom is a notable example: her long-lasting studies about the governance of public goods integrate social and natural sciences into powerful interpretations (see, for instance, Ostrom and Nagendra 2006). Another promising use of a combined social and ecological analysis is that of the syndrome approach: narratives of "archetypical non-sustainable patterns of civilization–nature interactions" (de Vries 2007). The syndrome approach is a response to the difficulties posed by the complex nature of the systems being studied. Instead of relying on simple cause–effect mechanisms, patterns of interactions between important variables are preferred which account for system's multiple states, self-organization, non-linearities, and eventually collapses (International Council for Science [ICSU] 2002; Millennium Ecosystem Assessment [MEA] 2005; Costanza et al. 2007).

4.4.2 Panarchy, adaptive cycles and resilience

A dynamic view of sustainable development was provided by Gunderson and Holling's (2002) theory of panarchy. Refurbishing and elegantly merging existing theories in the fields of ecology and sociology, the theory of panarchy rests on the concepts of resilience, connectedness, and potential to explain the cyclical patterns of a complex system's evolution. A panarchy thus consists of a nested set of adaptive cycles, each undergoing its own evolution through four different phases: long periods of slow accumulation and transformation of resources (from exploitation to conservation) and faster periods that create opportunities for innovation (from release to reorganization) (Holling 2001). One of the interesting traits of this theory is its ability to address the relationships between geographical and temporal scales or how "slower and larger levels set the conditions within which faster and smaller ones function" (Holling 2001, p. 397). The whole panarchy promotes a system's sustainability and development: sustainability because it enhances, tests, and maintains its adaptive capability and development because it fosters the emergence of new opportunities that may prove essential for its survival. Holling (2001) argued that the term "sustainable development" therefore is not an oxymoron, since the combination of the two properties shapes a "logical partnership". Learning and adaptive capacity play a central role in the theory of panarchy and are stressed by several scholars as fundamental conditions needed for a sustainability transition (Bossel 2000; ICSU 2002; Holling et al. 2002; Kates and Parris 2003; Clark et al. 2004; Lambin 2004; MEA 2005; Hjorth and Bagheri 2006).

5 Discussion and conclusions

Sustainability was characterized in Chapter 3 by four key principles: the limits principle, the means and ends principle, the needs principle, and the complexity principle. The scientific approaches at the root of each of these principles were described in the previous chapter. It is important now to understand how all approaches fit into a dynamic evolution from disciplinary or partial approaches into the more integrated and holistic vision provided by sustainability.

A first distinctive principle of sustainability is the stressing of biophysical and thermodynamical limits. Ecological economics is built around a pre-analytic vision that considers the human economy as embedded in the ecosphere. As such, sustainability considers that the scale of the human economy must not exceed environment's carrying capacity. This line of reasoning was introduced by Boulding, Georgescu-Roegen, and Daly. Natural capital becomes a limiting production factor which only partially may be replaced by increased human or built capital. The fraction of natural capital that is not substitutable by other kinds of capital is considered critical for the functioning of the Earth system and therefore must be preserved.

A second principle is that sustainability is oriented toward societal welfare and development. Sen, for instance, is very much in tune with the spirit of ecological economics, in the sense that he dismisses the neoliberal approach stressing growth as a goal in itself in favor of a more balanced model of development. Daly and Meadows suggested a hierarchy where resources have an instrumental value in attaining ultimate ends, similarly to Sen's distinction between determinants and constituents of well-being. While efficiently communicating the strong sustainability approach endorsed by ecological economics, the hierarchy is lacking some of the dynamics, process orientation, and scale dependence referred by contemporary literature. It highlights, however, the substantive character of sustainable development: at a broad scale, according to National Research Council (1999), sustainability aims at maintaining nature, life support systems, and the community and at developing people, society, and economy; at the individual scale, freedom, equality, solidarity, tolerance, respect, and shared responsibility were identified by the Millennium Declaration as the core values of sustainable development. A different vision of development is offered by Sen. He puts the emphasis on the expansion of human capabilities such as political liberties, social opportunities, security, wealth, and transparency, recovering its classical definition.

The third principle of sustainability identified in this paper is the understanding that each system, and particularly every human being, has its own minimum needs in order to be viable. No compensation between different needs is possible beyond this critical point (e.g., money serves of no compensation for a serious health problem). This holistic vision has several consequences. At the individual level, the irreducible human needs identified by Maslow and Max-Neef are worth mentioning (Alkire 2002). At an intermediate level, for instance, when a project is devised, sustainability argues that evaluation must be made against a broad set of criteria and that it is not correct to aggregate them into a single measure. This requires appropriate evaluation methodologies such as multi-criteria analysis—contrary to cost-benefit analysis, which attempts to reduce all criteria into a monetary unit. At a macro scale, the vision translates into the strong sustainability approach advocated by ecological economics: human or built capital cannot fully replace natural capital. At an even broader scale, the implications reach the research process itself: sustainability science is intrinsically multi-disciplinary, process oriented, and guided by the rules of legitimacy, saliency, and credibility.

Powerful insights and concepts imported from ecosystem dynamics by Holling and colleagues comprise the fourth sustainability principle identified: that systems exhibit complex behavior which is difficult to model or predict accurately. This complexity arises from the numerous system components and variables, whose interconnections can become a real challenge for scientists. Complexity can assume a variety of forms: e.g., systems can have multiple stable equilibria, modify according to non-linear equations, or change abruptly near a threshold to adopt a new unpredictable state or even to collapse. The meta-theory of panarchy portrays this complex system dynamics through a nested set of adaptive cycles that span across several scales. Each adaptive cycle evolves through four different stages (exploitation, conservation, release, and reorganization), which correspond to the different combinations of three main system variables: resilience, potential, and connectedness. In spite of the dynamic and comprehensive view transmitted by the theory of panarchy, one may question if only three variables are enough to conveniently illustrate a

Table 2 Comparison of mottos and values as expressed by major scientific approaches to sustainable development

Approach	Motto	Sustaining natural capital and life support systems	Minimizing human impacts	Developing human and social capital	Developing economy and institutions	Integrative efforts
The limits principle						
“The population bomb” (1968)	Exponential population growth cannot continue because natural resources are in limited supply	Natural resources	Population growth	Affluence	Technology	
“The tragedy of the commons” (1968)	Common pool resources must be effectively managed in order to avoid their free ride	Common pool resources	Carrying capacity		Property rights Institutional regime	
Thermodynamics (1970s–)	The sustainability and level of complexity that a system can attain depends on the availability of exergy	Exergy	Entropy			
“The limits to growth” (1972)	The limits to growth will be reached if the growth trends in population, industrialization, pollution, food production and resource consumption persist	Natural resources environment	Population growth	Nutrition	Technology Industrialization	
The means and ends principle						
Steady state economics (1970s–)	Development must be based on a higher economic efficiency and effectiveness so that economic scale can be kept constant and the level of natural assets is maintained	Stocks (capital assets)	Throughput	Well-being	Services Efficiency Effectiveness	
Sustainability pyramid (1973 and 1998)	A call to expand the economic calculus to include the top (development) and the bottom (sustainability) of the pyramid	Ultimate means (natural capital)		Intermediate means (human and built) Ultimate ends (happiness, identity, freedom, fulfillment)	Intermediate ends (human and social capital)	
“Development as freedom” (2001)	Development is enhancing freedom through the expansion of political liberties, economic capacities, social opportunities, transparency, and security			Social opportunities Security Political liberties	Economic capacities transparency	

Table 2 continued

Approach	Motto	Sustaining natural capital and life support systems	Minimizing human impacts	Developing human and social capital	Developing economy and institutions	Integrative efforts
The needs principle						
“Our common future” (1987)	Sustainable development is the development that meets the needs of the present generation without compromising the ability of future generations to meet their own needs	Resources	Population growth	Meet basic needs Equity	Growth and quality of growth Technology Decision making International cooperation	Risk
Incommensurable needs (1990s–)	A system, in order to be sustainable, must satisfy each of its irreducible needs beyond a certain threshold. Likewise, the development of society has multiple goals that cannot be aggregated into one dimension			Irreducible needs	Multi-criteria decision making	Adaptability
The complexity principle						
Complex social–ecological systems (1990s–)	Understanding the complex and non-linear patterns of interactions between society and nature	Resource system		Human system	Norms and institutions	Non-linearities Self-organization Complexity Interactions
Panarchy, adaptive cycles and resilience (2001–)	Sustainable development is the goal of fostering adaptive capabilities while simultaneously creating opportunities					Resilience potential Connectedness

system's behavior or if they are too much of a simplification, let alone the measurement difficulties they pose. It is also excessively process oriented, disregarding that sustainability is also about desired goals. A number of implications stemming from complexity theory were actively endorsed by sustainability science: the acceptance of basic ignorance in understanding nature and its connections with human economy, and its incorporation in models; the need for transdisciplinary work in order to transcend the limitations of sectarian or piecemeal approaches; the focus on a transition to sustainability, or a move toward this goal instead of regarding it as a fixed end state; and the development of new concepts, such as that of resilience, capable of conveying a more dynamic and accurate idea of carrying capacity that links environment and human society.

As a synthesis, a definition and keywords describing each of the approaches at the root of sustainability are given in Table 2. For organizational purposes, the table is divided into a framework of five essential sustainability goals identified by Quental et al. (2009): sustaining natural capital and life support systems; minimizing human impacts; developing human and social capital; developing economy and institutions; and integrative efforts.

Some of scientific approaches at the root of sustainability coexist today and constitute distinct bodies of knowledge. It is not the case, therefore, that recent approaches substitute older ones in a simplistic manner. Instead, a continuous and complex evolution takes place: some approaches may become obsolete, some may persist, and others may extend their influence through other novel contributions which they help to give rise. In the case of sustainability, there is a perceptible evolution among its root scientific approaches which can be summarized as follows:

- From a static view of environmental limits and human impacts, scientific approaches progressed to a more dynamic and integrative vision of them. Carrying capacity became an attribute of the coupled socioecological systems and not of the ecosystems *per se*. Far from static, carrying capacity can be increased through better technology or more efficient management and institutional regimes. Specific concepts such as risk, resilience, and vulnerability have been proposed to convey this rationale;
- Goals shifted from a concern with the human impacts and availability of natural resources to a more balanced position that puts human and social capital—particularly freedom—at the center of them. At the same time, the process of transition toward those goals became as important as the goals themselves. For sustainability science, for instance, the definition of research priorities is also a task for policy makers and not only for scientists. To be fruitful, the research process must respect the rules of saliency, credibility, and legitimacy.

We argue that the four principles of sustainability—as understood from the characteristics of ecological economics, sustainability transition and sustainability science—incorporated in varying degrees a broad range of scientific contributions. Sustainability may, as such, be regarded as a step toward consilience, an attempt to bring together scholars from different backgrounds and disciplines in order to create an integrated thesis. Whether this thesis is coherent and helpful in researching and finding solutions to the sustainability crisis, it is still to be seen.

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