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SCIENCE AND TECHNOLOGY, SUSTAINABILITY AND SUSTAINABLE DEVELOPMENT

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INTRODUCTION

The present document represents an attempt to develop a coherent, systemic framework to analyze the challenge posed to science and technology (S&T) by the quest of sustainable development.

This is intended to help the identification of issues and problems of particular relevance to the region, and to help define science and technology priorities, at a later phase.

The document begins by presenting a basic notion of sustainability in systems terms, moving thereafter to the issue of polar conceptions of the relationship between society and nature and to the concept of sustainable development, differentiated from that of sustainability.

A general conceptual model highlighting the distinction between the concepts of development, underdevelopment and maldevelopment and their relation with sustainability is presented, and used to discuss the different paths available for developing and developed countries.

Having set the conceptual basis related to the issue of development, the discussion moves to analyze the new world situation in terms of complexity, connectedness and uncertainty, and the challenges posed to scientific research and priority setting.

A set of core epistemological issues requiring change to cope with the S&T challenges posed by the search for sustainable development are identified and briefly discussed, and a preliminary set of conclusions is presented.

A. A BASIC NOTION OF SUSTAINABILITY

The concept of sustainability is a complex one; however, it is possible to distil some of its most basic and general characteristics by adopting a systemic approach.

For the present purposes, a system is simply defined as a set of interrelated elements (or subsystems). The elements can be molecules, organisms, machines or their parts, social entities, or even abstract concepts. The interrelations, interlinkages, or "couplings"[1] between the elements may also have very different manifestations (economic transactions, flows of matter or energy, causal linkages, etc.).

[1] In abstract terms, the elements and the relation between the elements defines a system. The term "relation" is used here broadly to include also similar terms such as "constraint", "structure", "organization", "cohesion", "interaction", "interconnection", “correlation", "pattern".

All physically existent systems are *open*, having exchanges of energy, matter and information with their environment that are significant for their functioning.[2]

Therefore, what the system "does", its behaviour, depends not only on the system itself, but also on the factors, elements or variables coming from the environment of the system and impinging on it (the "input variables").

Thus, the state of the system (the set of values adopted by all the variables of the system) at a given time, will be determined by the previous state of the system and by the inputs received by the system in the last period of time.

This can be represented, for notational (Gallopín, 1996) simplicity (the same reasoning applies for continuous systems), the classical definition of a (finite) state–determined general system (Gill 1969):

$$\begin{cases} S_{t+1} = \mathsf{F}\ (S_t, I_t) \\ O_{t+1} = \mathsf{G}\ (S_t, I_t) \end{cases}$$

where **S** is the state of the system, **I** is the input vector (the list of all input variables) to the system, **O** is the output vector from the system, and **F** and **G** are functions. The subindex **t** stands for time. The output variables are those considered of interest for the performance of the system; some (or all) of them may be state variables. In the general case, all the variables may vary over time, space and population. The pair of equations above defines the *behaviour* of the system.

Sustainability can be defined in elementary terms (more sophisticated definitions are possible, such as using the integral of the outputs through time) by:

$$\mathsf{V}\ (O_{t+1}) \geq \mathsf{V}\ (O_t)$$

where **V** is a valuation function of the outputs of the system (i.e., a sustainable system is a system for which the net "worth" —not necessarily in economic terms— of the output produced is non–decreasing in time).

Sometimes we are interested in the *sustainability of the system itself* (e.g., a natural ecosystem); in this case, the output variables are the same as the state variables. When the output variables are different from the state variables, we are referring to the *sustainability of the output(s) of the system* (e.g. agricultural yield of an agroecosystem), not necessarily to the sustainability of the system.

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[2] Systems open to energy but closed to exchanges of matter are sometimes called *isolated*, but this distinction is not fundamental here.

When referring to the sustainability of a system it should be made clear which type of sustainability is being considered.

Sometimes, we want to sustain part of the output but change the system.[3] Sustainable development implies change; sometimes we want to develop the system, sometimes we want to change the system to improve some of its outputs. Of course, this is directly related to how we define the system. For instance, one could conceive of different "phases of development" as either representing different systems, or different states of the same evolving system.

B. SUSTAINABILITY OF WHAT?

The precedent discussion helps to clarify some of the underlying differences in the debates on sustainability and sustainable development. Those who will only pay attention to the sustainability of the social, or socio-economic system, and those who will privilege only the sustainability of Nature represent the poles. The alternative views can be characterized, in a simplified way, as follows:

Sustainability of the human system only. This position, taken to the extreme, could result in an artificial planet if total substitutability of natural resources and services is possible. The classical economicist view, for instance, regards the economy as the relevant system, and relegates nature to a role of provider of natural resources and a sink for the wastes produced by human activities. This is consistent with the notion of "weak sustainability" (Pearce, 1993). The weak sustainability approach asserts that the different forms of capital can substitute for one another to some degree. The substitutability of different types of capital implies that the preservation of an aggregate level of capital, rather than the preservation of natural capital in particular, is crucial. The sustainability of ecological systems is viewed as important only as far as required for the sustainability of the human component. But there is too much we do not know (in this situation the *precautionary principle* is called for). There is also the issue of desirability: would we like to live in an artificial planet? (Figure 1).

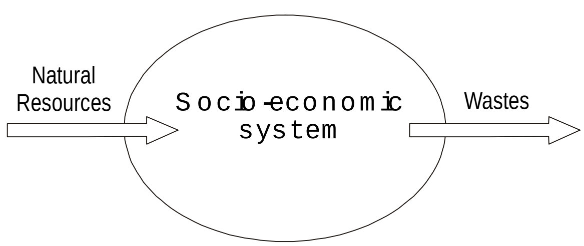

Figure 1

Sustainability of the ecological system primarily, even if it means elimination or displacement of the human component. Those who would value ecological sustainability above and beyond, rather than equal to, economic and social sustainability represent an extreme "deep green" position. Pursuing ecological sustainability by way of diminishing

[3] For example, when the intent is to move from a military dictatorship to a democratic system while simultaneously maintaining the manufacturing sector developed under the military dictatorship.

social and economic concerns, even if it means the elimination or displacement of humans, is not acceptable for the majority of us.[4]

Sustainability of the whole socio–ecological system.[5] The only option that makes sense in the long–term is to seek the sustainability of the whole socio–ecological system. The rationale for considering the whole system is based upon the existence of important interlinkages between society and nature. A s*ocio–ecological system* (Gallopín *et al*., 1989) is any system composed of a societal (or human) component (subsystem) and an ecological (or biophysical) component. It can be either urban or rural, and it may be defined at different scales from local to global.[6] (Figure 2 or, an alternative representation, Figure 3) This outlook is consistent with the notion of “strong sustainability”. The strong sustainability approach (Pearce, 1993) holds that different types of capital are not necessarily substitutable, so that sustainability requires the maintenance of a fixed (or minimum) stock of each component of natural capital. Under this notion, any development path that leads to an overall diminishment in the stocks of natural capital (or, specially, to a decline below the minimum) fails to be sustainable even if other forms of capital increase.

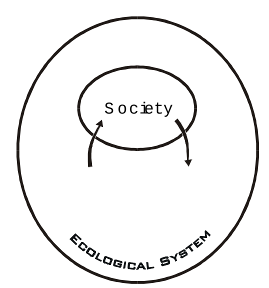

Figure 2

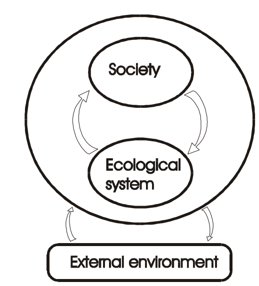

Figure 3

C. SUSTAINABLE DEVELOPMENT[7]

Although sometimes sustainability is presented as meaning the maintenance of a fixed state of a system, sustainability should not be seen as constancy; even pristine ecosystems are in permanent change, involving renewal and destruction of components, adapting to changes in their environment and coevolving with it. There are many examples involving fisheries, managed forests and wildlife, and other forms of management of ecological resources that have shown that attempts to “freeze” the variables of the system in attempts to obtain “optimal performance” often lead to loss of resilience of the system and even its collapse (Holling, 1973, 1986).

All living systems are changing systems (*albeit* in some cases they change in a bounded region near a dynamic steady state). The essential point is to avoid the destruction of the sources of renewal, from which the system can recover from the

4 There are those who would hold that this position could be well-justified in some very specific, localized situations such as keeping people out of national parks; there is room for debate on this issue.
5 Note that the term “socio” includes all that is human (economic, social, demographic, cultural, etc.).
6 Local may be a household and its interactions with its immediate surroundings, and global is understood as the whole of humankind and its interactions with the natural world.
7 Gallopín and Christianson (2000).

unavoidable stresses and disturbances to which it is exposed because of its condition of being an open system.

The concept of sustainable development is quite different from that of sustainability in that the world "development" clearly points to the idea of change, of directional and progressive change. As will be discussed later, development does not necessarily mean quantitative growth, being more akin to the notion of qualitative unfolding of potentialities and increasing complexity (which, depending on the concrete situation, may or may not include or require quantitative growth).

Here, what is sustained, or has to be made sustainable, is the process of improvement of the human condition (or better, of the socio-ecological system to which humans pertain), a process that does not necessarily require indefinite growth in the consumption of energy and materials.

We are living through a period of tremendous demographic, technological, and economic transformation. In an attempt to ensure that the changes affecting humanity are changes for the better, the world community has initiated the process of redefining progress. This attempt at redefining progress has come to be known as sustainable development.

The speed and magnitude of global change, the increasing connectedness of social and natural systems, and the growing complexity of societies and of their impacts upon the biosphere, highlight that SD must aim not only to preserve and maintain the ecological base for development and habitability, but also to increase the social and ecological capacity to cope with change, and the ability to retain and enlarge the available options to face a natural and social world in permanent transformation.

Thus, the concept of sustainable development cannot mean merely perpetuation of the existing situation. The central question is what is to be sustained, and what is to be changed. Moving towards sustainable development requires:

- Removing accumulated rigidities and impediments;
- Identifying and protecting the accumulated foundations of knowledge and experience that are important as a basis upon which to build;
- Sustaining the social and natural foundations for adaptation and renewal, and identifying and enhancing the lost renewal capacity needed;
- Stimulating innovation, experimentation and social creativity.

In dealing with sustainable development issues, the systems approach can offer a more useful perspective than the analytical approach, because sustainable development clearly implies the need for integration across environmental, economic and social dimensions, as well as across different time and space scales.

The body of literature pertaining to the topic of sustainable development is both voluminous and dissonant. The multitude of opinions on sustainable development may be indicative of the high-stakes involved. Indeed, trying to formulate a new framework for human reasoning capable of underlying the arrangements of our evolving society is of significant concern.

Amid the diversity of approaches to sustainable development there are, of course, some recurrent elements that provide some degree of internal consistency to the body of literature. The aim of this section is to review basic elements of the sustainable development concept.

a) The ethical foundations of sustainable development

Opinions about what constitutes the ethical foundation of sustainable development vary to some degree. One ethical concern that is often referred to in the sustainable development literature is that of intergenerational justice (Costanza, 1991, Vercelli, 1998). This concern is explicitly mentioned in the general definition of sustainable development prepared by the World Commission on Environment and Development (see the following concept subsection for definition). Intergenerational justice is linked with the reasoning put forth by John Rawls in his seminal work "A Theory of Justice".

Notably, the idea that future generations should be compensated for reductions in the endowments of resources brought about by the actions of present generations is in tension with another often cited ethical basis for sustainable development–intragenerational equity. Intragenerational equity is concerned with the reduction of resource disparities among those presently living today.

Another ethical concern, that complements the anthropocentric objectives of intergenerational and intragenerational justice, is the ecocentric concern for biodiversity, sometimes referred to as Biophilia (Wilson, 1986). Biophilia represents an appreciation of the intrinsic values in nature. The ecocentric objective of Biophilia is to preserve diversity, from species to ecosystems (Bergh and Jeroen, 1996). Variations on Biophilia have been put forth by the Deep Ecology school of thought.

b) Dynamism

Sustainable development cannot exist as some static equilibrium state which can be regulated by reference to constant limits and some simple notion of balance between the various dimensions (Brooks, 1992). Permanent technological innovation and changes in social organization necessitate that sustainable development exist in some form of dynamic equilibrium. Rates of change are important determinants of sustainable development (Froger and Zyla, 1998). A dedication to learning how rates of change affect the behaviour of social, ecological and economic systems over time is an important part of the process of enabling sustainable development.

c) Concept

Since its introduction in the late 1970s the concept of sustainable development has suggested a synthesis between economic development and environmental preservation

(Bergh and Jeroen, 1996). The need for this type of synthesis derives in large part from the fact that permanently decreasing environmental stocks cannot support increasing or even constant levels of material economic throughputs for an indefinite period of time (Drummond and Marsden, 1999).

Definitions of sustainable development hold in common a respect for the need to integrate economic and environmental concerns. Beyond this basic consideration, commonalties among definitions of sustainable development are more subtle.

The most often cited definition of sustainable development is the one proposed by the United Nations Commission on Environment and Development (otherwise known as the Brundtland Commission) in 1987. In its report to the United Nations General Assembly, entitled Our Common Future, the Commission defined sustainable development as “development that meets the needs of the present without compromising the ability of future generations to meet their own needs”.

Many attempts to promote sustainable development involve strategies designed to define and subsequently monitor some form of “sustainability limits” (Farrell and Hart, 1998). This approach is premised upon the observation that natural resources are finite and that there are limits to the carrying capacity of the Earth’s ecosystems.

Another approach to sustainable development, which is often linked in some manner with the sustainability limits approach, is the “competing objectives” approach, which focuses on reconciling social, economic and ecological goals (Peterson, 1997).

To generalize, approaches to sustainable development from an ecological perspective stress the importance of focusing on the societal ability to resist or recover from disturbances, stresses and shocks rather than on its ability to produce goods (Vercelli, 1998). Alternatively, approaches to sustainable development from an economic perspective define economic development (sometimes assumed to be synonymous with economic growth) as sustainable whenever a certain crucial variable may be ‘sustained’, in the sense that it is not bound to diminish in the future as a consequence of growth itself. In the literature, approaches to sustainable development may be grouped into three sets according to whether the crucial variable is welfare (or utility) consumption or (man-made and/or natural) capital. The choice of the crucial variable has far-reaching implications since its sustainability often implies the unsustainability of other plausible candidates for this role (Vercelli, 1998). The later author departed from those categorizations by proposing that the freedom of future generations should be taken as the basic variable to be preserved through time by economic development.

d) Implementation

If sustainable development is to be achieved, understanding the interlinkages between social, ecological and economic dimensions of our world is of significant importance. To understand such interlinkages, it is worthwhile to adopt a systems approach to observing worldly phenomenon. A key feature of the systems approach is the recognition that outcomes are not necessarily predictable since our activities may ‘force’ a system into a whole new form of behaviour (that could include collapse) never seen before (Holling, 1973, 1986; Gunderson *et al*., 1995).

Complementary to the need for a systems approach is the need to integrate multiple perspectives into the process of implementing sustainable development. A noteworthy point regarding sustainable development, a point that differentiates the concept from narrower ideas such as environmentalism, is that the concept is more than the sum of its parts (Brooks, 1992).

A means of assessing progress towards sustainable development is integral to implementing the concept. Traditional market indicators are unable to signal whether or not the integrity of a natural system is being dangerously eroded. Thus these indicators need to be complemented by sustainability indicators. Some sustainability indicators that have been proposed include: reducing the impact that human activities have on the environment (particularly the rates at which renewable and nonrenewable resources are used); not exceeding the carrying capacity of natural resources and ecosystems; integrating long-term economic, social and environmental goals, and preserving biological, cultural and economic diversity (Bergh and Jeroen, 1996).

Sustainability indicators must ultimately be linked with achievable goals. Setting goals for sustainable development amid large groups of stakeholders is a most difficult process. Amid large groups of stakeholders diversity of value perspectives, derived from different life experiences and cultural histories, tends to undermine the possibility of any consensus on the criteria for sustainable development (Peterson, 1997). To achieve global sustainable development, in light of this constraint, it may be best to allow for different regions to characterize sustainable development according to their specific interests and situation. A multi-region approach to global sustainable development would be based on the sustainable provision of natural resources and the sustainable import and export of resources, goods, services and waste (Redclift, 1994).

A multi-region approach to global sustainable development would entail the elaboration of multiple concrete manifestations of sustainable development, that is, each region would be able to craft a distinct take on the sustainable development *problématiqu*e. In order to give justice to the cultural, social, economic and ecological diversity of the world, multiple ways of interpreting sustainable development must be encouraged.

e) A variety of perspectives

Table I presents a summary of theoretical perspectives used to characterize sustainable development.

It is important to recognize that sustainable development can be treated as both a model and a point of legitimation (Farrell and Hart, 1998). Accordingly, the term sustainable development is often used for different purposes in scientific and political realms (Drummond and Marsden, 1999). In the final analysis, no single group has authority to define sustainable development. Consequently, the concept is wed to ambiguity. This ambiguous character exemplifies the inherent rationalism of sustainable development (Drummond and Marsden, 1999*)*.

Table I
THEORETICAL PERSPECTIVES ON SUSTAINABLE DEVELOPMENT

Theory	**Characterization of sustainable development**
Equilibrium-Neoclassical	Welfare non-decreasing (anthropocentric); sustainable growth based on technology and substitution; optimising environmental externalities; maintaining the aggregate stock of natural and economic capital; individual objectives prevail over social goals; policy needed when individual objectives conflict; long-run policy based on market solutions.
Neo-Austrian-Temporal	Teleological sequence of conscious and goal-oriented adaptation; preventing irreversible patterns; maintaining organization level (negentropy) in economic system; optimising dynamic processes of extraction, production, consumption, recycling and waste treatment.
Ecological-Evolutionary	Maintaining resilience of natural systems, allowing for fluctuation and cycles (regular destruction); learning from uncertainty in natural processes; no domination of foodchains by humans; fostering genetic/biotic/ecosystem diversity; balanced nutrient flows in ecosystems.
Evolutionary-Technological	Maintaining co-evolutionary adaptive capacity in terms of knowledge and technology to react to uncertainties; fostering economic diversity of actors, sectors and technologies.
Physico-Economic	Restrictions on materials and energy flows in/out the economy; industrial metabolism based on materials – product chain policy: integrated waste treatment, abatement, recycling and product development.
Biophysical-Energy	A steady state with minimum materials and energy throughput; maintaining physical and biological stocks and biodiversity; transition to energy systems with minimum pollutive effects.
Systems-Ecological	Controlling direct and indirect human effects on ecosystems; balance between material inputs and outputs to human systems; minimum stress factors on ecosystems, both local and global.
Ecological Engineering	Integration of human benefits and environmental quality and functions by manipulation of ecosystems; design and improvement of engineering solutions on the boundary of economics, technology and ecosystems; utilizing resilience, self-organization, self-regulation and functions of natural systems for human purposes.
Human Ecology	Remain within the carrying capacity (logistic growth); limited scale of economy and population; consumption oriented toward basic needs; occupy a modest place within the ecosystem foodweb and biosphere; always consider multiplier effects of human actions, in space and time.
Socio-Biological	Maintain cultural and social system of interactions with ecosystems; respect for nature integrated in culture; survival of group important.
Historical-Institutional	Equal attention interests of nature, sectors and future generations; integrating institutional arrangements for economic and environmental policy; creating institutional long-run support for nature's interests; holistic instead of partial solutions, based on a hierarchy of values.
Ethical-Utopian	New individual value systems (respect for nature and future generations, basic needs fulfilment) and new social objectives (steady state); balance attention for efficiency, distribution and scale; strive for small-scale activities and control of 'side effects' ('small is beautiful'); long-run policy based on changing values and encouraging citizen (altruistic) as opposed to individual (egoistic) behaviour.

Source: Bergh and Jeroen (1996).

D. THE DIFERENT GUISES OF DEVELOPMENT[8]

Development is about increasing the quality of life of human beings. Development is not necessarily about increased GNP; not even of "greened" GNP which accounts for depletion of ecological capital.

Hence development is not synonymous with economic growth; the latter is only one of the means to the former.

Quality of life embodies the satisfaction of material and non-material human needs (resulting in the level of health reached) and the fulfillment of human desires and aspirations (resulting in the level of subjective satisfaction obtained). Human needs, desires and aspirations can be met through a variety of alternative material and non-material satisfiers (Gallopín and Öberg, 1992; Mallmann, 1980).

Economic growth is not necessarily synonymous with material growth. Material economic growth is now confronting both source limitations (scarcity of natural resources) and sink limitations (saturation of the natural capacity for dilution and neutralization of pollutants and wastes). Non-material economic growth has been increasing in the recent past; this relative dematerialization of the economy is evident in the increasing share of the services sector in the GNP (although not all services are non-material, many are much less material-intensive than the primary and secondary sectors of the economy) and the higher energy –and resource– efficiency of the new and emerging knowledge–intensive technologies.

Figure 4 represents the basic relation between development, economic growth, and material economic growth in the form of a Venn diagram familiar in set theory. Sustainability, in principle, increases along the axis material economic growth/non-material economic growth/no economic growth.[9] The figure is useful for mapping possible combinations of economic growth and changes in the quality of life (Gallopín, 1996a).

One could say that *underdevelopment* occurs when neither quality of life increases nor economic growth takes place, a situation that affected many Latin American countries during the eighties and continues to plague many countries today, mostly in the south.

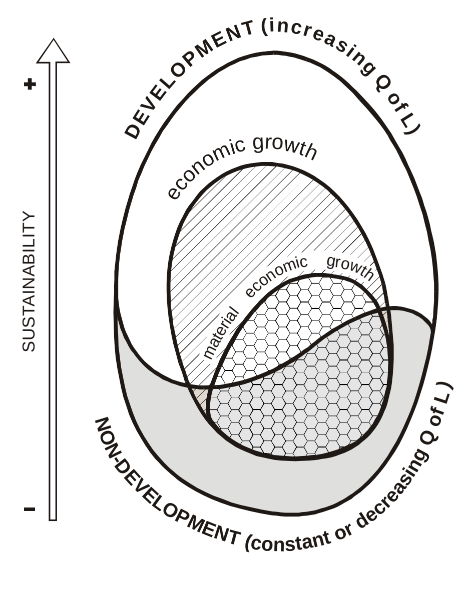

Figure 4

8 Gallopín (1996a), Gallopín and Christianson (2000).
9 "No economic growth" can be consistent with development in the form of qualitative transformations.

The situation where there is material economic growth, but quality of life does not increase, can be defined as *maldevelopment*; it occurs both in the north and in the south.

The combination of non-development with non-material economic growth is rare. However, it could characterize the situation of some fiscal havens or countries with service-based economies whose populations, for the most part, are resigned to a stagnant quality of life.

The combination of increasing quality of life with material economic growth is what is usually viewed as *development*. It currently occurs mostly in the north, but also in some countries in the south. However, in the long-term this situation is environmentally unsustainable, and in some instances critical environmental thresholds may have already been surpassed.

On our finite planet, even allowing for rapid technological change, a basic sustainable level of per capita material consumption will have to be reached. To do this will involve both increasing the material consumption of the billions of people living now in poverty and reducing material over-consumption by the rich minority.[10] Similarly, the global population will have to stabilize eventually.[11]

Ultimately, there are two basic types of truly sustainable development situations: increasing quality of life with non-material economic growth (but no net material economic growth) and zero-growth economies (no economic growth at all). Sustainable development need not imply the cessation of economic growth: a zero-growth material economy with a positively-growing non-material economy is the logical implication of sustainable development. While demographic growth and material economic growth must eventually stabilize, cultural, psychological and spiritual growth is not constrained by physical limits. Those situations are represented in Figure 5.

The challenge of SD lies in how to move from non-development to development in a sustainable way.

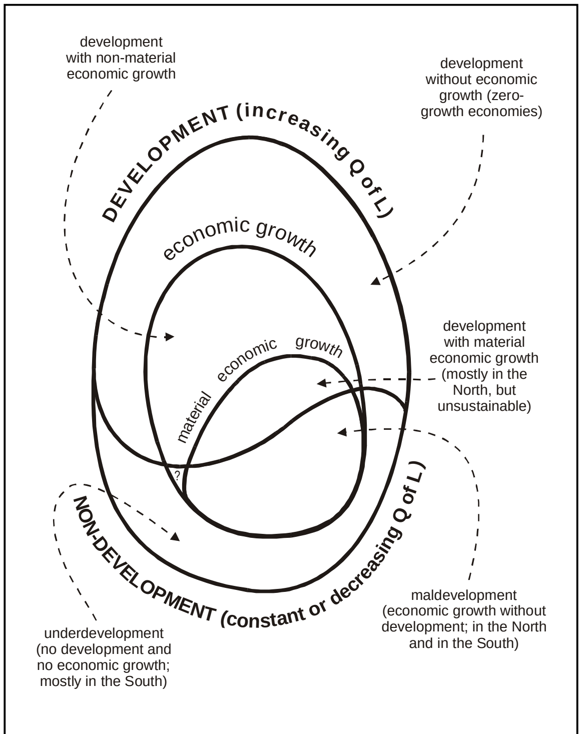

Figure 5

[10] Reducing material over-consumption by the rich minority can be achieved by reducing individual consumption levels and/or by increasing the overall material and energetic efficiency of the economy.

[11] Global population stabilization can be achieved through improving peoples living conditions and their quality of life. Stabilization through imposition and violence, besides being ineffectual, cannot be conducive to sustainable development.

Rich countries should attempt to move from maldevelopment or development with material economic growth, to development with non-material economic growth (or, if society so desires, the transition could be to a zero-growth economy).

In most cases however, underdeveloped countries will be unable to move from non–development to development without material economic–growth or to zero–growth economies, because of the fact that some level of accumulation and material economic activity is required to sustain development. The path from underdevelopment to maldevelopment is possible, but obviously inappropriate. Nevertheless, many countries continue to try and follow it.

After considering the alternatives, the only path realistically appropriate for developing countries, if sustainable development is to be achieved, is the one that goes from underdevelopment to development with material economic growth, and then to development without material economic growth.

The paths discussed above, and the alternatives available in principle to rich and poor countries, are depicted in Figure 6.

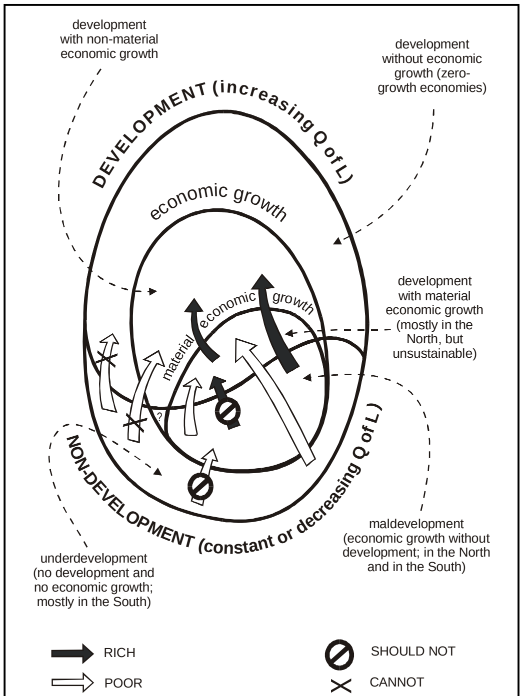

Figure 6

E. THE NEW SITUATION AND SCIENCE AND TECHNOLOGY[12]

1. Is science in need of change?

There is a growing feeling from many quarters that science is not responding adequately to the challenges of our times and, particularly, those posed by the quest for sustainable development. We are not including in our consideration the attacks to science coming from antiscientific sectors, but only the criticism and complaints generated by those who are supportive of the role of science for the understanding of the world and for solving practical problems.

The recognition that a new "Social Contract for Science" is necessary to deal with the new planetary situation, that business as usual in science will no longer suffice, that the world at the close of the 20th century is a fundamentally different world from the one in which the current scientific enterprise has developed, is coming now from the mainstream scientific establishment itself (Lubchenco, 1997). The challenge to focus on

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[12] Gallopín *et al.* (2001).

the linkages between the social, political, economic, biological, physical, chemical and geological systems is seen as a current imperative; dynamic cross–systemic explanations are sought where static and reductionist models once prevailed (as emphasized by the Board of Directors of the AAAS–Jasanoff *et al*., 1997).

Lack of satisfaction with current research styles is becoming evident in many areas. For instance, the Consultative Group on International Agricultural Research (CGIAR) stated that ‘as yet, there is no accepted research model which embraces the physical, biological and human dimensions of long term (agricultural) sustainability. Developing such a model is a goal of truly international importance’ (CGIAR 1993, p. 8).

The World Conference on Science, under the rubric “Science for the Twenty–First Century”, met in Budapest in mid–1999 with over 1,800 delegates from 155 countries. The main documents produced abound in the need for a new relationship between science and society, a reinforcement of scientific education and cooperation, the need to connect modern scientific knowledge and traditional knowledge, the need for interdisciplinary research, the need to support science in developing countries, the importance of addressing the ethics of the practice of science and the use of scientific knowledge, and other important issues.

The Conference called for a strengthening and democratisation of science, and emphasized the need for a new role of science in society, but it remained remarkably silent on the possibility that science itself may also be in need of change (other than mentioning the need for integration and particularly for interdisciplinary research between natural and social sciences).

We believe that is timely and fruitful to consider how appropriate current mainstream science (its method and its practice) is as a guiding tool for the pursuit of sustainable development. We do not claim that all of science is in need of change, but we do think it is necessary to examine to what extent (and in which situations) problems with science are caused by the non–application (or misapplication) of the existing rules of enquiry, and to what extent (and in which situations) the scientific rules themselves have to be modified, or even replaced. All of this without going outside the essence of scientific thinking adopted by the Declaration of Science of the World Conference (ICSU 1999), as “the ability to examine problems from different perspectives and seek explanations of natural and social phenomena, constantly submitted to critical analysis”. We submit that this need is of an epistemological nature, based on the recent scientific developments themselves, quite apart from the (also relevant) considerations based on social values.

2. An evolving science

Science has been constantly evolving through its history. Up to the Second World War the dominant form (especially in the consciousness of science) was 'academic' curiosity–driven research. Then the leading form became 'industrialised' (Ravetz, 1996), alternatively described as 'incorporated' (Rose and Rose, 1976). In these, research is 'mission oriented', and researchers change from being independent craftsmen to employees. Now traditional curiosity–driven research has been totally marginalized. Its associated form of intellectual property, 'public knowledge', is rapidly being driven out of the leading fields (as biotechnology) by 'corporate know–how'.

The products of research and the media are being correspondingly transformed. The old distinction between 'discovery' and 'invention', the foundation of the patent system, has been obliterated. Not merely are life–forms being patented wholesale, but the identification of a possible function for a DNA sequence is sufficient for it to count as an 'invention', the property of he/she who stakes claim to it. Also, the traditional peer–reviewed public journals are being displaced as the primary source of communication. Results are reported in consultancy advice, “grey literature”, or kept confidential within institutions or even totally secret under “lawyer–client confidentiality”. The tasks of quality assurance of these new processes and products are very difficult.

A parallel diversification is now occurring in types of knowledge–production that are accepted as legitimate. The democratisation of knowledge now extends beyond the juries who competently assess the quality of technical evidence (Jasanoff, 1998), to include those who use special–interest groups of the Web to master aspects of their predicament (e.g. illness, contamination, pollution, oppression, discrimination, exploitation) that were previously esoteric, the preserve of specialists. In addition, some sort of claimed knowledge is present in even more diverse contexts, as among indigenous peoples, and in complementary and “traditional” therapies; and these are commanding increasing commercial and political support among various publics. Modern science, with its characteristic methodology and social location, is relocating itself as a part of this enriched whole.

Those changes in science have not been independent of the unfolding of historical processes in the economic, technological, social, cultural and environmental domains. The changes reflect, and impinge upon, the social practice and the public image of science and the issue of ‘quality assurance‘ of scientific understanding and research. A response to the need for societally relevant criteria for quality assurance has been the proposal of a “post–normal science” (Funtowicz and Ravetz, 1992, 1993, 1999).

But changes also affect in some cases fundamental scientific rules and criteria of truth. One example is the tension and shifting dominance between the analytical and the integrative streams in the science of Ecology (Holling, 1998). The differences between them include basic assumptions on causality, criteria of truth and epistemological acceptability and evaluation criteria, among others (see Table II).

The analytical stream focuses in investigating parts, and it emerges from traditions of experimental science where a narrow enough focus is chosen in order to pose hypotheses, collect data, and design critical tests to reject invalid hypotheses. Because of its experimental base, the chosen scale typically has to be small in space and short in time.

Table II
COMPARING THE TWO STREAMS OF THE SCIENCE OF ECOLOGY

Attribute	**Analytical**	**Integrative**
Philosophy	•narrow and targeted •disproof by experiment •parsimony the rule	•broad and exploratory •multiple lines of converging evidence •requisite simplicity the goal
Perceived Organization	•biotic interactions •fixed environment •single scale	•biophysical interactions •self–organization •multiple scales with cross scale interactions
Causation	•single and separable	•multiple and only partially separable
Hypotheses	•single hypotheses and nul rejection of false hypotheses	•multiple, competing hypotheses •separation among competing hypotheses
Uncertainty	•eliminate uncertainty	•incorporate uncertainty
Statistics	•standard statistics •experimental •concern with Type I error (in hypothesis testing, rejecting the proposition when it is true)	•non–standard statistics • concern with Type II error (failing to reject the proposition when it is false)
Evaluation goal	•peer assessment to reach ultimate unanimous agreement	•peer assessment, judgment to reach a partial consensus
The danger	•exactly right answer for the wrong question	•exactly right question but useless answer

Source: Holling (1998).

The premise of the integrative stream is that knowledge of the system is always incomplete. Surprise is inevitable. There will rarely be unanimity of agreement among peers —only an increasingly credible line of tested argument. Not only is the science incomplete, the system itself is a moving target, evolving because of the impacts of management and the progressive expansion of the scale of human influences on the planet.

Those changing aspects (fundamental procedures, social practice, public image, quality assurance) are most critically important for policy–related research, driven by political issues such as the permissible concentration of pollutant, health hazards and, obviously, the production and use of science for sustainable development —'sustainability science' for short.

The quest for sustainable development poses new, deep challenges to the ways we define problems, identify solutions and implement actions.

Although scientific theory and practice have been historically very successful in solving what Weaver (1948) called “problems of simplicity” and problems of “disorganized complexity”, changes in both theory and practice of science and its utilization for policymaking may be required in order to deal with many of the current and emerging more complex and “messy” situations and issues characteristic of the problems of “organized complexity”.

The inadequacies of the traditional scientific approach have been revealed with dramatic clarity in the episode of "mad cow" disease (2), a paradigmatic “messy” situation. For years the accredited researchers and advisors assured the British Government that the likelihood of transfer of the infective agent to humans was very small. They did not remark on the sorts of decision–stakes involved in the policy, in which public alarm and government expense were the main perceived dangers. The risk of an epidemic among humans (with its attendant costs) was discounted by the experts and eventually officially denied. When the human cases of neo–variant CJD (3) were confirmed and related to CJD, it was admitted by both experts and officials that an epidemic of this degenerative disease was a "non–quantifiable risk". The situation went out of control, and the revulsion of consumers threatened not only British beef, but also perhaps the entire European meat industry.

At this stage there had to be a “hard” decision to be taken, on the number of cattle to be destroyed, whose basis was a very “soft” estimate of how many cattle deaths would be needed to reassure the meat–eating public. At the same time, independent critics who had been dealt with quite harshly in the past were admitted into the dialogue. Without in any way desiring such an outcome, the British Ministry of Agriculture, Forests and Fisheries had created a situation of extreme systems uncertainty, vast decision stakes, and a legitimated extended peer community (Funtowicz *et al*., 1999).

3. The new situation

The prevailing mindset is showing critical inadequacies. It is becoming recognized as not accidental that in a number of important cases, the very success of classical compartmentalized approaches has led to the aggravation of the environmental and developmental problems addressed. Fundamental uncertainty is introduced both by our limited understanding of human and ecological processes, by the intrinsic indeterminism of complex dynamic systems (involving natural, human–made and human components), and by myriad of human choices and goals. In addition to that, the present historical context and dynamics exhibits major differences with that of the past few decades.

On the one hand, the world now is moving through a period of extraordinary turbulence reflecting the genesis and intensification of deep economic, social, political and cultural changes associated to the current techno–economic revolution. In addition, the speed and magnitude of global change, the increasing connectedness of the social and natural systems at the planetary level, and the growing complexity of societies and of their impacts upon the biosphere, result in a high level of uncertainty and unpredictability, presenting new threats (and also new opportunities) for humankind.

On the other hand, the current trends are seen to be unsustainable (both ecologically and socially). The need for a change in direction has been officially recognized at the Earth Summit in June 1992. However, the new direction is not yet clearly defined; also, most of the discussions and recommendations are still very compartmentalized.

The complexity of the situations and problems is quickly increasing in the current decades (Gallopín 1999, Munn *et al.*, 1999). This is due to a number of reasons, such as the following:

Ontological changes: human–induced changes in the nature of the real world, proceeding at unprecedented rates and scales and also resulting in growing connectedness and interdependence at many levels. The molecules of carbon dioxide emitted by fossil fuel burning (mostly in the north) join the molecules of carbon dioxide produced by deforestation (mostly in the south) to force global climate change: an economic crisis in Asia reverberates across the global economic system affecting far away countries.

Epistemological changes: changes in our understanding of the world related to the modern scientific awareness of the behaviour of complex systems, including the realization that unpredictability and surprise may be built in the fabric of reality, not only at the microscopic level (i.e. the well–established Heisenberg uncertainty principle) but also at the macroscopic level, as described later.

Changes in the nature of decision–making: in many parts of the world, a more participatory style of decision–making is gaining space, superseding the technocratic and the authoritarian styles. This, together with the widening acceptance of additional criteria such as the environment, human rights, gender, and others, as well as the emergence of new social actors such as the non–governmental organizations and transnational companies, leads to an increase in the number of dimensions used to define issues, problems and solutions and hence to higher complexity.

F. SYSTEMS AND COMPLEXITY[13]

It is becoming increasingly clear that the quest for sustainable development requires integrating economic, social, cultural, political and ecological factors. It requires the constructive articulation of the top–down approaches to development with the bottom–up or grassroots initiatives. It requires the simultaneous consideration of the local and the global dimensions and of the way they interact. And it requires broadening the space and time horizons to accommodate the need for intra–generational as well as intergenerational equity. In other words, what is needed is nothing less than a fundamental shift in the way we approach development and the relations between society and nature.

In terms of the implications for science, this calls for integration at a much broader (and deeper) level than fostering an interdisciplinary style of research. It calls for a truly complex–systemic approach to both the practice and the method of science.

[13] Gallopín (1999), Gallopín *et al*. (2001).

The systems approach is a way of thinking in terms of connectedness, relationships and context. According to that view, the essential properties of an organism, a society, or other complex system, are properties of the whole, arising from the interactions and relationships among the parts. The properties of the parts are not intrinsic but can be understood only within the context of the larger whole. Systems–thinking concentrates not on basic building blocks, but on basic principles of organization. It is "contextual" which is the opposite of analytic thinking.

Looking at the system from a scientific viewpoint implies two basic tasks: one is the identification and understanding of the most important causal interlinkages; the linkages between different factors and different scales originate the possibilities of changes in one component of the system reverberating into other parts of the system. The other task is understanding the dynamics of the system. Besides the structure of components and linkages, the analysis of the forces generating the behaviour of the system is essential, including the investigation of how different components and processes interact functionally to generate system responses and emergent properties, how the system adapts and transforms itself.

We do not ignore the existence of a growing volume of excellent systems oriented research. However, systemic research is not the norm, but the exception in modern science. By the reasons given above, it is clear that a science relevant to sustainable development should be primarily systemic, looking at the wholes rather than merely to the parts, and with an interdisciplinary research style. Moreover, the systems of interest for sustainable development are complex systems, in the sense discussed below.

The complexity of the systems to be dealt with in the domain of science for sustainable development is one of the most critical arguments for the need of changes in the production and utilization of science.

We distinguish complex systems from the merely complicated, and those from simple systems (6). A system is “simple” if it can be adequately captured using a single perspective or description and by a standard (e.g. analytical) model providing a satisfactory description or general solution through routine operations (e.g. ideal gases, mechanical motion).

A system is “complicated” when it cannot be satisfactorily captured through the application of a standard model, although it is possible to improve the description or the solution through approximations, computations, or simulations. However, a complicated system can still be characterized by using a single perspective (e.g. a system of many billiard balls in movement, cellular automata, the pattern of communications in a large switchboard).

We consider as the basic criterion to separate “complex” from complicated, the need to use two or more irreducible perspectives or descriptions in order to characterize the system. Complex systems share with complicated ones the property of not being capturable through the application of a generic model through routine operations.

The definition of complexity is not trivial, and different conceptions exist, but one point we want to emphasize is that complexity is not an automatic outcome of increasing the number of elements and/or relations in a system. Complex systems generally exhibit a number of attributes that make them more difficult to understand and manage than simple and complicated systems:

Multiplicity of legitimate perspectives. For instance, it is difficult to understand an adaptive system without also considering its context; the resolution of a conflict over common property cannot be reached without taking into account the perspectives and interests of different stakeholders (none of them being the ”correct” or “true” perspective).

Non–linearity. Complex systems are non linear, in the sense that many relations between their elements are non linear, resulting in the magnitude of the effects not being proportional to the magnitude of the causes, and in a very rich repertoire of behaviour (e.g. chaotic behaviour, multi–stability because of the existence of alternative steady states, runaway processes, etc.). Non–linearities play a crucial role in the generation of the counterintuitive behaviour typical of many complex systems.

Emergence. Denoted by the phrase "the whole is more than the sum of its parts", this is a systemic property, implying that the properties of the parts can be understood only within the context of the larger whole and that the whole cannot be analysed (without residue) in terms of its parts. True novelty can emerge from the interactions between the elements of the system.

Self–organization. The phenomenon by which interacting components cooperate to produce large–scale coordinated structures and behaviour (such as the patterns created by the dissipative structures studied by Prigogine–Prigogine and Stengers 1979; Nicolis and Prigogine 1977, Jantsch, 1980).

Multiplicity of scales. Many complex systems are hierarchic, in the sense that each element of the system is a subsystem of a smaller–order system, and the system itself is a subsystem of a larger order “supra–system”. The important point is that in many complex systems there is strong coupling between the different levels and therefore the system must be analysed or managed at more than one scale simultaneously (7). But systems at different scale levels have different sorts of interactions, and also different characteristic rates of change. Therefore it is impossible to have a unique, correct, all–encompassing perspective on a system at even one systems level; plurality and uncertainty are inherent in systems behaviour.

Irreducible uncertainty. Many sources of uncertainty arise in complex systems. Some of them are reducible with more data and additional research, such as the uncertainty due to random processes (amenable to statistical or probabilistic analysis), or that due to ignorance (because of lack of data or inappropriate data sets, incompleteness in the definition of the system and its boundaries, incomplete or inadequate understanding of the system). When we consider the complex socio–ecological systems involved in sustainable development issues, it is clear that those sources of uncertainty can be insurmountable in practice, even if not in principle. Fundamental, irreducible uncertainty may arise from non–linear processes (e.g. chaotic behaviour), in the processes of self–organization (e.g. Prigogine showed that the new systemic structure arising from the reorganization of the elements of the system can be inherently unpredictable even in simple chemical systems – Prigogine and Stengers 1979, Nicolis and Prigogine 1977) and through the existence of purposeful behaviour including different actors or agents each with their own goal. Furthermore, complex “self–aware” (or “reflexive”) systems, which include human and institutional subsystems, are able to observe themselves and their own evolution thereby opening new repertoires of responses and new interlinkages. In those systems, another source of “hard” uncertainty arises; a sort of “Heisenberg effect”, where the acts of observation and analysis become part of the activity of the system under study, and so influence it in various ways. This is well known in reflexive social systems, through the phenomena of “moral hazard”, self–fulfilling prophecies and mass panic.

While some of the above attributes exhibited by complex systems can be displayed by some complicated, and even simple systems (such as non–linearity or uncertainty), the point is that any complex system is likely to have all of them.

G. SCIENTIFIC RESEARCH IN A COMPLEX–SYSTEMIC WORLD[14]

Scientific research about complex, self aware systems such as those relevant for sustainable development may have to deal with a compounding of complexity at different levels. The interplay between the factors across the different levels and layers adds to the complexity intrinsic to each of the layers. There are at least three levels at which complexity impinges upon scientific enquiry:

- Physical reality, where the properties of self–organization, irreducible uncertainty, emergence, and others, come into play.
- The need to consider different “epistemologies” (a plurality of perceptions or viewpoints must be acknowledged and respected, even if not accepted as equally valid).
- The need to consider different “intentionalities” (differing goals).

Attention to those complex systems properties is not only necessary for the improvement of scientific research, but the existence and nature of those properties is interesting and important as a topic of scientific research.

On the other hand, attention to the complex systems properties presents difficulties for established conventions of scientific practice and expert advice within the scientific community. Much insight can be obtained concerning the sorts of potentials that a given system might have. But the "space of feasible outcomes" in such circumstances is characterized *ex ante* by an inherent indeterminacy and *ex post* by irreversibilities. Knowledge in the sense of insight and understanding is absolutely not synonymous with capacity for predictions. Equally, awareness of risks is not synonymous with capacity to intervene to reduce or control the risks.

The fuzziness of production possibilities, or in other words the new recognition (even if it is not really all that new) of the deep irreversibilities entailed by the scientific adventure, has quite weighty consequences for the framing of societal choices (Funtowicz, Ravetz and O'Connor, 1998; Funtowicz and O'Connor, 1999). One theme that emerges from the extensive literature on uncertainties and technological risks is the suggestion that scientific enquiry could promote a reflexive attitude about risk, along the following lines of reasoning:

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[14] Gallopín *et al*. (2001).

- Nature (including human living beings) involves delicately structured processes vulnerable to perturbation;
- The pursuit of knowledge is not a simple observation process that simply augments the stock of knowledge about raw materials that is put on the market shelf. Rather, it is an intervention process that, through learning by doing, gives knowledge about possibilities of induced transformation;
- In the "classical" science project, it had been further postulated (or hoped) that these transformation possibilities can be harnessed in the sense that these transformation potentials can be controlled and contained;
- But, the prospect of uncontrolled and, sometimes, runaway consequences of the interventions (or, equally, of the attempted tapping and harnessing mechanisms) is ever–present.

Many scientists will argue that this is not new, and that ignorance and incompleteness of knowledge have always been admitted within the scientific project. At stake, however, is not the admission of partial ignorance but, rather, the significance to be attached to the forces of change being engaged under conditions of inability to exercise mastery over eventual outcomes.

There has been, in the past (and is still widespread today), an important ideological process that has protected science practice from having to address deeply this feature of inherent uncontrollability. First, the tendency was to define the domain of science as that where "solutions can be found". Second, and closely related, there has been a strong ideological privileging of the intended purpose, a desired outcome, over the unintended "side–effects" (which may have inconvenient or undesirable aspects).

In brief, science progress was seen as part of the perfectibility of the human condition. Any uncontrolled change effects are interpreted as symptoms of the imperfection in the current knowledge and/or its application, with the presumption that more knowledge will reduce uncertainties, increase capacity for control, and permit the remedying of past mistakes.

Here, we see that an instrumental notion of science substitutes for what, arguably, is a more truly scientific spirit that would allow for the uncontrolled effect as being not only unavoidable but perhaps the very essence of the learning–knowing process.

H. CORE EPISTEMOLOGICAL ISSUES IN SUSTAINABILITY SCIENCE

Three epistemological issues of particular relevance to the scientific investigation of sustainability and sustainable development (sustainability science for short) are: integration, the appropriate conceptual unit(s) of study, and criteria of truth. Differences in these issues between sustainability science and traditional ways of thinking about science and technology will be briefly discussed.

1. The unit of analysis

It is proposed here that the appropriate unit of analysis (the basic entity being analyzed by a study and for which data are collected in the form of variables) for sustainability science should be the socio-ecological system. As defined before, a socio-ecological system can be defined at any scale from the local to the global. The socio-ecological system brings the focus to the whole system composed by the two major, human and ecological subsystems and their mutual interactions (obviously the human and ecological subsystems can be differentiated further, i.e. by defining an economic, a social, a cultural, and an institutional subsystem, and also differentiating within the ecological subsystem according to the problem being considered –Gallopín 1994, Gallopín and Christianson, 2000). By doing so, it includes not only the major interactions between humans and nature, but also the interactions between humans and humans, and between ecological components that need to be included to understand and anticipate the behaviour of the whole system. At the global level, the whole socio–ecological system has been called the Earth System (Schellnhuber, H.J., 1998), including both the “Ecosphere” and the “Human factor”. However, a lot of the international global research such as the International Geosphere–Biosphere Program (IGBP) and even the more social oriented International Human Dimensions Programme on Global Environmental Change (IHDP) are very much biased toward the ecological, or bio–geo–physical, subsystem and only include the human component either as a box generating perturbations or as the generator of human activities and recipient of environmental impacts.

Regarding the scale of analysis, it is clear that the subject of Sustainability Science should not be limited to the planetary (or even regional) scales. Many arguments and examples are available from the literature and case–studies showing the importance of considering the local context and local communities in the quest for sustainability and sustainable development. In fact, this is already part of the conventional wisdom in the sustainable development agenda.

More generally, sustainability is a concept that can be defined at different scales from the most local (such as a household, or a farm system) to the whole planet; similarly to the case of the science of ecology (where the ecosystem may range from a poodle in the forest floor to the whole ecosphere) the subject of sustainability science should not be limited to any particular scale.

2. Integration[15]

The fact that the unit of observation includes both human and natural subsystems makes sustainability science interdisciplinary of necessity.

Scientific information is generated through research activities. Integration of scientific research in terms of relevance for decision–making requires a systemic approach (looking at wholes rather than merely to their component parts), an interdisciplinary research style, and considering not only the relevant quantitative information but also the relevant qualitative one.

Integrative research is obviously not just about adding more variables, nor just broadening the scope to include a larger portion of reality; it implies adopting a systemic

[15] Gallopín (1999).

approach and performing a careful analysis of what is to be included in the characterization of the system and what is to be left out, for the purposes of the problem addressed.

Looking at the whole from a scientific viewpoint implies at least two basic aspects:

Identification and understanding of the most important causal interlinkages. Components and relationships (interlinkages) between them make up the structure of any system. The linkages between different factors originate the possibilities of changes in one component of the system reverberating into other parts of the system. Sometimes it is convenient to distinguish between different kinds of linkages.

Horizontal interlinkages may include *intra–sector* links (e.g. links between variables associated to the water dynamics); *inter–sectors* links (e.g. links between the dynamics of fish populations and the behaviour of fishermen and other social actors); and *inter–systems* links (e.g. links between neighbouring ecosystems, links between oceanic and atmospheric circulation, links between countries).

Vertical (interlevel) interlinkages are cross–scale, such as links between cumulative effects of individual consumption patterns and climate change; dynamic links between fast and slow variables.

Understanding the dynamics of the system. Besides the structure of components and couplings (or linkages) between them, the analysis of the forces generating the behaviour of the system is essential. Nonlinearities play a crucial role in the generation of the counterintuitive behaviour typical of many complex systems. This implies that it is necessary to investigate how do different components and processes interact functionally to generate system responses and emergent properties, how the system adapts and transforms itself. This is an area for deep basic and applied research.

Interdisciplinary research is often required to obtain integration. As with the case of integration, there is a big gap between the rhetoric and the practice of interdisciplinary research. It is not enough to put together a group of researchers from different disciplines to work in a project; it is also necessary to establish a true dialogue between the disciplines, an iterative and interactive process of mutual education and learning. This transformative dialogue is what differentiates interdisciplinary from multidisciplinary research.

Education and training in how to perform interdisciplinary research is often lacking in most education systems both in the south and the north.

3. Criteria of truth

The criteria used to decide what is “true” (or better, the falsification criteria used to disprove scientific hypothesis) and other rules of science need to be reexamined for the adequacy for sustainability science. The question of to what degree (if any) and in which way the existing rules of scientific enquiry, criteria of truth, and practice of science need to be modified in sustainability science is an important one. As put by a group of prominent scientists (Lowel Statement 2201, (http://www.uml.edu/centers/lcsp /precaution/), research frequently focuses on narrow, quantifiable aspects of the problems, thus inadvertently excluding from consideration potential interactions among different components of the complex biological systems of which humans are a part.

Occam's Razor is a good example of a scientific rule that might be changed in the new sustainability science. The rule as usually stated "one should not increase, beyond what is necessary, the number of entities required to explain anything" is still valid in a complex systemic world, but the characterization of "what is necessary" may need drastic broadening to account for the interlinkages between the object of study and other parts of reality.

CONCLUSIONS

We argue that the quest for sustainable development, and the historical development of our times require modifications and improvements not only in the diffusion and use of scientific findings, but also in the way science itself is performed.

We maintain that the identification and testing of the necessary changes in scientific methods, criteria of truth and of quality, and conceptual frameworks, is by itself a legitimate and interesting subject for scientific research.

The investigation of the necessary changes will take time and will need the involvement of researchers from different, natural and social disciplines. Here, we highlight only a few of the practical implications that can be derived from our analysis.

- We are putting a fundamental systemic property forward. This does not imply that every single piece of research should adopt a systemic approach; there are many cases in which interlinkages and context can be safely ignored. But we posit that it is the responsibility of the scientist to consider the potential impacts of his/her scientific research from the beginning, and to assess to what extent the systemic, interlinked nature of reality can be safely neglected. Note that this argument is based on scientific grounds, not social values or individual preferences.
- In a more restricted sense, at least for the cases of toxic products, long–lasting active wastes, or novel products having a permanent perturbation potential (such as genetic recombination products), any scientist or innovator promoting a new product or solution should consider the possible significance of "Type–II Error" (failure to reject a false hypothesis) and justify publicly the decision to neglect it, given that the absence of proof of danger is not the same as proof of the absence of danger.
- A useful practice in scientific research would be to always define the system within which we isolate or delineate the problem investigated, and to look for relevant interlinkages. In other words, look outwards to examine how the issue/problem is linked to other variables, issues or systems (horizontal and vertical or cross–scale linkages), in time and space. Only then we can meaningfully ignore the rest of the system (if the linkages are negligible (8) or decide how, and to what degree, to include the broader system in the research.
- The complexity of the systems and subsystems involved in sustainable development research, with their associate irreducible uncertainty and self–organization capabilities, suggest that we should move away from recipes and rigid rules towards the search for general principles and guiding questions for steering the investigations.
- In the characterization of the issue or problem and its possible evolution, include all important factors, even those that are not quantifiable. Different scientific and non–scientific analysis and truth–criteria may be used to deal with different factors, but if they are not included in the initial definition of the problem they are unlikely (or difficult) to be included later. It is better to get an approximate answer for the whole problem/issue, than a precise answer for an isolated component.

- In dealing with an issue or problem, clearly distinguish between the knowledge base (including scientific uncertainties) and the political decisions (that will incorporate social values).
- Ensure that the scientific conceptualisation of the problem includes, from the very beginning of the scientific process, the identification of policy relevant indicators. Involve policy makers and stakeholders in the initial problem characterization.
- Consider the possible repertoire of behaviour of the whole system, as broadly as possible (not just the historical behaviour). On this basis, prepare for novelty, structural change and surprise.
- Value the information generated by the responses of the system to policies and human actions.
- One of the challenges of sustainability science is how to incorporate or articulate meaningfully and usefully the different perceptions, knowledge and perspectives that are usually at stake in dealing with sustainability and sustainable development.

Ours is most certainly not a call for a relaxation of scientific rigor; on the contrary, we believe that a "sustainability science", besides being of great practical and societal importance, should be the more rigorous by being better informed about the interlinked and complex nature of reality, a reality that science itself is revealing to us.

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