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ARTIGOS ORIGINAIS

The precautionary principle and environmental risk management: contributions and limitations of economic models

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ABSTRACT

This article presents the most relevant economic approaches and models that have been developed for the economic interpretation of the precautionary principle. The aim is to identify their contribution to the debate on precaution and discuss their practical significance in public decision-making. In addition to analysing their virtues and main limitations some actions aimed at overcoming these limitations are also identified. The concept of precaution is of great relevance in environmental regulation in many countries. However, legislation about the use of the precautionary principle in environmental decision-making is somewhat vague. As a result, there is broad consensus on the need for a regulatory framework for the principle's operational implementation so that concepts and management procedures that are appropriate to the nature of environmental risks are clarified.

Keywords: Precautionary principle; Environmental risk; Economic models.

RESUMEN

En este artículo se presentan los modelos más relevantes que se han desarrollado para la interpretación económica del principio de precaución y su aplicación con el fin de conocer su contribución al debate sobre la precaución y discutir su relevancia

práctica para la decisión pública. Sus principales virtualidades y limitaciones también se analizan. Se identifican algunas medidas para superar las limitaciones existentes. El concepto de precaución tiene una gran relevancia en el presente en la regulación ambiental en muchos países. La legislación es, sin embargo, vaga en cuanto a la aplicación del principio de precaución en la toma de decisiones sobre la gestión de los riesgos ambientales. Por lo tanto, ha sido ampliamente mencionada la necesidad de cuadros reguladores para la implementación operativa de este principio, para aclarar conceptos y procedimientos adecuados a la naturaleza de los riesgos.

Palabras-clave: Principio de precaución; Riesgo ambiental; Modelos económicos.

Introduction

The concept of precaution is of great relevance in environmental regulation in many countries. Despite the somewhat vague nature of the legislation, some attention has recently been given to the precautionary principle within frameworks and models of economic interpretation and their application.

A significant part of the literature on the subject highlights the need for regulatory frameworks for the operational implementation of the precautionary principle in public decision-making. Appropriate concepts and management procedures for environmental risks should be clarified. It is therefore important to know the most relevant economic approaches and models for the debate on precaution and to discuss their practical relevance for public decision.

This paper outlines formal models that interpret the precautionary principle and its main virtues and limitations in the context of environmental risk management. In order to contribute to the debate on the operational implementation of the precautionary principle, some actions are also identified that can overcome the models' limitations.

The paper is structured as follows. Section 2 introduces the concept and main aspects of the precautionary principle. Section 3 briefly describes the most pertinent economic models for the interpretation of this principle. The relevance and limitations of formal models for precautionary decision-making is also analysed. Section 4 presents a set of initiatives that may help overcome some of the limitations of formal models for precautionary decision-making. Finally, Section 5 concludes.

The precautionary principle: concept and key elements

The precautionary principle is currently a fundamental principle of environmental regulation in many countries. In the European Union, it was enshrined in article 130 R (2)[1] of the Treaty of Maastricht (1992), and reference is made to it by Member States (in national, regional and local legislation) and the European Commission (in action programmes, directives, declarations and recommendations). In the U.S., programmes and precautionary measures are applied at state and at local level[2] and, although not explicitly mentioned in legislation and federal policies, the

precautionary principle is subjacent to a large part of environmental legislation. It has also been explicitly mentioned in many conferences and international treaties, e.g. the UN Conference on Environment and Development (Rio Summit) (1992) and the Convention on Biodiversity (2000) (UNCED, 1992; Protocol of Cartagena, 2000) and other instruments of international law, such as international trade legislation.

Not only do existing publications and international declarations and treaties offer different definitions of precaution, but the level of intervention demanded also varies - more optional in some cases (such as in the Rio Declaration) and more binding in others (e.g., the European Commission Communication (CE, 2000)).

Principle 15 of the Rio Declaration is one of the most representative definitions: 'In order to protect the environment, the precautionary principle should be widely applied by States according to their capabilities. Where there are threats of serious or irreversible damage on the environment, lack of full scientific certainty should not be used as a reason for postponing cost - effective measures to prevent environmental degradation' (UNCED, 1992).

Much has been published on the interpretation and practical implementation of the precautionary principle[3]. Despite some ambiguity of the different discourses on precaution, most definitions share common key elements. Essentially, the scientific community and policy makers do not differ in their identification of the main issues when putting precaution into practice, namely (GONÇALVES, 2008):

- The duty to take advance action to protect the environment and public health when dealing with suspected risks (uncertain), especially if they are potentially serious or irreversible;

- The demand for more and better scientific information for the assessment of hazards and risks;

- The consideration of a broad set of options for action;

- As complete an analysis and assessment as possible of the costs and benefits of policy alternatives, including the analysis of their distribution among the different actors;

- The continuous monitoring and review of the precautionary measures adopted in light of the development of information and scientific knowledge.

The precautionary principle has gained relevance in recent decades with the emergence of the 'new risks' of technology and the environment, which are generally characterised by limited and uncertain scientific knowledge, a collective and involuntary nature, and the low probability of potentially or even irreversible high damage (OECD, 2003; STIRLING, 2007). This applies for example to climate change, biodiversity loss, radiological exposure, the effects of chemicals, food safety, biotechnology and nanotechnology (SEHN, 2009; ROGERS, 2011).

Precautionary situations are generally risk scenarios in which the causal chain that goes from the hazard to the final effects is in some way uncertain because the causal relation can neither be established nor rejected. This involves complex situations where risks are multi-causal and involve uncertainty and/or ambiguity (RENN, 2008)[4]. It includes electromagnetic fields (mobile phones and antennas) and their link with certain cancers, or nanomaterials and their specific and massive effects on populations (CPP, 2010).

However, the principle has still not been clearly or practically formulated and continues to be insufficient as a guideline for the design of regulatory policies. Many controversies have arisen about the level of environmental risk required to trigger the principle, the role of economic and social consequences and the severity of precautionary measures, particularly in situations where it is thought economic activity might be prejudiced[5] . Political (or judicial) entities are responsible for defining the configuration of this principle, and regulatory frameworks are required to implement it.

Economic models for the interpretation of the precautionary principle

The economic frameworks and models interpreting the precautionary principle can be grouped into two paradigms: rational - instrumental and deliberative - constitutive (FISHER *et al*, 2006).

The first considers the theory of choice under uncertainty; it involves economic concepts as well as psychology and statistical decision theory. Given the characteristics of the precautionary principle, the formal analysis within this paradigm is based on two main streams. The first stream is the theory of expected utility (Von Neumann and Morgenstern, 1944) and the effect of irreversibility and learning, initiated by ARROW and FISHER (1974) and HENRY (1974) and developed by GOLLIER *et al*. (2000) and GOLLIER and TREICH (2003). The decision-maker maximises expected utility based on the estimated costs and benefits of different options and alternatives, in a context that involves irreversibility. He/she also expects to get better information in the future and to be able to perform alternative sequential decisions on different dates. In addition, there are models that generalise the expected utility theory, allowing non linear weights to be placed on probabilities or the introduction of subjective probabilities (ALLAIS, 1953; ELLSBERG, 1961; KAHNEMAN and TVERSKY, 1979; QUIGGIN, 1982; SCHMEIDLER, 1989; BARGIACCI, 2004; SLOVIC *et al.*; 2010). The second stream is a response to the limitations of expected utility frameworks in situations of divergent expectations about uncertainty by different individuals. The models, referred to as 'ambiguity models' (MOREAU and RIVAUD-DANSET, 2004), consider imprecise and multiple probabilities and use decision criteria based on individual attitudes towards risk (GILBOA and SCHMEIDLER, 1989; LANGE and TREICH, 2009).

Secondly, the deliberative-constitutive paradigm considers multi-criteria frameworks and models, which include multiple objectives (environmental, economic, social, etc.) in decision-making and enable the integration of deliberative and participative processes (MUNDA, 2008; STIRLING and MAYER, 2005).

Table 1 provides a summary description of the economic models for interpreting the precautionary principle.

Table 1 – Summary description of the economic models for precaution

Model	Summary description
Classic framework of Expected Utility	- Precise scenarios of costs and benefits in the study of alternative options; - Known and objective probability distributions.
Model with irreversibility and learning	- Irreversibilities (in investment expenditures and environmental damage) and reduced uncertainty exist due to the gradual acquisition of new scientific information[vi]; - Strategies of sequential decision making; - The attitude of decision-makers towards risk is instrumental to choices[vii].
Model with nonlinear weights on probabilities	- Rank-dependent utility models[viii]; - Distorted behaviour of the likelihood of an extreme result (pessimistic or optimistic behaviour).
Model with subjective probabilities	- In situations without an objective database, "subjective" probability distributions are defined from expectations based on individual experience[ix].
Ambiguity model	- Intervals of probabilities; - When assessing the expected utility of each option, probability distribution that leads to the least favourable outcomes is retained (focus on the worst case scenario and its prevention); the action offering the maximum utility is then selected ("maximin" decision criterion).
Multicriteria model	- Multiple dimensions and objectives in precautionary decisions ; - Assessment based on multiple dimensions and their relative importance; - Participative and deliberative methods may be incorporated.

Advantages and limitations of models

Advantages

All formal models that convert the precautionary principle into economic terms help clarify the concept of precaution and decision-making. They frame a decision problem concerning the prevention and management of risks. They make an economic analysis of the impact of risks on individual and collective welfare.

Although theoretical models involve many simplifications, in general terms, they seek to represent interactions of multiple parts of a complex system with compelling axiomatic foundations. They reveal a number of challenges for implementation and the problems that need solving and they contribute to a better understanding of the behaviour of important system parameters.

a) The challenges of implementation

Formal models reveal a number of challenges for implementation such as incorporating the nature of attitudes towards risk, identifying the type and scope of the information to be integrated, and selecting decision making rules that allow a suitable description of economic choices.

Models based on expected utility consider the decision-maker's preferences based on his/her expectations of dangers given known and objective (or subjective, in the Savage model) probabilities. The Gollier *et al*. model also takes the progress of scientific knowledge about risks into consideration in these expectations. In ambiguity models, the decision maker's attitude to imprecision is found explicitly in the decision-making criterion considered in the choice of one among the various possible decisions.

The type and scope of information to be considered depends on the specification of models and scenarios defined for the consequences of decisions. In particular, Gollier *et al.* model includes scenarios that consider the possibility of reviewing the decision-maker's expectations due to the improvement of scientific knowledge. In ambiguity models, the consequences of each decision can be evaluated using multiple probability distributions, which allow different scientific theories to be represented, and thus, the opinion of all experts. Finally, multicriteria analysis allows qualitative and multidimensional information to be included together with the inclusion and weighting of possible conflicts of interest.

In the different models within the framework of expected utility theory, with their different payoff functions, the principle of the maximization of a social welfare function by the public decision-maker is subjacent to the decision rule. Ambiguity models consider decision-making criteria under uncertainty that reflect the decision maker's attitude towards uncertainty, e.g. the 'maximin' criterion. Finally, multicriteria models use functions that weight the multiple criteria considered.

b) Understanding the system's behaviour

In their own specific ways, the theoretical models contribute to a better clarification of the phenomena and of the reasoning behind individual and collective choices and their effects. They therefore contribute to the understanding of the behaviour of important parameters, such as risk perceptions, impacts and associated economic costs, and the level of protection required.

The GOLLIER *et al.* model, for example, establishes the rational nature of precautionary behaviour, understood as behaviour to reduce consumption, in the context of dynamic risk management. In ambiguity models, a choice is made between a set of possible actions based on a number of divergent expectations about risk scenarios. Multicriteria analysis allows the interests of the various entities involved in decision making to be monitored more closely, with the possible use of deliberative procedures.

The different models also allow the impacts and economic costs associated with different scenarios of consumption, production or pollutant emissions to be analysed and therefore the study of precautionary strategies.

Limitations

However, formal models have some strong limitations as they are focused more on concepts than practice. The use of models also raises the problem of obtaining relevant data and information to characterise the socio-political context and the space of events and results associated with the emergence of risk. These problems, and the conceptual and theoretical difficulties, have limited the practical application and the political relevance of precautionary decision tools.

On the other hand, formal models also present some important theoretical shortcomings, that are considered below.

a) Each model is only applicable to certain kinds of risks

As the different models are only applicable to certain kinds of risks, they cannot always be applied and must be selected on the basis of the nature of risks. This will also clarify the nature of precautionary analyses.

Thus, for example, whereas expected utility models are appropriate where risks are well-characterised or proven, this is not the case in the controversial context of 'new risks', where the probability distributions to represent the expectations are unknown or even non-existent. In such situations, multiple probabilities and ambiguity models are preferable.

Models that incorporate the role of irreversibility and learning should be applied when managing phenomena where there is a real possibility of improved future information and even confirmed risks, such as the greenhouse gas emissions or the ozone layer protection, but not to others, such as GMO crops, which could have an unacceptable human and social cost.

In addition to the nature of the risks, it is very important to clarify all the requirements of the precautionary principle in the specific context of each case, since the result of precautionary decision (whether or not to recommend conservation) is also dependent on other factors (TISDELL, 2005).

b) The inadequacy of single dimensional assessment

Controversies on the application of the precautionary principle often involve disputes about how to find a balance between competing interests in a context of great uncertainty where there is no clear technical solution (COONEY and DICKSON, 2005; Whiteside, 2006). In this situation, it is often necessary to evaluate and weight the technical, ecological, economic, social, ethical and political factors and interests interact in a complex system, and to manage any conflicts (COONEY and DICKSON, 2005).

The single-dimensional evaluation in most models is inadequate, notably in models in the expected utility theory that mainly strive for efficient choices according to preferences of decision-makers. In these models, the level of risk that society as a whole should bear is decided by a single decision maker. The multicriteria models are more suitable to address multidimensionality but they imply 'incommensurability of values'[10], and this may lead to operational constraints. Thus,

these models must be applied with great objectivity and transparency, especially in very complex and controversial areas.

c) Poor connection between individual and collective values

The analysis of public decisions involving collective risks requires the definition of levels of risk that are reasonable and accepted by society. In this regard, Gollier *et al*. considered an individual behaviour of lowering consumption in response to risks and disregarded other risk perceptions and attitudes. In the context of subjective probabilities, the risks perceived by the decision-maker may be in line with the scientific community's analysis, but the conditions for validiting the value judgements for collective decision-making remain unidentified.

As the ambiguity models lead to the representation of divergent expectations about hazards, they seem to allow the transparency of a consultation procedure for stakeholders and the possibility of reaching an agreement (MATHEU, 2002). However, the criterion they propose for collective management is unsuitable for the proportionate nature that precautionary measures should have.

Given the models' limited ability to link individual and collective values, it raises the question of defining institutional procedures to determine collective choices.

d) Unique solutions are inadequate

In formal models, the decision generally consists of a definition of the precise action to be taken. In some models, it is based on a decision-maker utility maximisation function, which represents the aggregation of interpersonal preferences. In others, it is based on decision-making criteria that reflect the adoption of a given attitude by the decision-maker facing uncertainty.

Although the precautionary principle can be understood as a search for a minimum security level, it does not a priori mean adopting extreme aversion to uncertainty. The precautionary principle in the broadest sense of the term should mean the need to respond to uncertainty through sound risk-taking and reasonable decisions.

In addition, consideration should also be given to the proportionate nature of the measures to be taken, a key component of the precautionary principle. Proportionality requires the definition of the specific nature of the risks to be managed and the expected level of security, and the opportunity costs associated to precautionary measures must also be taken into account (GODARD, 2005).

Practices to consider in precautionary decision-making

The preparation of public decisions on environmental hazards is often limited. This is due largely to the insufficient characterisation of short and long term environmental as well as social and economic impacts, but also to the inadequate identification and integration of agents to provide the decision-maker with

institutional support in the dialogue process and in the decision instruction (BOLO and DE BONVILLER, 2008).

There is a clear lack of mechanisms and generally accepted operational frameworks to guide the implementation of the precautionary principle. The conditions for applying the principle have been severely constrained by factors such as the decision-makers' objectives, their attitudes towards risk and uncertainty, and the rules and decision criteria used.

A number of authors (RANDALL, 2009; VAN ASSELT and VAN BREE, 2011) as well as several national and international forums have therefore stressed the need for a methodological reflection to clarify the issues and procedures of public decision under uncertainty, particularly when it concerns the precautionary principle. A recent example was the public hearing of the parliamentary committee in France for the evaluation of scientific and technological choices on the outcome of the application of the precautionary principle four years after it became constitutional (ETIENNE, 2009).

In order to contribute to this debate, and following the analysis presented in the previous sections, some practical interventions that should be implemented have been identified in this paper. Aimed at overcoming the above mentioned limitations, the appropriateness of these actions was demonstrated by the analysis of the models. These actions should also be incorporated in a common procedural framework, as referred at the end of this section.

Comprehensive treatment of information and knowledge

The practical implementation of the precautionary principle does not involve a uniform decision-making criterion: decision-makers should take potential dangers into account but no specific action is imposed and very different measures can be taken from simple warnings to the banning of dangerous products or technologies. As a principle, it is not defined as a mechanical measure or application. Different decision-making criteria can clarify its implementation, but no unambiguous criterion can translate the precautionary principle. The key question for decision-making is how to make an informed judgment about an empirical context.

Analyses must be made that are based on more contextualised models, adapted to the conditions of uncertainty, irreversibility and learning of specific cases, so that they can "resolve" regulatory issues and data limitations.

Therefore, scenarios with explicit and debated costs and benefits, appropriate to each case, should be analysed to help decision-makers make a suitable choice having identified the various courses of action as fully as possible. In the context of complex environmental problems, in particular (FUNTOWICZ and RAVETZ, 1997), it should be recognised that appropriate policy decisions do not automatically result from the availability of technical and scientific data. In fact, there is not necessarily a linear relationship between science and politics (SAREWITZ, 2004).

Integration of multiple values in decision-making

The resolution of many situations in which the precautionary principle is applied involves evaluating and weighting multiple and sometimes divergent factors and interests so as to identify measures that are proportionate to the seriousness of risks and their potential consequences.

The decision context and the nature and quality of available data may justify the use of different models and operating methods or the combination and integration of methods in order to obtain more robust and consensual results.

Modelling should only formalise the subject of the discussion. It would be too ambitious to integrate multiple dimensions. All models of decision-making under uncertainty inevitably omit some relevant factors. The role of the expert should also be limited to providing only the safest and most legitimate expectations.

A more democratic decision

Procedures for the interpretation and application of risk management measures with the precautionary principle should gather technical and non-technical information in an interactive social process.

An analysis of the individual aspirations of people affected by the risks (experts, lay persons, etc.) and collective forms of deliberation and justification which govern social situations of risk emergence could throw light on a reasonable decision which reconciles collective responsibility and respect for the plurality of aspirations of individuals within a society in the context of new risk governance strategies (JASANOFF and MARTELLO, 2004; RENN, 2008).

Public authorities must intervene to establish socially acceptable levels of risk for a given hazard, based on procedures for technical and scientific research and on public debates. Experiments have shown the importance of effective risk communication strategies (DI GIULIO *et al*., 2010 and 2012).

In some European countries, e.g. France and the UK, legislation requires public inputs in decision making in areas characterised by uncertainty (ROWE and FREWER, 2004). In the authors' opinion, this growing interest for public participation in technical policy matters is related to the recognition of basic human rights in democracy and to the importance of avoiding unpopular policies, as well as the need for increasing public confidence in decision making and information sharing. But it is still necessary to develop appropriate tools and processes for analysing practices and measuring the effectiveness of public participation (CORNWALL, 2008).

Defining a range of solutions

In complex situations, rationality is constrained by the limited capacity to collect and process information, and also by the difficulty of settling conflicts between divergent interests. It would be better to consider issues in terms of the general characteristics of choice rather than as parametric properties of particular models.

The precautionary principle provides general indications on the course to follow in the face of potentially serious risks, but cannot be reduced to a single criterion. Therefore, a good solution would be to validate a nucleus of criteria which could select a limited set of decisions that, in certain circumstances, could serve precautionary purposes.

A formal economic analysis of the decision-making problem should then be capable of identifying an area of acceptable solutions that society might well find acceptable, and not a single solution inadequately considered to be optimal.

Using a common procedural framework

Public authorities need to establish a common mode of action with precise procedures for the assessment of collective risks and the implementation of precautionary measures. A regulatory framework is required that is not only coherent, proportionate and efficient, but also suited to the nature of the potential dangers; it should have common procedures that organise research, expertise and public information and debate.

It is essential to distinguish the different elements of the decision in order to clarify the decision process, namely risk and uncertainty assessment, costs and benefits involved and their distribution by population, and actors' behaviour and its possible impact on risk and on actions implemented to prevent it.

An agreement should be reached about the definition of acceptable levels of potential dangers, so that decisions have the support of the population and can be applied more effectively and democratically. For example, a recent study in France includes a proposal for the formalisation of a step-by-step process of public decision-making under uncertainty, which systematically incorporates elements of expertise and debate in light of their contributions and their limits (CPP, 2010). This process includes the following two important phases. In the first phase - preliminary risk assessment - the problem in question is classified as prevention or precaution depending on whether the risk is proven or uncertain. In the second phase, and in the case of proven risk, prevention measures are chosen in line with the risk level, whereas in the case of any uncertainty, lasting precautionary measures are defined when there is evidence of risk or surveillance measures in the absence of evidence.

Other frameworks for the practical implementation of the precautionary principle have been presented at both the sector level and more generally in public reports and scientific publications. Some are more focused on objectives and guidelines, and others are more operational and describe the analysis and decision process as a set of successive phases and steps (THE CALIFORNIA DEPARTMENT OF HEALTH SERVICES, 2008; IRGC, 2008; RENN *et al*., 2009; BONDI, 2011; WILSON, 2011, EC 2011; KLINKE and RENN, 2012). Their most important features are the potential severity of impacts on the environment or on health, the level of evidence and the degree of precaution required, and the proportionality of precautionary measures to deal with the potential consequences and with risk.

Other methodological frameworks may contribute to the implementation of precautionary measures, even though they do not explicitly refer to the precautionary principle. This is the case of "tolerability of risk" approach in the UK, particularly in health and safety sectors. This approach seeks to reconcile decisions based on reliable risk estimates with adequate consideration of public perceptions (BOUDER *et al*., 2007). Another case is the use of a set of indicators developed by the German Advisory Council on Global Change (WBGU) for risk appraisal and management. These indicators include: extent of potential damage, probability of occurrence, level of uncertainty (in relation to knowledge, modelling of complex systems and predictability in assessing a risk), geographical dispersion of damage, persistence, reversibility of effects, delay effects, fairness in the distribution of risks and benefits and potential for mobilisation of individuals and groups (RENN, 2008).

Conclusions

The formal models of economic interpretation of the precautionary principle seek to analyse the economic impact of risk on individual and collective welfare and to contribute to risk management.

In their diversity, they contribute to a better understanding of the logic of individual and collective choices and of the behaviour of important parameters such as risk perception, required levels of protection and risk impacts.

However, difficulties in obtaining information about the socio-political context and the space of events and results associated with the emergence of risks, and also some theoretical shortcomings, have limited the practical application of the models and their political relevance.

These difficulties stem from the nature of risk and the complexity of situations where the precautionary principle is applied: collective and unproven risks, uncertainty context, potential consequences in multiple dimensions and values, sometimes conflicting, and solutions to adapt to each particular case.

Thus, each model applies only to certain kinds of risks: proven risks in some models, unproven in others. Another limitation of most models is their use of single-dimensional assessment criteria based on an economic cost-benefit analysis. They do not incorporate the multiple dimensions that generally arise in precautionary decisions. The criteria used for collective management of risks are also unsatisfactory. Finally, models generally lead to unique solutions, of utility maximisation or minimisation of risks, but the precautionary principle should not be reduced to a single assessment criterion and to a unique solution.

Due to all these difficulties, formal models only provide restricted scope to interpret potential risks to the community and precautionary behaviour.

The aim of this article is to contribute to the clarification of issues and modalities of public precautionary decision and identify some actions to overcome the limitations of formal models that lead to balanced and proportionate solutions adapted to each particular case.

Firstly, information and knowledge on each specific situation should be as comprehensive as possible so that decisions on a given empirical context are well founded. Secondly, the decision-making process should incorporate the multiple interests and values involved in the risk situation considered. Moreover, social interactive procedures should be designed to allow a more democratic decision. They should gather technical and non-technical information and seek to reconcile collective responsibility and respect for the plurality of aspirations of people affected by the risks. This process design should take into account the experience of new risk governance strategies and, in particular, appropriate instruments of public participation. Finally, a nucleus of assessment criteria should be used instead of a single criterion to select a limited range of solutions that can serve the purposes of precaution.

Given the complexity of problems concerning collective risks, it can be concluded that formal models should be used primarily to formalise the subject of discussion in order to gain relevance, even at the risk of losing accuracy. Naturally, the precautionary principle cannot be defined solely as an economic model as it is a multidisciplinary concept with great social relevance with political (or judicial) entities that are responsible for its configuration. It is also essential to have a

regulatory framework with clear and precise procedures, commensurate to the nature of risks and socially acceptable both for risk assessment and the implementation of precautionary measures. This will lead to better informed and effective solutions that are achieved democratically.

Notes

[1] Current Article 191, paragraph 2, of the Treaty on the Functioning of the European Union. The only explicit reference to the precautionary principle is: 'European Union policy on the environment (...) shall be based on the precautionary principle and on the principles that preventive action should be taken, that environmental damage should as a priority be rectified at source and that the polluter should pay'.

[2]For example in the management of pesticide use (California and Washington), in the management of chemicals and chemical products (Massachussets), in new technologies (New York) and in public health (Minnesota) (Terra Bowling, 2008).

[3] Such as the following: Raffensperger and Tickner (1999), EC (2000), Harremoes *et al.* (2002), UNESCO (2005), Myers and Raffensperger (2005), Wiener *et al.* (2011).

[4]Complexity refers to the difficulty of identifying and quantifying causal relationships between potential causal agents and specific observed effects. Uncertainty involves some key components such as variability, random or systematic error in modeling, indeterminate or genuine stochastic effects, system boundaries and ignorance or lack of knowledge. Ambiguity arises when there are different, meaningful and legitimate perspectives about the results of the risk assessment and its interpretation in terms of tolerability or acceptability (RENN, 2008).

[5]The United States of America (USA) has been more circumspect in the application of the precautionary principle than the European Union. The attention given to environmental issues and precaution seems to depend mainly on the context of each particular case: technology, location, culture and perception of social risk, legal systems more or less open to enterprises or to groups of citizens (RANDALL, A., 2009, WIENER *et al*., 2011).

[6] In these models, scientific uncertainty (or no proven risk), which characterises precautionary situations, differs from risk (proven risk), which characterises prevention situations, mainly due to its possible reduction over time.

[7] See the empirical results of the model application in INGHAM and ULPH (2005).

[8] Another framework is 'prospect theory' (KAHNEMAN and TVERSKY, *1979*). The two frameworks have been combined in 'cumulative prospect theory'(TVERSKY *et al*., 1990). Mention should also be made of the recent literature on risk perception that attempts to explain the factors that influence behaviours and attributions (SLOVIC *et al.*, 2010).

[9] Thus, this model would remove the distinction between uncertainty and risk, and therefore between precaution and prevention (where the probabilities are objective).

[10]'Incommensurability of values', i.e., "the absence of a common unit of measure for plural values" as defined by MARTÍNEZ-ALIER *et al*. (1998).

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