

## Science for the twenty-first century: from social contract to the scientific core

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### Abstract

The article addresses the need, posed by the challenges of sustainable development and the changing context at the beginning of the 21st century, for changes in the method and practice of science. The major challenges for a "sustainability science" arise from increasing complexification at the ontological, epistemological and political levels, calling for an integrated science going far beyond an interdisciplinary style of research. The requirement is for the development, adoption, and dissemination of a truly complex-systems scientific research model. Complex socio-ecological systems share a number of fundamental properties that require changes in scientific methods, criteria of truth and quality, and conceptual frameworks. These properties include non-linearity, plurality of perspectives, emergence of properties, self-organization, multiplicity of scales, and irreducible uncertainty. Some implications of the analysis are pointed out, in the form of practical recommendations. The authors argue for the involvement of both natural and social scientists in the investigation of the necessary steps to develop a sustainability science.

## Introduction

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 twentieth 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 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.

Two principal documents embody the results of the conference: the Declaration on Science and use of Scientific Knowledge, and the Science Agenda-Framework for Action (ICSU 1999).<sup>1</sup>

The documents 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 inter-disciplinary 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 inter-disciplinary research between natural and social sciences).

When reading the documents of the conference, it is difficult to escape the feeling that their main message is that the problems with science lie essentially in the way science is used, misused and, mostly, underused, but that the model of science, and its practice, is fine as it is, for the new century as for the past one, and for sustainable development as well as for fundamental understanding and the resolution of practical problems.

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.

## **An evolving science**

Science has been constantly evolving through its history. Up to the World War II 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 & 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". With traditional peer-review as the norm, the tasks of quality assurance of these new processes and products are nearly unrecognisable. A type of critical literature has developed, some authors directing criticism at the scientist (Huber 1991), and some appreciating the problems raised by the new context (Crossen 1994, Jasanoff 1990).

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 property 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 socially relevant criteria for quality assurance has been the proposal of a "post-normal science" (Funtowicz & 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 I).

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.

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 policy making 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 "organised complexity".

The inadequacies of the traditional scientific approach have been revealed with dramatic clarity in the episode of "mad cow" disease,<sup>2</sup> 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<sup>3</sup> were confirmed and related to BSE, 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, Fisheries and Food had created a situation of extreme systems uncertainty, vast decision stakes, and a legitimated extended peer community (Funtowicz et al. 1999).

All these changes can be understood systemically, as part of the changing character of science, and new contradictions within it. It is no accident that the extreme reductionist,

analytical style should be that of research in the service of 'corporate know-how'; for in that way the contextual aspects of science, particularly its effects on the human and natural environments, can be considered as 'externalities', left to the regulators and ethicists to catch up with when they can. In contrast and opposition, a new consciousness of science, systemic and humanistic, assimilating uncertainty and value-commitments, and embracing extended peer communities, is taking up the cause of 'public knowledge' just as the academic sector is being reduced to impotence. The issue becomes clear in cases like genetically modified organisms (GMOs), where gross environmental uncertainties are either ignored or recognised, and also in those of biomedical engineering, where 'health' is merely a cured disease, and the treatment of medical and moral hazards is similarly polarised among the parties to the debate.

## **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 compartmentalised 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 was 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 compartmentalised.

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

realisation 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 organisations and transnational companies, leads to an increase in the number of dimensions used to define issues, problems, and solutions and hence to higher complexity.

## **Systems and complexity**

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 inter-generational 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 inter-disciplinary style of research. It calls for a truly complex-systemic approach to both the practice and the method of science.

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 organisation. 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 inter-linkages; 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 for changes in the production and utilization of science.

By system we mean a conceptualisation of a portion of reality in terms of a set of interrelated elements. The elements can be molecules, organisms, machines or their parts, social entities, or even abstract concepts. The interrelations, interlinkages, or "couplings"<sup>4</sup> between the elements may also have very different manifestations (economic transactions, flows of matter, energy or information, causal linkages, etc.). The behaviour and properties of a system arise not merely from the properties of its component elements, but to a large degree also from the nature and intensity of the dynamic interlinkages between them. This is particularly true in socio-ecological systems,<sup>5</sup> which can be considered the basic units for sustainable development.

An infinite number of systems can be defined on the same portion of reality, depending on viewpoint, objective, and previous experience. On the other hand, each of those views or systems, if constructed with a modicum of care, will have some correspondence with what is "really out there".

We distinguish complex systems from the merely complicated, and those from simple systems.<sup>6</sup> 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-organisation.* 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 Jantsch 1980, Nicolis & Prigogine 1977, Prigogine - Prigogine & Stengers 1979).

*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.<sup>7</sup> 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 system's 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-organisation (e.g., Prigogine showed that the new systemic structure arising from the reorganisation of the elements of the system can be inherently unpredictable even in simple chemical systems – Nicolis & Prigogine 1977, Prigogine & Stengers 1979) 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 inter-linkages. 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.

## Scientific research in a complex-systemic world

We want to illustrate some of the implications of systemic complexity for scientific research through the consideration of the following two points:

1. Fluctuations can drive averages. This has been demonstrated for a number of physical, chemical, and biological cases by Prigogine and his colleagues (Nicolis & Prigogine 1977), and in the management of natural resources by Holling and his colleagues (Gunderson et al. 1995) in the sense that micro fluctuations (external or internal to the system) can, in certain circumstances, lead to drastic restructurations at the macro level. Let us consider research for the development and testing of pharmaceutical drugs in a systemic, self-organising world. Drug testing is usually considered statistically low-risk, with an average of less than one person in a thousand dying or suffering irreversible damage. However, if the system is “Prigoginean”, a perturbation can amplify itself so as to change the average values. In that case, attempts to deal statistically with those situations are unsatisfactory not only socially but also scientifically, and the “side-effects” can be unpredictable and more important than the intended effects.

2. Scientific research about complex, self-aware systems such as those relevant for risk-analysis of environmental changes, health or nuclear hazards, and the like, 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-organisation, 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.

We might give numerous examples. Some that are currently in the news, include greenhouse gas emissions into the atmosphere and perturbations to climate patterns; cloning processes where the transmission of cell "biological age" is a complex phenomenon; medical drugs whose "side-effects" are unpredictable in time and from one species to another; genetic splicing and eventual population biology consequences (including the possible cross-fertilisation of genetically modified and non-modified strains of commercial food plants); nuclear fuel cycle experiments; new chemicals produced, or by-produced, for industrial processes.

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 & O'Connor 1999, Funtowicz, Ravetz & O'Connor 1998;). We will not seek to review the extensive literature that has emerged, over the past 30 years, on uncertainties and technological risks. One theme that emerges, is the suggestion that scientific enquiry could promote a reflexive attitude about risk, along the following lines of reasoning:

- 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 and, at a deeper level, an ideology of domination is at work. This partisan ideology 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.

## 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 inter-linkages 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.

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 characterisation of "what is necessary" may need drastic broadening to account for the inter-linkages between the object of study and other parts of reality.

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 inter-linkages. 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)<sup>8</sup> 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-organisation 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 characterisation 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 characterisation.

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.

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 inter-linked and complex nature of reality, a reality that science itself is revealing to us.

**Table 1. Comparing the two streams of the science of ecology.**

Attribute	Analytical	Integrative
Philosophy	<ul style="list-style-type: none"> <li>•narrow and targeted</li> <li>•disproof by experiment</li> <li>•parsimony the rule</li> </ul>	<ul style="list-style-type: none"> <li>•broad and exploratory</li> <li>•multiple lines of converging evidence</li> <li>•requisite simplicity the goal</li> </ul>
Perceived organisation	<ul style="list-style-type: none"> <li>•biotic interactions</li> <li>•fixed environment</li> <li>•single scale</li> </ul>	<ul style="list-style-type: none"> <li>•biophysical interactions</li> <li>•self-organisation</li> <li>•multiple scales with cross scale interactions</li> </ul>
Causation	<ul style="list-style-type: none"> <li>•single and separable</li> </ul>	<ul style="list-style-type: none"> <li>•multiple and only partially separable</li> </ul>
Hypotheses	<ul style="list-style-type: none"> <li>•hypotheses and null rejection of false hypotheses</li> </ul>	<ul style="list-style-type: none"> <li>•multiple, competing hypotheses</li> <li>•separation among competing hypotheses</li> </ul>
Uncertainty	<ul style="list-style-type: none"> <li>•eliminate uncertainty</li> </ul>	<ul style="list-style-type: none"> <li>•incorporate uncertainty</li> </ul>
Statistics	<ul style="list-style-type: none"> <li>•standard statistics</li> <li>•experimental</li> <li>•concern with Type I error (in hypothesis testing, rejecting the proposition when it is true).</li> </ul>	<ul style="list-style-type: none"> <li>•non-standard statistics</li> <li>•concern with Type II error (failing to reject the proposition when it is false).</li> </ul>
Evaluation goal	<ul style="list-style-type: none"> <li>•peer assessment to reach ultimate unanimous agreement</li> </ul>	<ul style="list-style-type: none"> <li>•peer assessment, judgment to reach a partial consensus</li> </ul>
The danger	<ul style="list-style-type: none"> <li>•exactly right answer for the wrong question</li> </ul>	<ul style="list-style-type: none"> <li>•exactly right question but useless answer</li> </ul>

*Source:* Holling (1998).

## Notes

1. It is to be noted that the term “Science” in the conference was used in most cases as meaning “natural sciences”.
2. Bovine spongiform encephalopathy (BSE).
3. Creutzfeldt-Jakob disease. The most common human spongiform encephalopathy which is characterised by a rapidly progressive dementia.
4. In abstract terms, the elements and the relations between the elements defines a system. The term "relation" is used here broadly to include also similar terms such as "constraint", "structure", "organisation", "cohesion", "interaction", "inter-connection", “correlation”, "pattern".
5. A socio-ecological system has been defined as any system including both ecological (or biophysical) and human components, ranging in scale from the household to the planet (Gallopín et al. 1989).
6. See the Internet site <http://inn.ingrm.it/compsys/manife.htm>.
7. In more general terms, the issue is multiplicity of levels in a hierarchical system (of which scale is a particular case). For a broader discussion of hierarchical systems in the context of sustainable development see Gallopín (1991).
8. But not just because, e.g., the experimental setup is pre-designed to eliminate linkages.

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