

Risk, precaution and science: towards a more constructive policy debate. Talking point on the precautionary principle

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Science, Precaution and Risk Assessment:
towards more measured and constructive policy debate

manuscript for submission to EMBO Reports

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1 Introduction

Few issues in contemporary risk policy are as momentous (or contentious) as the precautionary principle. Emerging first in German environmental policy (Boehmer-Christiansen, 1994), it has long been championed by environmentalists and resisted by the industries they oppose (Raffensberger and Tickner, 1999). Various versions now proliferate across different international instruments (Trouwborst, 2002), national jurisdictions (Fisher, 2002) and policy areas (de Sadeleer, 2002). From a guiding theme in EC environmental policy (CEC, 2000), it has become a general principle of EC law (Vos and Wendler, 2006). Its influence has extended from the regulation of environmental, technology and health risk, to the wider governance of science, innovation and trade (O’Riordan and Cameron, 1994). As it has expanded in scope, so it has grown in profile and authority (Harding and Fisher 1999).

An early classic formulation neatly encapsulates the key ubiquitous features.

According to Principle 15 of the Rio Declaration: *“In order to protect the environment, the precautionary principle shall be widely applied by States according to their capabilities. Where there are threats of serious or irreversible damage, lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation”* (UNCED, 1992). This injunction concerning the justification for action under scientific uncertainty against harm to the environment has given rise to a wide range of criticisms (Sand, 2000). Some of the main concerns are associated with the following arguments (O’Riordan et al. 2001):

- Sound scientific techniques of risk assessment already offer a comprehensive and rational set of ‘decision rules’ for use in policy (Byrd and Cothorn, 2000);
- These science-based approaches yield a robust and practically operational basis for decision making under uncertainty (Morris, 2000);
- The precautionary principle fails as a basis for any similar operational kinds of decision rule in its own right (Peterson, 2006);
- The precautionary principle is of practical relevance only in risk management, and not in risk assessment (CEC, 2000);
- If applied in assessment, the precautionary principle threatens a rejection of useful and well established risk assessment techniques (USDA, 2000);

Each of these concerns involves a set of strong assumptions over: (i) the nature and standing of scientific rationality and rigour; (ii) the scope and character of uncertainty; (iii) the applicability and limits of risk assessment; and (iv) the particular implications of precaution in all these respects. With the aim of helping to build more positive and measured policy debate on these matters, this paper will briefly review each of these main arguments in turn. In the process, it will explore ways more constructively to satisfy at the same time imperatives for robustness, rationality, rigour and precaution.

2 How Rational and Rigorous is Risk Assessment?

Amid the many complexities, most criticism of the precautionary principle rests on unfavourable comparisons with established ‘sound scientific’ methods in the governance of risk. These include a range of quantitative and/or expert-based risk assessment techniques, involving various forms of scientific experimentation and modeling, probability and statistical theory, cost-benefit and decision analysis and Bayesian and Monte Carlo methods. These conventional ‘science-based’ techniques are assumed (often implicitly) to offer a comprehensively rigorous basis for informing decision-making (Byrd and Cothorn, 2000). In particular, they are held to provide decision rules that are applicable, appropriate and complete with respect to the required forms of knowledge (Peterson, 2006). In considering the relative strengths and weaknesses of the precautionary principle, then, equal attention should be given to these claims on behalf of conventional approaches to risk assessment.

All such ‘science-based’ approaches to risk assessment rest on the articulation of two fundamental parameters. These are then reduced to an aggregated concept of risk. First, there are the things that might happen: ‘hazards’, ‘possibilities’ or ‘outcomes’. Second, there is the likelihood – or probability – associated with each. Either of these parameters may be subject to variously complete or problematic knowledge. As shown in Figure 1, this yields four logical permutations of possible states of incomplete knowledge (Stirling, 1999). Of course, these are neither discrete nor

mutually exclusive. In the real world, they typically occur together in varying degrees. However, by distinguishing their different properties, we can gain important insights into the applicability of alternative assessment methods. Conventionally, each of these conditions is addressed by essentially the same battery of risk assessment techniques: quantifying and aggregating different outcome parameters and multiplying by their respective probabilities to yield a single reductive picture of ‘risk’.

Figure 1: contrasting states of incomplete knowledge, with schematic examples

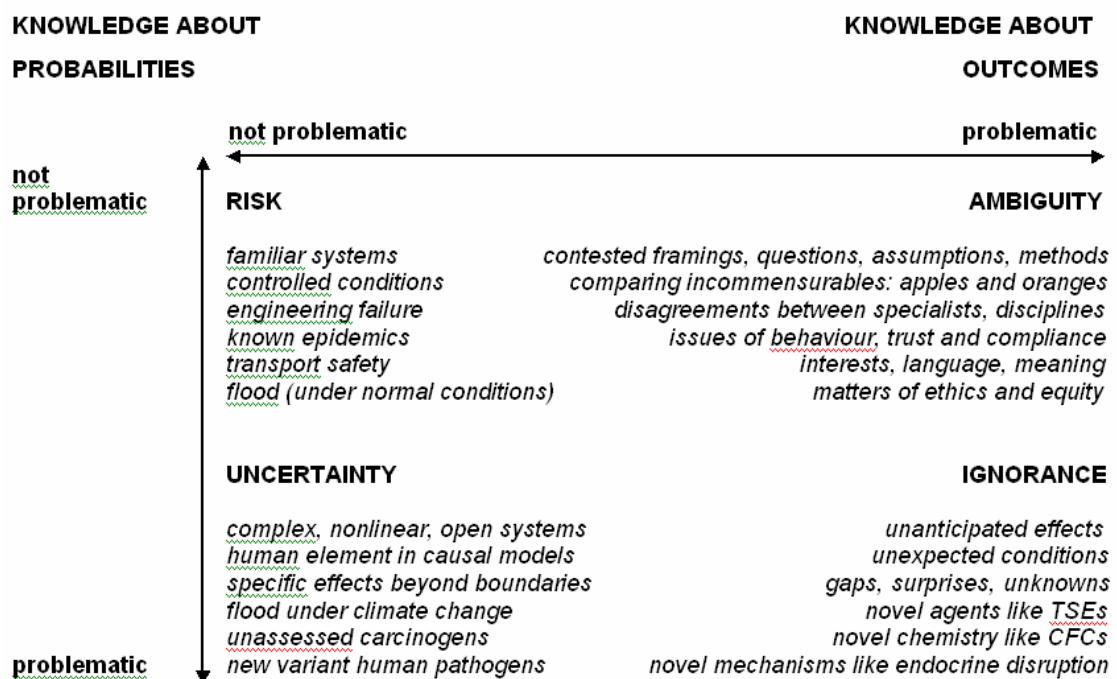


Figure 1 provides schematic examples to illustrate areas in which each of these four logically possible states of knowledge may variously come to the fore in policy making. As can be seen, there exist many important fields where the expected applicability of past experience or reliability of scientific models may foster high confidence in the quality of knowledge concerning both the different possible outcomes and their respective probabilities. In the strict scientific sense of the term, this is the formal condition of risk. It is under these conditions that the conventional techniques of risk assessment offer a scientifically rigorous approach. What is also clear in Figure 1, however, is that this same formal definition of risk also implies less tractable states of uncertainty, ambiguity and ignorance. These relate directly to the

conventional concept of risk itself, but describe a range of circumstances under which the reductive techniques of risk assessment are quite simply not applicable.

Under the strict definition of uncertainty in Figure 1, then, we can be confident in our characterisation of the different possible outcomes, but the available empirical information or analytical models simply do not present a definitive basis for assigning probabilities (Knight, 1921; Keynes, 1921; Rowe, 1994). It is under these conditions – in the words of the celebrated probability theorist de Finetti – that “probability does not exist” (1974). Of course, we can still exercise subjective judgements and treat these as a basis for systematic analysis (Luce and Raiffa, 1957; Morgan, et al, 1990). However, the challenge of uncertainty is that such judgements may take a number of different – equally plausible – forms (Wynne, 1992). Rather than reducing these to a single expected value or prescriptive recommendation, the scientifically rigorous approach is therefore to acknowledge the open nature of a variety of possible interpretations. The point remains, that under uncertainty, attempts to assert a single aggregated picture of risk are neither rational nor ‘science based’.

Under the condition of ambiguity illustrated in Figure 1, it is not the probabilities but the characterisation of the outcomes themselves that is problematic. This may be the case, even for events that are certain or have occurred already. Disagreements may exist, for instance, over the selection, partitioning, bounding, measurement, prioritisation or interpretation of outcomes (Wynne, 2002; Stirling, 2003). Examples may be found in decisions over the right questions to pose in regulation: “is this safe?”, “safe enough?”, “acceptable?” or “the best option?”. Likewise, in the regulation of GM food, ambiguities arise over contending ecological, agronomic, safety, economic or social criteria of harm (Grove-White et al, 1997; Levidow et al, 1998; Stirling and Mayer, 1999)? How can we compare ‘apples and oranges’ like: different forms of damage; impacts on workers or the public; children or adults; present or future generations; humans or nonhumans? When faced with such questions over “contradictory certainties” (Thompson and Warburton, 1985), Nobel prize-winning work in rational choice theory, has shown that analysis alone is unable to guarantee definitive answers (Arrow, 1963; Kelly, 1978; MacKay, 1980). Where

there is ambiguity, then, reduction to a single ‘sound scientific’ picture of risk is also neither rigorous nor rational (Collingridge, 1982; Bonner, 1986).

Finally, there is the condition of ignorance. Here, neither probabilities nor outcomes can be fully characterised (Keynes, 1921; Loasby, 1976; Collingridge, 1980). Where “we don’t know what we don’t know” (Wynne, 1992; 2002), we face the ever-present prospect of ‘surprise’ (Brooks, 1986; Rosenberg, 1996). This differs from uncertainty, which focuses on agreed known parameters (like carcinogenicity or flood damage). It differs from ambiguity, in that the parameters are not just contestable but are at least partly unknown. Some of the most important environmental issues have involved challenges that were – at their outset – of just this kind (Funtowicz and Ravetz, 1990; Faber and Proops, 1994). In the early histories of stratospheric ozone depletion (Farman, 2001), BSE (van Zwanenberg and Millstone, 2001) and endocrine-disrupting chemicals (Thornton, 2000), for instance, the initial problem was not so much divergent expert views or mistakes over probability, but straightforward ignorance over the possibilities themselves. Again, it is irrational to seek to represent ignorance as risk.

The picture summarised in Figure 1 is intrinsic to the scientific definition of risk itself and so difficult to refute in these terms. Risk assessment offers a powerful suite of methods under a strict state of risk. But these are quite simply not applicable under conditions of uncertainty, ambiguity and ignorance. Though attempts are sometimes made to downplay these distinctions through expedient use of terminology, the substantive distinctions themselves nonetheless remain. Contrary to the impression given in calls for ‘science based’ risk assessment, persistent adherence to these reductive methods under conditions other than the strict state of risk, are irrational, unscientific and potentially highly misleading.

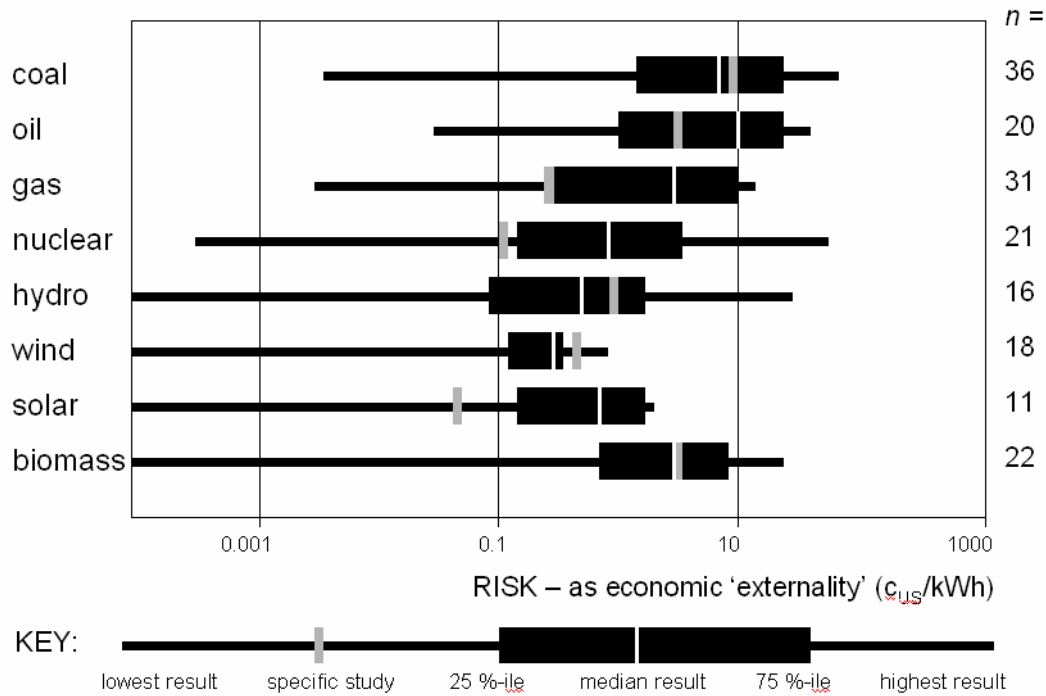
3 *Is Risk Assessment Practically Robust?*

There follow from these fundamental issues of scientific rigour, a series of implications for the practical robustness of conventional reductive risk assessment in decision making. In political terms, a precise quantitative expression of risk or a confidently definitive expert judgement on safety are typically of great instrumental value. Yet these kinds of worldly pressures have little to do with scientific rationality. They can encourage a neglect for the problems just discussed above. Any judgement of policy robustness must reach beyond such expedient short-term institutional issues and address the substantive efficacy of policy outcomes. As such, robustness is a function of the accuracy of assessment results, not of their professed precision. This question of accuracy is more difficult to establish, but some impression can be gained by looking across a range of comparable studies. When this is done, a rather striking picture emerges – one that underscores and compounds the theoretical challenges discussed above.

Nowhere are reductive science-based approaches to risk more mature, sophisticated and elaborate, than in energy policy (Holdren, 1982). It is here that the greatest efforts have been expended over long periods to conduct comprehensive comparative assessments across a full range of policy options (Keepin and Wynne, 1982). Results have been influential in areas of policy making like climate change, nuclear power and nuclear waste. Yet – as shown in Figure 2 – the apparently precise findings obtained in specific studies typically seriously understate the enormous variability inherent in the literature as a whole (Stirling, 1997; Sundqvist et al, 2004). In this literature – as elsewhere in chemical and industrial regulation (Amendola et al, 1992; Saltelli, 2001) – the bottom line is that overlaps between ranges yield different possible ordinal rankings across a wide variety of contending policy options.

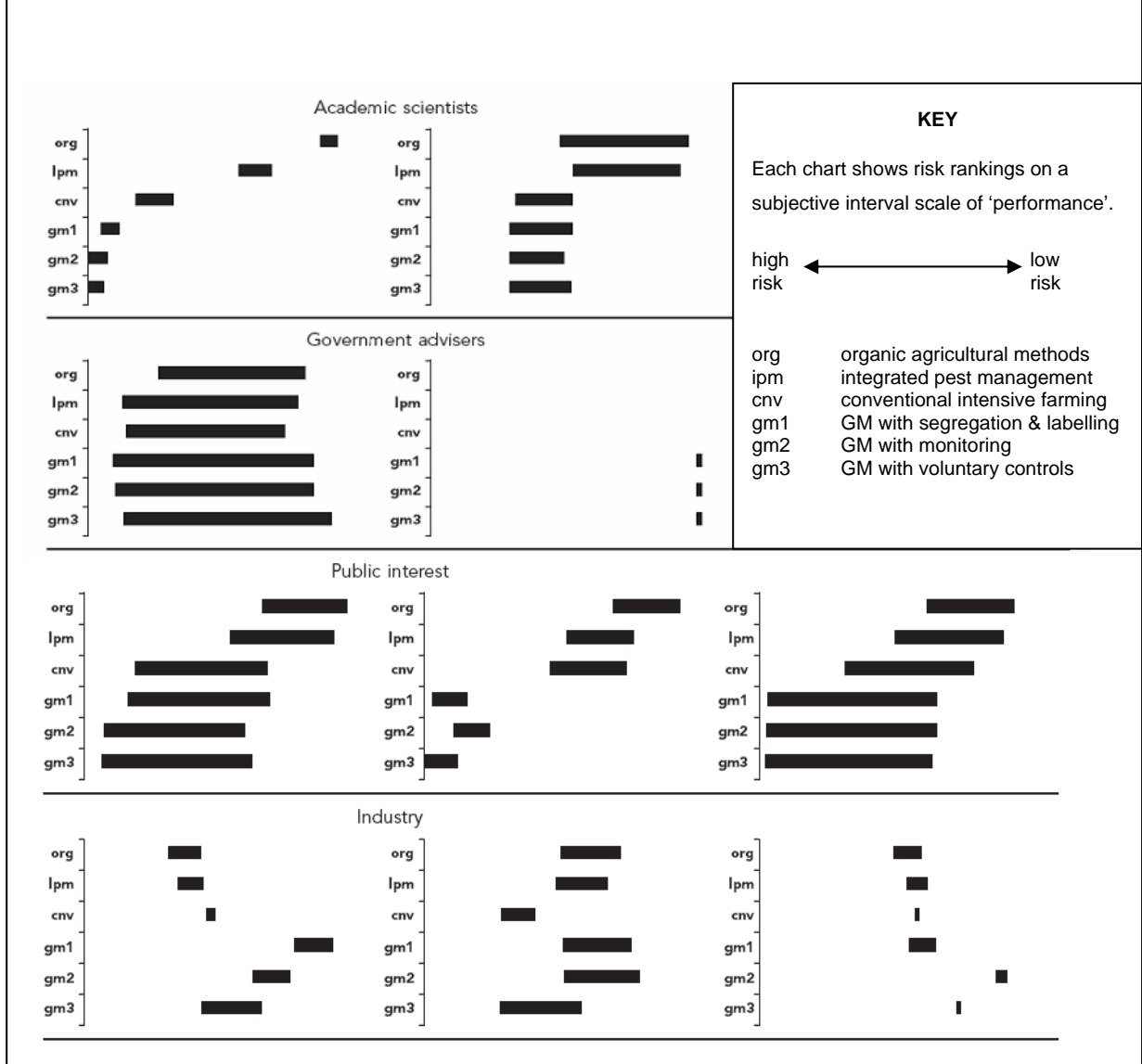
Figure 2: Practical Limits to Robustness in Risk Assessment (cf: Sundqvist et al, 2005)

(results obtained in 63 detailed risk- and cost-benefit comparative studies of electricity supply risks)



Such findings are not restricted to formal quantitative analysis. Figure 3 displays the variety of judgements exercised by different experts involved in advising the UK government on the regulation of GM technology in the late 1990s. Using an elicitation method called ‘multi-criteria mapping’ (Stirling, 1997; Stirling and Mayer, 1999), individual respondents express their judgements in quasi-quantitative graphical terms. The results reveal starkly contrasting understandings concerning the relative merits of GM when compared with other agricultural strategies. Despite the fact that the advisory committees concerned typically represented their collective judgements as precise prescriptive recommendations to policy making, it is clear that the underlying individual expert perspectives display significantly greater diversity.

Figure 3: Divergent Specialist Judgements on Risk (after Stirling and Gee, 2002)



The reason that these kinds of 'sound scientific' procedures can yield such contrasting pictures of risk, is that the answers delivered in risk assessment typically depend on the 'framing' of analysis. Based on a wide literature (Wynne, 1987; Jasanoff, 1990; Schwartz and Thompson, 1990; EEA, 2001), Table 1 identifies a series of factors in the framing of science for policy, which can lead to radically divergent answers to apparently straightforward questions of the kinds illustrated in Figures 2 and 3. The point is not that scientific discipline carries no value. For any particular framing conditions, scientific procedures offer important ways to make analysis more systematic, transparent, accountable and reproducible. No matter what the framing, a

range of interpretations will remain just plain wrong. The issue is not that “anything goes”, but rather that – in complex areas of analysis for policy – science-based techniques like risk assessment rarely deliver a single uniquely robust set of findings. To paraphrase an apocryphal remark by Winston Churchill, the message is that science is essential, but that it should remain “on tap, not on top” (Lindsay, 1995).

Table 1: A selection of factors influencing the framing of scientific risk assessment

<u>setting</u> agendas	defining problems	characterising options
<u>posing</u> questions	prioritising issues	formulating criteria
<u>deciding</u> context	setting baselines	drawing boundaries
<u>discounting</u> time	choosing methods	including disciplines
<u>handling</u> uncertainties	recruiting expertise	commissioning research
<u>constituting</u> ‘proof’	exploring sensitivities	interpreting results

4 Is Precaution a Failed Decision Rule?

So what does this mean for the precautionary principle? As already mentioned, the criticisms are typically founded on unfavourable comparisons with conventional ‘sound scientific’ methods of risk assessment. The preceding discussion has shown that – for all their strengths under strict conditions of ‘risk’ – these techniques are neither rational and rigorous nor practically robust under conditions of uncertainty, ambiguity and ignorance. It is on this basis, that we may already see the value of the precautionary principle, as a salutary spur to greater humility. However, there remain some significant questions. Does precaution offer greater or lesser rigour in the formulation of decision rules under uncertainty? In what ways and to what extent might these be considered more or less robust than conventional methods of risk assessment?

The first point to make here, is that the precautionary principle is not – and cannot properly claim to be – a decision rule at all. Unlike many of the techniques with which it is compared so unfavourably, it is (as its name suggests) a general principle,

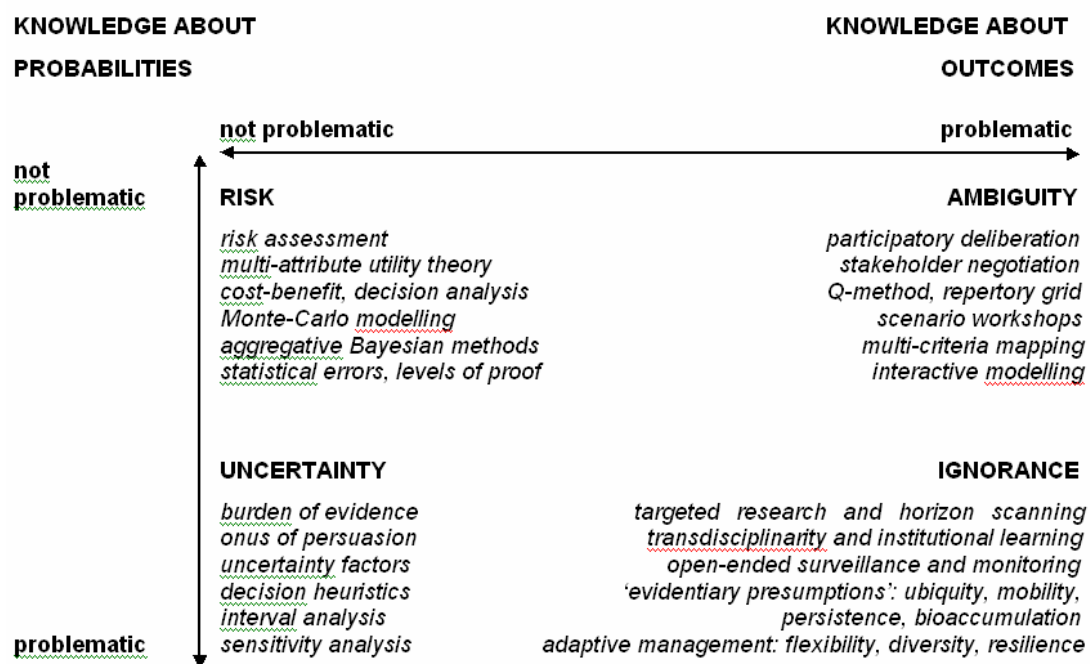
not a specific methodology. In other words, it does not purport to provide a detailed protocol for deriving precise understandings of relative risks and uncertainties – still less justifying particular detailed decisions. Instead, it provides a general normative guide, to the effect that policy making under uncertainty, ambiguity and ignorance should give ‘the benefit of the doubt’ to the protection of human health and the environment, rather than to competing organizational or economic interests. This in turn holds important practical implications for the levels of proof required to sustain an argument, the placing of the burden of persuasion and the allocation of responsibility for resourcing the gathering of evidence and the performance of analysis. This is useful, as far as it goes, because none of these are matters on which there can be a firm prior ‘sound scientific’ position.

Beyond this broad normative guidance, however, the concrete procedural implications of the precautionary principle certainly do not compare with the detailed specifications associated with well-established scientific methodologies. After years of development, a multiplicity of techniques for cardinal measurement of magnitudes – as well as methods like probabilistic calculus, Pareto optimization and utility maximization – are all highly elaborated and institutionalized in ways that remain undreamt of under the more recent concept of precaution. Instead, the precautionary principle is currently more comparable with the general principles of rational choice that underlie these more particular scientific methods. Interestingly, these underlying principles of ‘sound science’ are rarely explicitly enunciated, but instead tend to be implicitly assumed as intrinsic to rationality. Examples include the quantification of likelihood using probabilities, the assumption of multiplicative relationships between probability and magnitude, an insistence on the universality of trade-offs and an imperative to aggregate social preferences. Although not exposed to the same policy scrutiny as precaution, each of these is – as we have seen – contestable. Indeed, under conditions of uncertainty, ambiguity or ignorance all are, quite simply, unapplicable.

It is under these more intractable states of ‘incertitude’, then, that the precautionary principle comes into its own (Stirling, 2003). The value here is not as a tightly prescriptive decision rule – for such is, by definition, not scientifically possible under these conditions. Instead of prescribing decisions, the precautionary principle prompts attention to a broader range of more modest, non-reductive methods, which avoid

spurious promises to determinate ‘science based’ policy (Stirling and Mayer, 2000). Several of these are summarized in Figure 4 (Stirling, 2006). The intention here is not to imply a neat one-to-one mapping of specific methods onto individual states of knowledge. The purpose is rather to illustrate the rich variety of alternatives that exist, once it is acknowledged that risk assessment is not properly applicable under uncertainty, ambiguity and ignorance.

Figure 4: methodological responses to different forms of incertitude



It is in this light, then, that we can appreciate that the real failure as a decision rule is not that of the precautionary principle. Instead, it is the aspiration to a reductive, prescriptive ‘science based’ risk assessment, that is applicable beyond the narrow confines of risk itself. Indeed, if what we seek are simple methodological rules to remove the need for subjectivity, argument, deliberation and politics, then precaution offers no such promise. Instead, it points to a rich array of methods that reveal more explicitly and accountably the intrinsically normative and contestable basis for decisions, and the different ways in which our knowledge is so often incomplete. This is as good a ‘rule’ for decision-making, as we can reasonably get.

5 *Is Precaution Only Relevant in Risk Management?*

What is interesting about these practical methodological implications of the precautionary principle, is that they refute the often-repeated injunction – including at the highest levels of policy making (CEC, 2000) – that precaution is relevant to risk management, not risk assessment. All of the methods associated with uncertainty, ambiguity and ignorance in Figure 4 present alternative approaches to appraisal. Of course, each might be seen equally as a complement to risk assessment, rather than a potential substitute. The point is, that an insistence that precaution relates only to risk management entirely misses the real value in highlighting this richer and more diverse array of possible ways to gather relevant knowledge in appraisal.

Drawing on a wide literature (ESTO, 1999; EEA, 2001), Table 2 highlights the ways in which policy understandings of precaution are now moving away from rigid notions of a decision rule applicable only in risk management, and towards visions of more broad-based processes of social appraisal (van Zwanenberg and Stirling, 2004). In many ways, the qualities listed in Table 2 are simply common sense. In an ideal world, they would (and could) apply equally to the application of risk assessment. However, the incorporation of all these qualities as routine features in every instance of regulatory appraisal would be prohibitively demanding of evidence, analysis, time and money. The question therefore arises, as to how to identify those cases in which it is justifiable to adopt these more elaborate and onerous approaches to appraisal?

Table 2: Key features of a precautionary appraisal process (cf: ESTO, 1999; EEA, 2001)

Precaution ‘broadens out’ the inputs to appraisal beyond the scope that is typical in conventional regulatory risk assessment, in order to provide for (*with examples in italics*):

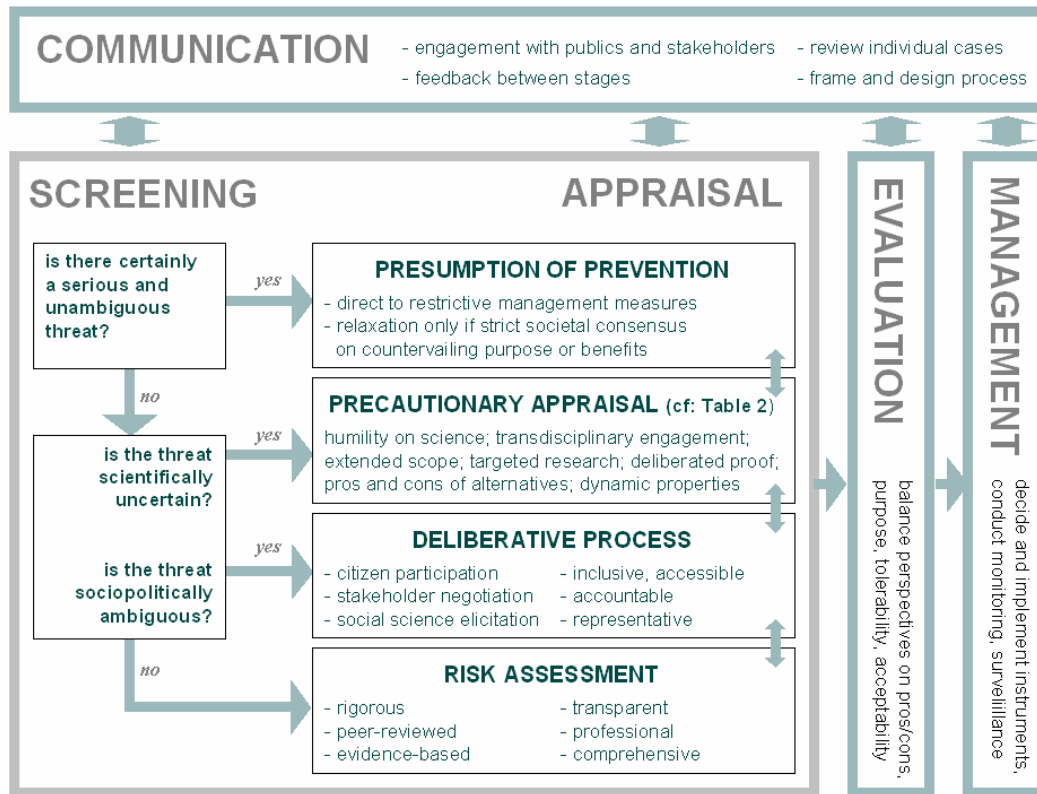
1. independence from vested institutional, disciplinary, economic and political interests;
as long constrained attention to problems due to asbestos (Gee and Greenberg, 2001)
2. examination of a greater range of uncertainties, sensitivities and possible scenarios;
addressed early with antimicrobials but later neglected (Edqvist and Pederson, 2001)
3. deliberate search for ‘blind spots’, gaps in knowledge and divergent scientific views;
as with assumptions over dispersal in the story of acid rain (Semb, 2001)
4. attention to proxies for possible harm (eg: mobility, bioaccumulation, persistence);
as encountered in managing chemicals like MTBE (Kraus and Harremoes, 2001)
5. contemplation of full life cycles and resource chains as they occur in the real world;
like failures in PCB containment during decommissioning (Koppe, Keys, 2001)
6. consideration of indirect effects, like additivity, synergy and accumulation;
of a kind neglected in occupational exposures to ionizing radiation (Lambert, 2001)
7. inclusion of industrial trends, institutional behaviour and issues of non-compliance;
such as the large scale misuse of antimicrobials (Edqvist and Pederson, 2001)
8. explicit discussion over appropriate burdens of proof, persuasion, evidence, analysis;
presently implicated in systematic neglect of Type II errors (Harremoes et al, 2001)
9. comparison of a series of technology and policy options and potential substitutes;
neglected in the case of the over-use of diagnostic X-rays (Lambert, 2001)
10. deliberation over justifications and possible wider benefits as well as risks and costs;
insufficiently considered in the licensing of the drug DES (Ibaretta and Swan, 2001)
11. drawing on relevant knowledge and experience arising beyond specialist disciplines;
like knowledge of birdwatchers relating to fisheries management (MacGarvin, 2001)
12. engagement with the values and interests of all stakeholders who stand to be affected;
as experience of local communities in pollution of the Great Lakes (Gilbertson, 2001)
13. general citizen participation in order to provide independent validation of framing;
significantly neglected in the management of BSE (Zwanenberg and Millstone, 2001)
14. a shift from theoretical modeling towards systematic monitoring and surveillance;
systematically neglected in many cases, including that of PCBs (Koppe & Keys, 2001)
15. a greater priority on targeted scientific research, to address unresolved questions;
as omitted over the course of the BSE experience (Zwanenberg and Millstone, 2001)
16. initiation at the earliest stages ‘upstream’ in an innovation, strategy or policy process;
fostering cleaner innovation pathways before lock-in occurs (Harremoes et al, 2001)
17. emphasis on strategic qualities like reversibility, flexibility, diversity, resilience.
these offer ways to hedge even the most intractable forms of ignorance (ESTO, 1999)

6 Does the Precautionary Principle Reject Risk Assessment?

The answer to this question is clearly stated in the precautionary principle itself. Ever since the canonical formulation in the Rio Declaration, precaution has been identified specifically as a response to uncertainty, under conditions where there is a threat of serious or irreversible environmental harm. In the more precise and rigorously grounded terminology developed in the literature reviewed in the present paper (Figures 1 and 4), this undifferentiated notion of uncertainty might more accurately be further partitioned into strict uncertainty, ambiguity and ignorance. Either way, the practical implications are clear. In calling for more rigorous approaches to these intractable states of incertitude, precaution need in no sense be seen as a blanket rejection of risk assessment. Under conditions where uncertainty, ambiguity and ignorance are judged not to present significant challenges, the elegant reductive methods of risk assessment discussed earlier present potentially powerful tools to inform decision making.

Figure 5: A Framework for Articulating Precaution and Risk Assessment

(adapted from Renn et al, 2006)



Drawing on – and adapted from – recent work in a series of collaborative research projects for the European Commission (Klinke and Renn, 2002; Renn and Klinke, Renn et al, 2003; 2006; Stirling et al, 2006; Klinke et al, 2006), Figure 5 provides one schematic outline of a general framework for the effective articulation of conventional risk assessment with these more broad-based qualities and associated methods in appraisal. Just as current risk assessment practice is preceded by hazard characterisation, so this framework envisages the use of a criteria-based screening process to identify key attributes of scientific uncertainty or socio-political ambiguity (Table 3). These criteria might be applied, subject to open interpretive judgement and in a transparent, accountable fashion, by a transdisciplinary advisory body of a kind that is well established in modern governance. Where none of these criteria are triggered, then the cases in question are subject to conventional risk assessment. Only where it is identified that there exist more demanding challenges of uncertainty and ambiguity does the process initiate a more elaborate precautionary appraisal or deliberative process.

Table 3: Illustrative Criteria of Seriousness, Uncertainty and Ambiguity

Criteria of Seriousness

- Clear evidence of carcinogenicity, mutagenicity, reprotoxicity in components / residues?
- Clear evidence of virulent pathogens?
- Clear violation of risk-based concentration thresholds or legal standards?

Criteria of Uncertainty and Ignorance

- Scientifically founded doubts on theory?
- Scientific doubts on model sufficiency or applicability?
- Scientific doubts on data quality or applicability?
- Novel, unprecedented features of product?

Criteria of Sociopolitical Ambiguity

- Divergent individual perceptions of risk?
- Institutional conflict between different agencies ?
- Amplification effects in news media ?
- Social / ethical concerns, distributional issues or political mobilization?

Of course, from any point of view, the devil will always be in the detail in any general framework of this sort. Current work is refining the specific methodological, institutional and legal implications in the area of food safety (Renn et al, 2006). However, the key points to make here are the following.

First, the framework as a whole is itself precautionary, in that explicit and deliberate attention is given to ambiguity, uncertainty and ignorance. The default response in the event of a certain, unambiguously serious threat is the immediate presumption of preventive measures in management.

Second, the framework does not necessarily imply that the adoption of precaution in appraisal will automatically entail any particular measure in management – such as bans or phase-outs. These will be a matter for accountable decision making, subject to the more transparent and broader based body of information provided – as appropriate – by precautionary appraisal and/or deliberative process.

Third, the framework shows how adoption of the precautionary principle need not imply a blanket rejection of risk assessment, still less of science itself. Instead, it involves a carefully measured and targeted treatment of different states of knowledge.

In this sense, this precautionary framework may be seen as significantly more rigorous and rational – and potentially more robust – than the indiscriminate use of often-inapplicable methods.

7 Conclusion

This paper began with a series of concerns over the precautionary principle. Taking each in turn, it has been found that the ‘sound scientific’ methods of risk assessment (with which precaution is so often unfavourably compared) do not – as is often assumed – offer an unqualified rational, rigorous or robust basis for decision making. In short, they are not applicable under uncertainty, ambiguity and ignorance. It is true that the precautionary principle also fails as a source of prescriptive ‘decision rules’ under these challenging conditions. However, this failure is less acute in the case of precaution, because prescriptive ‘decision rules’ are neither the aim nor the claim of this general normative guidance.

Though falling short of prescriptive decision rules, the precautionary principle does, however, suggest a range of more modest, open-ended, but nonetheless potentially highly effective methodologies and general qualities in appraisal. Taken together, these offer important ways to complement and improve upon the rigour and robustness of conventional risk assessment when taken on its own. As such, it becomes clear that – contrary to common assertions – the precautionary principle is of as much practical relevance to risk assessment as to risk management. Seen in this way, precaution does not automatically entail bans and phase-outs, but simply the devotion of more deliberate and comprehensive attention to the implications of contending policy or technology pathways. Far from being in tension with science, then, precaution offers a way to be more measured and rational about uncertainty, ambiguity and ignorance.

Of course, none of this is to deny that there remain important unresolved issues. Precaution is in the early stages of its institutionalization in governance, there remain

many serious challenges and open questions. Because it is inherently comparative, precautionary appraisal is as likely to spur favoured directions for innovation as inhibit those that are disfavoured. But there will inevitably arise real difficulties for legitimate interests in particular industries where uncertainties are most acute. Here, we can expect – and should welcome – the discipline of continuing criticism, concern and debate. The appropriate way to address this, is through open policy discourse and democratic accountability. What is not tenable is that these inherently political issues be concealed behind narrow, opaque, deterministic notions of the role of science. It is in prompting more rational, balanced and measured understandings of ‘sound science’ rhetorics on uncertainty, that precaution has arguably made its greatest contribution.

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