Article

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The Precautionary Principle and Ecological Hazards of Genetically Modified Organisms

This paper makes three points relevant to the application of the precautionary principle to the regulation of GMOs. *i*) The unavoidable arbitrariness in the application of the precautionary principle reflects a deeper epistemological problem affecting scientific analyses of sustainability. This requires understanding the difference between the concepts of "risk", "uncertainty" and "ignorance". *ii*) When dealing with evolutionary processes it is impossible to ban uncertainty and ignorance from scientific models. Hence, traditional risk analysis (probability distributions and exact numerical models) becomes powerless. Other forms of scientific knowledge (general principles or metaphors) may be useful alternatives. *iii*) The existence of ecological hazards *per se* should not be used as a reason to stop innovations altogether. However, the precautionary principle entails that scientists move away from the concept of "substantive rationality" (trying to indicate to society optimal solutions) to that of "procedural rationality" (trying to help society to find "satisficing" solutions).

INTRODUCTION

The precautionary principle was explicitly recognized during the United Nations Conference on Environment and Development (UNCED) in Rio de Janeiro, 1992, and included in the Protocol on Biosafety signed in the Convention on Biological Diversity, 28 January 2000 (1). It justifies early action in the case of uncertainty and ignorance in order to prevent potential harm to the environment and human health: "the principle states that potential environmental risks should be dealt with even in the absence of scientific certainty"(2). Obviously, its very definition introduces a certain ambiguity in its possible enforcement. How to decide if the potential environmental risk is sufficient to warrant action? In spite of the difficulty in its application, the precautionary principle has recently been restated as a key guiding concept for policy in a communication from the European Commission (1). This move has increased tension between stakeholders because there is "considerable confusion, and differing perspectives, particularly on different sides of the Atlantic, amongst scientists, policymakers, business people and politicians, as to what the precautionary principle does, or should, mean" (3). Given the difficulty in obtaining reliable cost-benefit quantifications for uncertain future scenarios of environmental hazards (4), the precautionary principle is often regarded as a disguised form of protectionism (5, 6) or even as a Trojan horse used by activists moved by ideological biases against technological progress (7).

Indeed, the message of the precautionary principle is clear in its substance, but extremely vague when it comes to practical applications. Its implicit demand for a more effective way of managing hazards than traditional scientific risk assessments (2) is generating heated discussions in the scientific community of traditional risk analysis. There are those that still stand for numbers and hard proofs as requisite for action, while others call for the adoption of a new paradigm in science for governance (8).

Against this background, I elaborate on 3 main points:

i) In order to understand the practical problems faced when trying to operationalize the precautionary principle, one should be aware of the clear distinction between the scientific concepts of risk, uncertainty, and ignorance. I discuss these concepts and question the current practice of only using traditional risk analysis when discussing large-scale release of genetically modified organisms (GMOs) into the environment and sustainability in general.

ii) Alternative analyses can be used to deal with the ecological hazards of large-scale release of GMOs. I illustrate the possible use of metaphors derived from systems analysis and network analysis, and of general ecological principles.

iii) A paradigm shift is needed when dealing with integrated assessment of sustainability. I will argue that the scientific community should move from the paradigm of 'substantive rationality' (trying to indicate to society optimal solutions) to that of 'procedural rationality' (trying to help society in finding 'satisficing' solutions).

SCIENTIFIC DISTINCTION BETWEEN RISK, UNCERTAINTY AND IGNORANCE

The distinction between risk, uncertainty, and ignorance described below draws on the work of Knight (9), Rosen (10), and Kampis (11). Knight distinguishes cases in which it is possible to use previous experience to infer future events from cases in which such an inference is not possible. Rosen, in more general terms, alerts to the need of being always aware of the clear distinction between a natural system, which is operating in complex reality, and the representation of a natural system, which is scientist-made. Finally, Kampis introduces the notion of 'self-modifying systems' which applies to self-organizing autopoietic systems—a class of systems investigated by Maturana and Varela (12). These systems continuously add new types and eliminate obsolete types from the set of their components. This implies the unavoidable emergence of new relational functions—true novelties in the form of interactions among components in relation to a given context. Clearly, this continuous process of 'becoming' would require the continuous addition of new variables and inferential systems to the scientific tool kit used to describe these systems, in order to be able to properly catch and simulate new interactions and new contexts.

Because scientists can handle only a finite information space, any scientific representation requires a prior mapping, within a structured information space, of some of the relevant qualities of the natural system (using a selection of a finite set of encoding variables). As a consequence, such finite and closed mapping implies: *i*) the inevitable loss of some of the qualities of the natural system (those not included in the selected set of relevant qualities included in the model); and *ii*) an unavoidable "expiration date" of the validity of the modeling relation when dealing with self-modifying systems.

Using these concepts it is possible to make the following distinction (for a more detailed discussion see (13)).

Risk applies to a situation in which it is possible to assign a distribution of probabilities to a given set of possible outcomes. For example, the risk of losing when playing roulette. Risk implies an information space, used to represent the behavior of the investigated system, that is closed, finite, discrete, known and useful; it includes all the relevant qualities to be considered for a sound problem structuring. Risk requires that we have a set of valid models and that we can forecast and usefully represent what will happen at a particular point in space and time. Then, the expected errors in predicting the future outcomes are negligible or at least predictable.

Uncertainty applies to a situation in which it is not possible to predict with accuracy what will happen. Even when there is some knowledge about possible outcomes and relevant attributes to be adopted in the model, there is doubt about the validity of this information. The concept of uncertainty implies an information space, which is finite, discrete, and assumed to be closed, known, and partially useful. But, at the same time, there is awareness that it is not possible to predict, with the required accuracy, the movement of the system in its accessible state space; and that the assumptions about the validity of the model can fail. This leads to two possible forms of uncertainty: uncertainty due to indeterminacy and uncertainty due to ignorance.

Uncertainty due to indeterminacy refers to a situation in which there is reliable knowledge about possible outcomes and their relevance, but in which it is impossible to predict, with the required accuracy, the movement of the system in its accessible state space. An example is the weather forecasting for New York City in 60 days from now. Indeterminacy is unavoidable when dealing with nested hierarchical systems or with “reflexivity” of humans. In these cases, simultaneous relevance of characteristics of elements operating on different scales (the need of considering more than one relevant dynamic in parallel on different space-time scales) and nonlinearity in the mechanisms of control (the existence of cross-scale feedbacks) entail that expected errors in predicting future outcomes can become high; e.g. due to loops or sudden changes in the structure of entailments in human societies—laws, rules, opinions. Uncertainty due to indeterminacy implies that we are dealing with problems which are classifiable—we have valid categories for the problem structuring—but not fully measurable and predictable.

Uncertainty due to ignorance refers to a situation in which it is not even possible to predict what will be the set of attributes that will result relevant for a sound problem structuring. Ignorance is unavoidable when dealing with evolving systems i.e. systems belonging to the class of self-modifying (11) systems, also called ‘becoming systems’ by Prigogine (14). In fact, in this case, the information space that would be required to catch the relevant behavior of the observed system is open and expanding. Any model of these systems based on a finite and discrete number of attributes, even if validated in the past, tends to miss relevant system qualities. Thus, ignorance implies acknowledging that the selection of the set of relevant qualities adopted to describe the problem is not completely valid. The worst aspect of scientific ignorance is that it shows only through experience, when the importance of events (attributes) neglected in a first analysis becomes painfully evident. For example, Marie Curie, who won two Nobel prizes (in physics and chemistry) for her outstanding knowledge of radioactive materials, died of leukemia. The link between leukemia and handling of radioactive material is well-known today, but was not fully understood in the early days of this scientific field.

Even admitting that ignorance means exactly that it is not possible to guess the nature of future problems and possible consequences of our ignorance, this does not mean that it is not possible to predict, at least, when such ignorance can take on dangerous forms. For example, in a situation of rapid transition involving large-scale structural changes, we may expect that we will soon have to consider new relevant qualities, include new criteria of performance in our analyses, and use new epistemological categories in our models.

In conclusion, in all cases in which uncertainty or ignorance can be expected to substantially affect scientific analyses, one should not exclusively rely on models reflecting a finite information space. No matter how well these models were validated in the past, the resulting body of knowledge is likely to miss some qualities of the system that were irrelevant until now, but that may be relevant in the future. In such a situation, the exclusive use of numbers and hard proofs, as the ultimate source of truth in decision making, is just a sign of ignorance of the unavoidable existence of scientific ignorance.

ECOLOGICAL PRINCIPLES AND HAZARDS OF LARGE-SCALE ADOPTION OF GENETICALLY MODIFIED ORGANISMS

Is there someone that can calculate the risks, e.g. probability distributions, for a world largely populated by genetically modified organisms? Given the above definition of risk, the answer must be no. Nobody can know or predict the consequences of a large-scale alteration of genetic information in plants and animals. The consequences of this perturbation should be considered on various different hierarchical levels and nonequivalent dimensions of interest (human health, health of local ecosystems, health of economies, health of communities, health of the planet as a whole) (13).

The mad-cow disease nicely illustrates this issue. In the discussion of the use of animal protein to feed herbivores in the 1980s, with the aim to augment the efficiency of beef production, nobody could have calculated the ‘risk’ of the insurgence of Bovine Spongiform Encephalopathy (BSE). To do that, one should have known that a hitherto unknown brain protein, known nowadays as *prion*, could lead to an animal disease that also affects human beings (15).

When dealing with a complex problem, such as the forecasting of possible side effects of a change imposed on an adaptive self-organizing system, metaphors—even if developed within other scientific disciplines—can be more useful than validated models developed in the field of interest. In the specific case of animal feed regulation, for example, one could have found useful indications from the field of network analysis. Network analysis shows that a ‘hypercycle’ in a network is a source of trouble, e.g. microphone feedback to the amplifier to which it is connected (16). Indeed, also in dynamic system analysis it is known that a required level of accuracy in predictions cannot be maintained in the presence of autocatalytic loops. That is, when an output feeds back as input, even small levels of indeterminacy can generate unpredictable large effects—the so-called ‘butterfly effect’.

For example, the idea of cows eating cows implies a clear violation of basic principles describing the stability of ecological food webs (probable troubles). Therefore, the need of extreme precaution when implementing such a technique of production could have been guessed before knowing of the technicalities regarding the specific mad cow disease (the specific set of troubles). The lesson to be learned is clear. When dealing with a new situation it is not wise to rely only on the ‘assessment of probabilities’ provided by experts that claim to prove that there is negligible risk. Numerical assessments of risks must necessarily assume that the old problem structuring will remain valid in the future. This is usually an incorrect assumption for complex adaptive systems (10, 11, 16, 17). Thus, in these cases system thinking may be more useful because it shows that large-scale infringing of systemic principles will lead, sooner or later, to some yet-unknowable, and possibly unpleasant, events. Below, I further elaborate an example of system thinking to characterize potential problems related to large-scale adoption of genetically modified organisms in agricultural production.

REDUCTION OF EVOLUTIONARY ADAPTABILITY AND INCREASED FRAGILITY

Adaptability and flexibility are crucial qualities for the sustainability of adaptive systems (11, 16–19). They both depend on the ability of preserving diversity. The ability to preserve diversity is also the foundation of democracy. However, the goal of preserving diversity *per se* collides with that of augmenting efficiency at a particular point in space and time (analogous to the problematic of total anarchy). Efficiency, in fact requires: a) elimination of those activities that are less-performing according to a given set of goals, functions and boundary conditions; and b) amplification of those activities perceived as best-performing at a given point in space and time. Clearly this general rule applies also to technological progress in agricultural production. Improving world agriculture, according to a given set of goals expressed by the social group in power and according to the present perception of boundary conditions, has led to a reduction of the diversity of systems of production, e.g. abandoning traditional systems of agricultural production. On the other hand, these 'obsolete' systems of production often show high performance when adopting different goals or criteria of performance (20).

Several ecologists, following the pioneering work of E.P. Odum (21), H.T. Odum (22) and Margaleff (23), have pointed at the existence of 'systemic properties' of ecosystems that are useful to study and formalize the effect of changes induced in these systems. Recent developments of these ideas within the emerging field of complex system theory led to the generation of concepts such as ecosystem integrity (24) and ecosystem health (25). Methodological tools to evaluate the effect of human-induced changes on the stability of ecological processes focus on structural and functional changes of ecosystems (16, 23) using: relative size of functional compartments; the value taken by parameters describing expected patterns of energy and matter flows; the relative values of turnover times of components; and the structure of linkages in the network. In particular, network analysis can be usefully applied in the analysis of ecological systems (26, 27) to:

i) explore the difference between development (harmony between complementing functions, including efficiency and adaptability, reflected into the relative size of the various elements) and growth (increase in the throughput obtained by a temporary take over of efficiency over diversity);

ii) estimate the relative magnitudes of investments in efficiency and adaptability among the system processes.

When looking from this perspective at possible large-scale effects from massive use of GMOs in agricultural production, it shows that current research in genetic engineering goes against sound evolutionary strategies for the long-term stability of terrestrial ecosystems (28). That is, the current direction of technological development in agriculture implies a major takeover of efficiency over adaptability; based on the representation of benefits on a short-term horizon and using a limited set of attributes of performance. For example, the number of species operating on our planet is in the order of millions, within which the edible species used by humans are in the order of thousands (29). However, due to the continuous demand for more efficient methods of production, 90% of world food is produced today using only 15 vegetal and 8 animal species (30). Within these already few species used in agriculture, the continuous search for better yields (higher efficiency) is liquidating the wealth of diversity of varieties accumulated over millennia of evolution (31). FAO estimates that the massive invasion of commercial seeds resulted in a dramatic threat to the diversity of domesticated species. In fact, available data on genetic erosion within cultivated crops and domesticated animals are simply scaring (32, 33). This is a good example of an important and unexpected negative side effect generated by large-scale application of the green revolution (34).

C.S. Holling, another of the fathers of modern ecology, uses a famous line to indicate the negative consequences of lack of diversity of ecological processes in terms of increased fragility: "a homogeneous ecological system is a disaster waiting to happen" (35, 36). Technological progress in agriculture can easily generate the effect of covering our planet with a few best-performing high-tech biologically organized structures; e.g. a specific agent of pest resistance coded in a piece of DNA. In this case it will almost be sure that, due to the large scale of operation, something that can go wrong, even if having a negligible probability in a laboratory setting, will go wrong. The resulting perturbation, e.g. some unexpected and unpleasant feedback, could easily spread through the sea of homogeneity, i.e. genetically modified monocultures, giving little or no time to scientists to develop mechanisms of control.

The threat of reduction of biodiversity applies also to the diversity of habitats. Moving agricultural production into marginal areas (in agronomic terms), hitherto inaccessible to traditional crops, is often listed among the main positive features of GMOs. In this way, humans will destroy the few terrestrial ecosystems left untouched, escaping until now from excessive exploitation that provide diversity of habitats essential for biodiversity preservation. In this regard, note that humans already appropriate a significant fraction of the total biomass produced on earth each year (37).

But even when looking at potential positive effects, one is forced to question the credibility of the claim of GMOs developers that they will be able to increase the eco-compatibility of food production for 10 billion people. Given the basic principles of agroecology (38, 39), one is forced to question the idea that simply putting a few high-tech seeds of genetically modified crop plants in the soil could stabilize nutrient cycles within terrestrial ecosystems at a pace dramatically different from the actual ones. This is like trying to convince a physician that by manipulating a few human genes it will be possible to feed humans 30 000 kcal of food per day—ten times the physiological rate—without incurring any negative side effects. An ecological metaphor can also be used to check this idea (28). Even if we "engineer" a super spider, potentially able to catch 10 times more flies than the ordinary species, the super spider will be limited in its population growth by the availability of flies to eat. Flies in turn will be limited, in a circular way, by other elements of the terrestrial ecosystem in which they live. Unless we provide an extra supply of food for these super spiders, their enhanced characteristics will not help them to expand in a given ecological context. This concept can be translated to agriculture: If one takes away from an ecosystem many tonnes of biomass per ha with "super harvests", then one has to put enough nutrients and water back into the soil in order to sustain the process in time, to support the relative photosynthesis. This is why high-tech agriculture is based on the systematic breaking of natural cycles, independently from the presence of GMOs. That is high tech agriculture necessarily has to be a high-input agriculture (40). Talking of the green revolution, E.P. Odum notes: "cultivation of the 'miracle' varieties requires expensive energy subsidies many underdeveloped countries cannot afford" (21). Because of the high demand of technical capital and know-how of high-input agriculture many agro-ecologists share the view of the difficulty of implementing high-tech, GMO-dependent production in developing countries (41).

As soon as one looks at ecological effects of innovations in agriculture, one finds that important side effects often tend to be ignored. For example, 128 species of the crops that have been intentionally introduced in the United States have become serious weed pests, which are causing more than USD 30 thousand million in damage and control costs each year (42). When dealing with ecological systems, and in particular with the growing awareness of the possible impact of GMOs on nontarget species and additional ecological side effects (43), one should always keep the following (old) aphorism in mind: "You can never do just one thing".

PRECAUTIONARY PRINCIPLE AND THE REGULATION OF GENETICALLY MODIFIED ORGANISMS

The economic implications of national regulations for the protection of the environment, and of human, animal, and plant health can be huge. In relation to international trade of genetically modified food, the following quotation illustrates this quite clearly. "US soybean exports to EU have fallen from 2.6 billion annually to 1 billion . . . Meanwhile, Brazilian exporters are doing a brisk business selling "GE-free" soybeans to European buyers. . . . James Echle, who directs the Tokyo office of the American Soybean Association, commented, 'I don't think anybody will label containers genetically modified, it's like putting a skull and crossbones on your product'" (43).

This is why the trade dispute between the EU and the USA over genetically modified food is bringing the precautionary principle on the top of the political agenda. In this particular example, in spite of the increasing attention given to the relationship between environment and trade (44), the interpretation of the various key agreements on international trade is still a source of bitter controversy (45).

Also within the European Union, the precautionary principle is generating arguments between the Commission and individual member states in relation to the moratorium on field trials on GM crops (46), as well as among different ministers within national governments in relation to the funding of research on GMOs (46). Again, it is easy to explain such a controversy. The simple fact that there is 'hazard' associated with large-scale adoption of GMOs in agriculture does not imply *per se* that research and experimentation in this field should be stopped altogether. Current demographic trends clearly show that we are facing a serious hazard (social, economic, ecological) related to future food production, although the successful and safe translation of high-tech methods to an appropriate agricultural practice is widely recognized as being problematic. Such a hazard applies to all forms of agricultural development also when excluding GMOs.

However, deciding whether or not there is sufficient scientific evidence to justify action requires a broader perspective on the hazards, a perspective that goes beyond reductionist science. In particular, the weighting of evidence must be explicit, as well as the inclusion of issues of actual practice, technology, environment and culture.

Life is intrinsically linked to the concept of evolution, which implies that "hazard" is a structural and crucial feature of life. Current debates on the application of the precautionary principle to the regulation of GMOs are simply pointing at a deep and much more general dilemma faced by all evolving systems. Any society must evolve in time and as a consequence it must take chances, when deciding how and when to innovate. This predicament cannot be escaped, whether society decides to take action (because of what is done) or not to take action (because of what is not done) (47). Technical innovations have an unavoidable component of gambling. Possible gains have to be weighted against possible losses in a situation in which it is not possible to predict exactly what may happen (28). This implies that when dealing with processes expressing genuine novelties and emergence we are moving in a field in which traditional risk analysis is basically helpless.

The challenge for science, within this new framework, becomes that of remaining useful and relevant even when facing an unavoidable degree of uncertainty and ignorance. The new nature of the problems faced in this third millennium, due to the dramatic speed of technical changes and globalization, implies that more and more decision makers face situations *"where facts are uncertain, values in dispute, stakes high and decisions urgent"* (48). That is, when the presence of 'uncertainty/ignorance' and 'value conflict' is crystal clear from the beginning, it is not possible to individuate an objective and scientifically determined 'best course of action'. This requires moving from the concept of 'substantive rationality' to that of 'procedural rationality' (49, 50). Put in another way, when dealing with this growing class of problems the era of closed expert committees seems to be over. Crucial to this change of paradigm is the re-discovery of the old concept of scientific ignorance, which goes back to the very definition of scientists given by Socrates: "scientists are those who know about their ignorance."

These are relevant points since on the basis of the Agreement on the Application of Sanitary and Phytosanitary Measures (valid since January 1995) the World Trade Organization authorizes (or prevents) (article 2.2) all member countries to enforce the precautionary principle if there is [not] "enough" scientific evidence (51). In particular, article 2.2 has been used to oppose compulsory labeling of genetically modified food. The reasoning behind this opposition appears to be based on the concept of "substantive rationality" and it is well illustrated by a paper of Miller (7) on the Policy Forum of Science. Labeling requirements should be prevented since they "may not be in the best interest of consumers" (7). The same paper identifies the best interest of consumers with lower production costs, possibility of achieving economies of scale, and keeping at maximum speed research and development of GMOs, i.e. maximization of efficiency. Referring to a decision of the U.S. Court of Appeals, against labeling requirements, he comments: "labeling cannot be compelled just because some consumers wish to have the information" (7).

Two questions can be used to put in perspective the difference between the paradigm of substantive rationality and that of procedural rationality when dealing, as in this case, with scientific ignorance and legitimate contrasting perspectives:

- What if the perception of 'the best interest of consumers' adopted by the committee of experts does not coincide with the set of criteria considered relevant by the consumers themselves? For example, assume that there is a general agreement among scientists that the production of pork is more efficient and safer than production of other meats. Should then the government deny Muslims or Jews the right to know—through a label—whether or not the meat products they buy do include pork? If we agree that Muslims and Jews have a right to know, then why should consumers that are concerned with the protection of the environment have less right to know—through a label—if the food products they buy contain components that are derived from GMOs?
- What if the assessment of 'better efficiency and negligible risk' provided by the committee of experts will turnout to be wrong? Actually this is exactly what happened in the European Union with the decisions regulating the use of animal protein feeds for beef production, the move that led to the insurgence of mad cow disease.

Globalization implies a period of rapid transition in which the global society as a whole has to learn how to make tough calls finding the right compromise between 'too much' and 'too little' innovation. Since nobody can know *a priori* the best possible way of doing that, satisficing solutions (49), rather than optimal solutions, to this challenge can only be found through a process of social learning on how to better perceive, describe and evaluate the various trade-offs of sustainability. Scientists have a crucial role to play in this process. But to do that, they have to learn how to help rather than hamper this process. In this respect, the concept of "scientific ignorance" is very useful to put back scientists within society ("procedural rationality" requires a two-way dialogue) rather than above the society ("substantive rationality" implies a one-way flow of information).

References and Notes

1. Commission of the European Communities 2000. *Communication from the Commission on the Precautionary Principle.* COM(2000)1, Brussels, 02.02.2000. (http://europa.eu.int/comm/off/com/health_consumer/precaution.htm)
2. Macilwain, C. 2000. Experts question precautionary approach. *Nature 407*, 551.
3. European Environment Agency. *Late Lessons from Early Warnings: The Precautionary Principle 1898–1998.* Copenhagen (In press).
4. O'Connor, M. and Spash, C. (eds) 1998. *Valuation and the Environment: Theory, Methods and Practice*. Edward Elgar, Cheltenham.
5. The EU Committee of the American Chamber of Commerce in Belgium 2000. *Position paper on the Precautionary Principle.* (http://www.eucommittee.be/pop/pop2000/Env/env)
6. Foster, K.R., Vecchia, P. and Repacholi, M.H. 2000. Science and the precautionary principle. *Science 288*, 979–981.
7. Miller, H. 1999. A rational approach to labeling biotech-derived foods. *Science 284*, 1471–1472.
8. Funtowicz, S.O. and Ravetz, J.R. 1992. Three types of risk assessment and the emergence of post-normal science. In: *Social Theories of Risk*. Krimsky, S. and Golding, D. (eds). Praeger, Westport (CT) and London, pp. 251–273.
9. Knight, F.H. 1964. *Risk, Uncertainty and Profit.* A. M. Kelley, New York.
10. Rosen, R. 1985. *Anticipatory Systems: Philosophical, Mathematical and Methodological Foundations.* Pergamon Press, New York.
11. Kampis, G. 1991. *Self-Modifying Systems in Biology and Cognitive Science : A New Framework for Dynamics, Information and Complexity.* Pergamon Press, Oxford, 543 pp.
12. Maturana, H.R. and Varela, F. 1980. *Autopoiesis and Cognition.* Reidel, Dordrecht.
13. Giampietro, M. Complexity and scales: the challenge for integrated assessment. In: *Scaling Issues in Integrated Assessment.* Rotmans, J. and van Asselt, M. (eds). Kluwer Academic Publisher, Dordrecht, The Netherlands (In press).
14. Prigogine, I. 1978. *From Being to Becoming*. W.H. Freeman and Company, San Francisco (CA).
15. For an overview of the issue visit (www.mad-cow.org/)
16. Ulanowicz, R.E. 1986. *Growth and Development: Ecosystem Phenomenology.* Springer-Verlag, New York.
17. Gell-Man, M. 1994. *The Quark and the Jaguar.* Freeman, New York.
18. Conrad, M. 1983. *Adaptability: The Significance of Variability from Molecule to Ecosystem.* Plenum Press, New York.
19. Holling, C.S. 1995. Biodiversity in the functioning of ecosystems: an ecological synthesis. In: *Biodiversity Loss.* Perring, C. et al. (eds). Cambridge University Press, Cambridge, pp. 44–83.
20. Altieri, M.A. 1987. *Agroecology: The Scientific Basis for Alternative Agriculture.* Westview Press, Boulder (CO).
21. Odum E.P. 1989. *Ecology and Our Endangered Life-Support Systems.* Sinauer Associated, Sunderland, MA.
22. Odum H.T. 1983. *Systems Ecology.* John Wiley, New York.
23. Margalef, R. 1968. *Perspectives in Ecological Theory*. University of Chicago Press, Chicago.
24. Ulanowicz, R.E. 1995. Ecosystem integrity: A causal necessity. In: *Perspectives on Ecological Integrity*. Westra, L. and Lemons, J. (eds). Kluwer Academic Publishers, Dordrecht, pp. 77–87.
25. Kay, J.J., Regier, H., Boyle, M. and Francis, G. 1999. An ecosystem approach for sustainability: addressing the challenge of complexity. *Futures 31,* 721–742.
26. Fath, B.D. and Patten B.C. 1999. Review of the foundations of network environ analysis. *Ecosystems 2*, 167–179.
27. Ulanowicz, R.E. 1997. *Ecology, The Ascendent Perspective.* Columbia University Press, New York (NY), 242 pp.
28. Giampietro, M. 1994. Sustainability and technological development in agriculture: A critical appraisal of genetic engineering. *BioScience 44,* 677–689.
29. Wilson E.O. (ed.) 1988. *Biodiversity.* National Academy Press, Washington D.C., 521 pp.
30. FAO statistics (http://apps.fao.org/page/collections?subset=nutrition)
31. Simmonds, N.W. 1979. *Principles of Crop Improvement.* Longman, U.K.
32. Food and Agriculture Organization (FAO) 1996. *The State of the World's Plant Genetic Resources for Food and Agriculture*. Background Documentation prepared for the International Technical Conference on Plant Genetic Resources, Leipzig, Germany, 17–23 June 1996. FAO, Rome.
33. Scherf, B.D. 1995. *World Watch List for Domestic Animal Diversity.* FAO, Rome.
34. Giampietro, M. 1997. Socioeconomic constraints to farming with biodiversity. *Agricult. Ecosyst. Environ. 62*, 145–167.
35. Holling, C.A.S. 1996. Engineering resilience vs ecological resilience. In: *Engineering within Ecological Constraints*. Schulze, P.C. (ed.). National Academy Press, Washington D.C., pp. 31–43.
36. Holling, C.A.S. 1986. The resilience of terrestrial ecosystems: local surprise and global change. In: *Sustainable Development of the Biosphere.* Clark W.C. and Munn, R.E. (eds). Cambridge University Press, Cambridge (UK), pp. 292–317.
37. Vitousek, P.M., Ehrlich, P.R., Ehrlich, A.H. and Matson, P.A. 1986. Human appropriation of the products of photosynthesis. *BioScience 36,* 368–373.
38. Gliessman, S.R. 2000. *Agroecology: Ecological Processes in Sustainable Agriculture.* Lewis Publisher, Boca Raton, FL.
39. Pimentel, D. and Pimentel, M. 1996. *Food, Energy and Society* (revised edition). University Press of Colorado, Niwot (CO).
40. Altieri, M. 1998. *The Environmental Risks of Transgenic Crops: An Agro-ecological Assessment.* Department of Environmental Science, Policy and Management, University of California, Berkeley.
41. Altieri, M. 2000. *Executive Summary of the International Workshop on the Ecological Impacts of Transgenic Crops.* (http://www.biotech-info.net/summary1.pdf)
42. Pimentel, D., Lach, L., Zuniga, R. and Morrison, D. 2000. Environmental and economic costs of non-indigenous species in the United States. *BioScience 50,* 53–65.
43. Cummins, R. 2000. GMOs around the world. *IFOAM – Ecology and Farming.* May-August 9 2000.
44. UNEP/IISD 2000. *Environment and Trade: a Handbook.* (http://www.unep.ch/etu/ or htpp://iisd.ca/trade/handbook)
45. Greenpeace 2000. *WTO Must Apply the Precautionary Principle.* htpp://www.greenpeace.org/majordomo/index-press-release/1999/msg00121.html.
46. Meldolesi, A. 2000. Green ag minister wreaks havoc on Italy's ag biotech. *Nat. Biotechnol. 18,* 919–920.
47. Ravetz, J.R. 2001. Safety in the globalising knowledge economy: an analysis by paradoxes. *The Journal of Hazardous Material* (special issue on risk and governance), De Marchi, B. (ed.) (In press).
48. Funtowicz S.O. and Ravetz, J.R. 1991. A new scientific methodology for global environmental issues. In: *Ecological Economics.* Costanza, R. (ed.). Columbia Press, New York, pp. 137–152.
49. Simon, H.A. 1976. From substantive to procedural rationality. In: *Methods and Appraisal in Economics.* Latsis, J.S. (ed.). Cambridge University Press, Cambridge.
50. Simon, H.A. 1983. *Reason in Human Affairs.* Stanford: Stanford University Press.
51. http://www.wto.org/english/tratop_e/sps_e/spsagr_e.htm

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