Science, Precaution, and Practice

ANDY STIRLING, MA, PHD[a]
DAVID GEE[b]

The precautionary principle has become an increasingly prominent theme in the debate over technological risk, raising many questions over its implications for policy making. A key issue is the relationship between precautionary and more traditional so-called science-based approaches to decision-making, such as cost-benefit and risk analyses. Some fear that a precautionary approach—unlike risk assessment—is too ambiguous and impractical to serve as a basis for real decision-making, and that it is somehow antagonistic to science and may even stifle technological innovation.

This article first examines some of the key issues affecting the relationship between science and precaution. Far from being in tension, these two concepts are actually consistent and even mutually reinforcing. A more useful distinction is found to lie between the narrow risk assessments of many regulatory appraisals and the broader precautionary approaches to hazard reduction and policy-making under conditions of scientific uncertainty, complexity, and high decision stakes. This article identifies a series of key features characterizing a precautionary approach to regulatory appraisal. It cites a recent European Environment Agency (EEA) study that provides examples of how some of these key features could have improved past decision-making on risk.[1] Finally, it illustrates a method that addresses these issues and delivers an approach to regulatory appraisal that is both precautionary and scientifically robust.

THE SCOPE AND COMPLEXITY OF RISK

Risk is a complex concept. Even under the most narrowly defined of quantitative approaches, risk is a function of at least two variables—the *likelihood* of an impact and its *magnitude*. Let us first look at the variety of features that figure in any comprehensive analysis of the magnitude, or nature, of risks, before considering aspects of *likelihood*. Here, only very rarely is a series of technology, policy, or investment options considered to present only one form of hazard. Normally, the characterization of risks associated with any option requires consideration of a wide variety of disparate risks. In the energy sector, for example,

[a]SPRU—Science and Technology Policy Research, University of Sussex, Brighton, UK

[b]European Environment Agency, Copenhagen K, Denmark

Address correspondence to: Andy Stirling, MA, PhD, SPRU—Science and Technology Policy Research, Univ. of Sussex, Brighton BN1 9RF, UK; tel. +44 1273 686758; fax +44 1273 685865; e-mail <A.C.Stirling@sussex.ac.uk>.

different sources of risk include greenhouse gas emissions, radioactive wastes, heavy metals, persistent organic pollutants, soil erosion, thermal discharges, ambient noise, ecological disturbance, or aesthetic intrusion in the landscape.[2,3] Each of these risks is manifest in a different way, with different physical, biological, social, cultural, and economic connotations.

The conventional response in regulatory appraisal is to identify a single major yardstick of performance and seek to measure all the various aspects of risk using this as a metric. The chosen unit of measurement in conventional risk assessment is often human mortality rates, although human morbidity is sometimes included. In some areas, the techniques of cost-benefit analysis are used to impose a common monetary metric on a wider range of impacts and render them comparable with the associated benefits. In this way, the analysis attempts to reduce the multiplicity of risk magnitudes to a single metric, thus apparently simplifying the process of appraisal. This reduction process is an essential element in what is sometimes misleadingly described as a "science-based" approach to the regulatory appraisal of risk.[4]

Of course, one crucial consequence of this artificial narrowing and conflation of the full range of technological hazards is to exclude many classes of effect from consideration. For instance, only a minority of the types of energy risks mentioned above is meaningfully addressed by mortality, morbidity, or monetary metrics. Moreover, even with respect to the single issue of human health, risk is an inherently multidimensional concept. For instance, are exposures voluntary or controllable? Are they manifest as disease, injuries, or deaths? How familiar are the hazards? How immediately are they realized and how reversible once identified? To what extent are they concentrated in a few large events or dispersed in many small routine incidents? How are they distributed across space, time, and society? Mortality and even morbidity indices fail to capture these important contextual features.

Beyond this, further scope for divergent approaches to regulatory appraisal lies in the characteristics of the assessment process itself.[5–8] Should appraisal take account of social, economic, cultural, and ethical issues, as well as environmental and health factors? With respect to the more narrowly defined physical factors, to what extent should appraisal address the potential additive, cumulative, synergistic, and indirect effects associated with particular environmental and health risks? With how wide an array of potential alternatives should each individual technological or policy option be compared in appraisal? Should attention be confined simply to the implementation of the technological options concerned, or should it extend to their manufacture, processing, decommissioning, and disposal, as well as to the various inputs (such as energy and materials) and associated risks at each stage? To what extent should the relative benefits of different options be considered to offset the associated hazards and risks?

In an ideal world, the appropriate response to these factors is easily determined. All else being equal, the regulatory appraisal of risk should be as complete as possible with respect to different classes and dimensions of risk and benefits and as comprehensive as possible with respect to different policy alternatives. However, on their own, such aspirations provide only rather loose operational guidance in the practical regulation of risk. Moreover, even if appraisal was complete and comprehensive in some hypothetical sense, there would still remain the problem of how to frame and prioritize the different aspects of risk in analysis. For instance, what assumptions should be made about adherence to best practice in the various activities under appraisal? What relative priority should be attached to different effects, such as toxicity, carcinogenicity, allergenicity, occupational safety, biodiversity, or ecological integrity? What weight should be placed on these different impacts and on different groups, such as workers, children, pregnant and breastfeeding mothers, future generations, disadvantaged communities, foreigners, and those who do not benefit from the technology in question? And what about animals, plants, and ecological communities as entities in their own right? Even if the objectives of completeness and comprehensiveness were feasible, they would not address framing and prioritization. Within the bounds set by positive reality, no one set of assumptions or priorities can be claimed uniquely rational, complete, or comprehensive.

It is here that we come to a classic and well explored dilemma in the field of rational choice theory that underlies technical risk assessment. It is a lesson that seems to have been forgotten by those who claim their narrow quantitative aggregating techniques are distinguished as being based on "sound science." For the disciplines of risk assessment, economics and decision analysis have developed no definitive way of addressing this problem of comparing apples and oranges. Even the most optimistic proponents of rational choice acknowledge that there is no effective way to compare the intensities of preferences displayed by different individuals or social groups.[9] Indeed, even where social choices are addressed simply in relative terms, the economist Kenneth Arrow went a long way toward earning his Nobel Prize by demonstrating for-

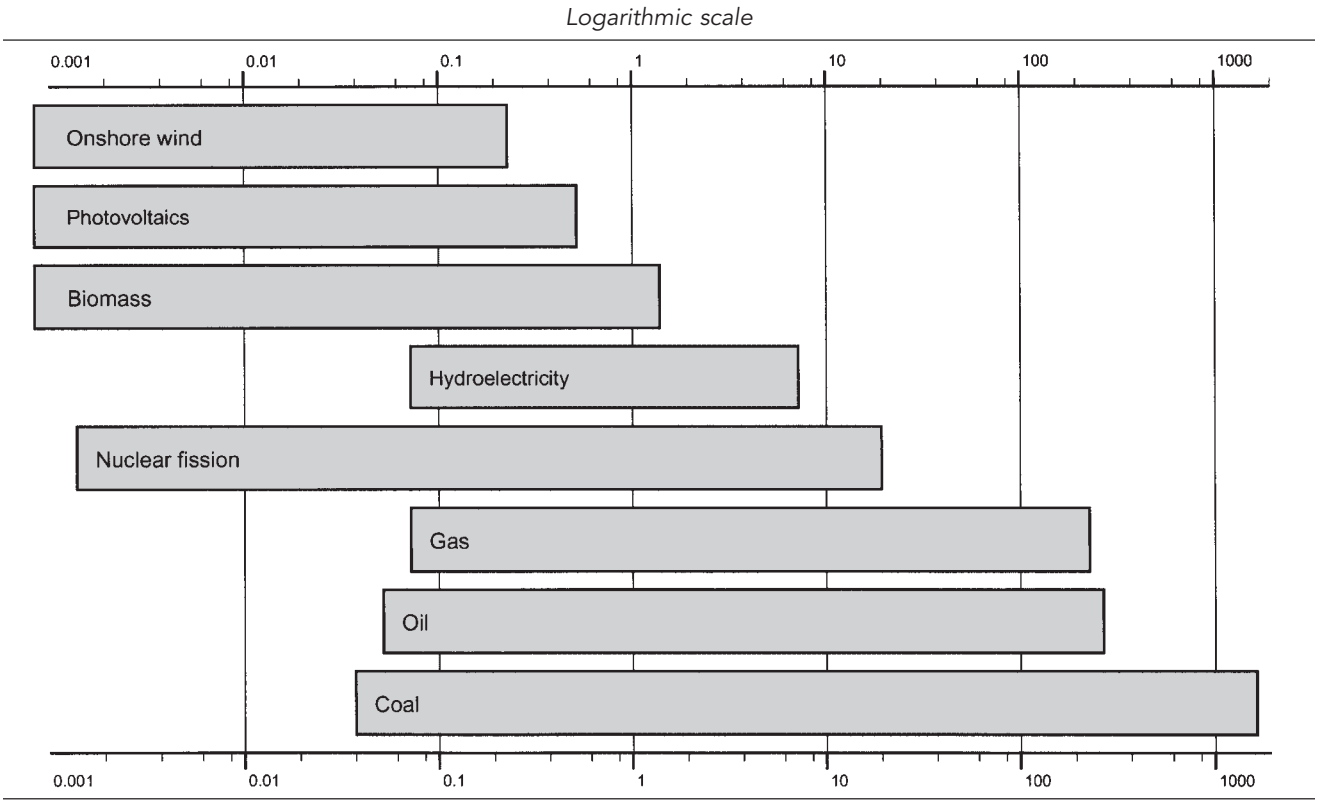
mally that it is impossible to definitively combine relative preference orderings in a plural society.[10]

Put simply, "it takes all sorts to make a world." Different cultural communities, political constituencies, or economic interests characterize different aspects of environmental and health risk in different ways and attach different degrees of importance to them. These translate into different—but equally reasonable—framing assumptions in formal quantitative appraisal. Within the bounds defined by the domain of available information and social discourse, there is much legitimate scope for divergent interpretation. No one set of values or framings can necessarily be ruled more rational or well informed than any other.

Although rarely acknowledged, evidence of this kind of intrinsic ambiguity in science-based characterizations of risk abounds, in areas extending from food safety through transport impacts and from chemical and industrial hazards to the effects of genetic modification technologies. Figure 1 illustrates this phenomenon in perhaps the most intensive, elaborate, and mature area for the policy application of science-based comparative risk assessment techniques: the energy sector. The figure summarizes the results obtained in 32 large-scale risk assessments of eight energy technologies conducted for official bodies in industrialized countries over the past two decades. Environmental and health effects are characterized using the techniques of cost-benefit analysis as monetary "external costs" expressed in standardized form per unit of electricity production for each technological option.[3] Although individual studies express their results with very high degrees of precision, the results for any one technology vary by several orders of magnitude. So great are the overlaps among the ranges obtained for the different technologies that not only the absolute values, but even the relative orderings of the options, remain intrinsically ambiguous.

This illustration—reproduced in virtually all areas where formal risk assessment techniques are applied—underscores the practical importance of the theoretical difficulties with notions of definitive prescriptive science-based assessment. It is a matter of rationality itself in the business of risk assessment, then, that there can be no analytical fix for the scope, complexity, and intrinsic subjectivity of environmental and health risks. The answer you get depends to a large extent on the set of assumptions privileged in analysis.

Figure 1. Summary of results in large-scale risk assessments of eight energy technologies



The notion that there can be a single science-based prescription in the regulatory appraisal of risk is not only naïve and misleading, but a fundamental contradiction in terms.

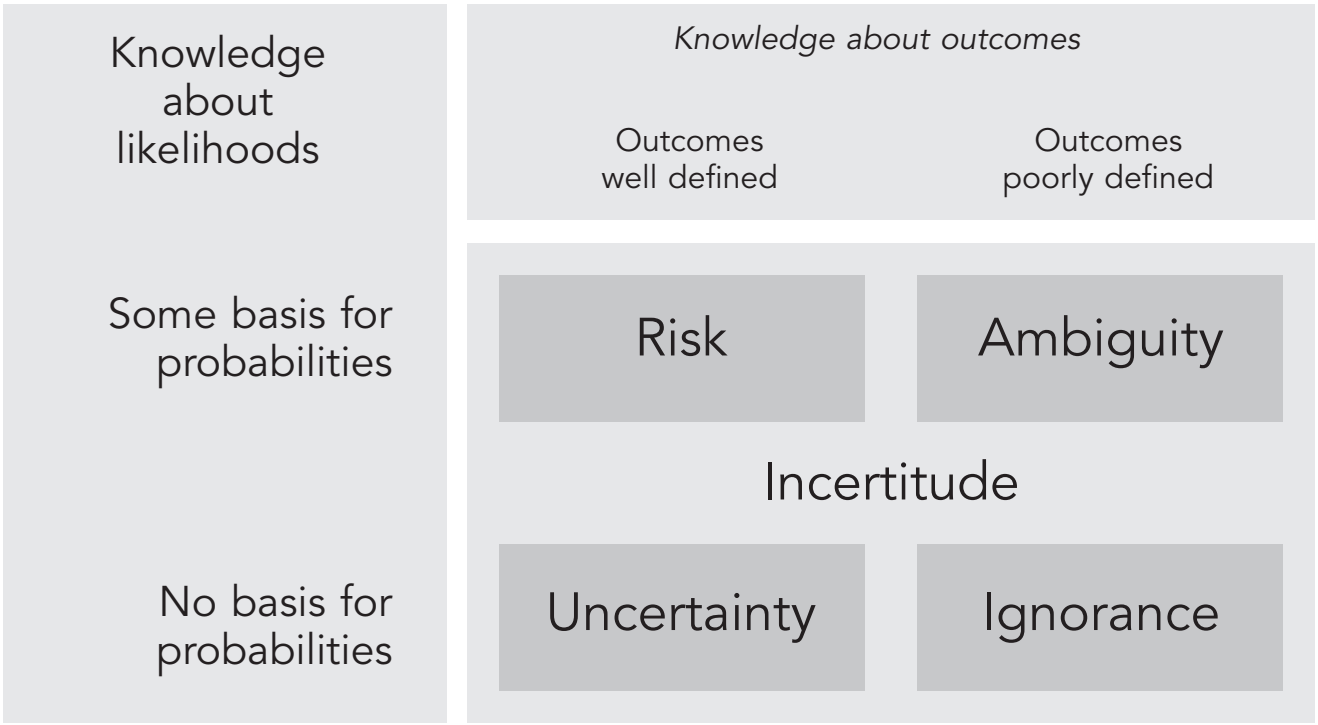
THE DEPTHS OF INCERTITUDE

Beyond these questions of rational choice, aspirations (or claims) to a "sound science" of risk assessment involve a further series of intractable difficulties. Thus far, we have considered only the issues associated with ambiguities in the characterization of the magnitude aspects of risk. What of the likelihoods? Here we come upon some profound limitations to the applicability and robustness of probabilistic approaches that are as seriously neglected in conventional regulatory appraisal as are the difficulties with comparison of magnitudes.

In economics and decision analysis, the well established formal definition of *risk* is a condition under which it is possible both to define a comprehensive set of all possible outcomes and to resolve a discrete set of probabilities (or a density function) across this array of outcomes. This is illustrated in the top left-hand corner of Figure 2. This is the domain under which the various probabilistic techniques of risk assessment are applicable, permitting (in theory) the full characterization and ordering of the different options under appraisal. Such assumptions may well be felt justified in areas where theoretical models are robust or where there are well documented empirical data bearing on relevant circumstances. This may be the case, say, with some transport-safety problems or in the epidemiology of certain well known diseases. Of course, there are a host of questions relating to the implementation of risk-based approaches (such as those hinging on the distinction between frequentist and Bayesian understandings of probability). But none of these alter the formal definition of the concept of risk founded on the applicability of probability theory.

The strict sense of the term *uncertainty*, by contrast, applies to a condition under which there is confidence in the completeness of the defined set of outcomes, but no valid theoretical or empirical basis to confidently assign probabilities to these outcomes. This is shown in the lower left-hand corner of Figure 2. Here, the analytical armory is less well developed, with various sensitivity and scenario analyses being the best that can usually be managed.[11] Examples of this condition abound wherever the metric of harm is not itself held to be problematic or worthy of discussion, but where the empirical or theoretical basis for risk assessment may be incomplete. In the case of newly emerg-

Figure 2. Formal definitions for risk, uncertainty, ambiguity and ignorance



ing pathogens, for example, the possible incidence will lie somewhere on a discrete scale of mortality frequency, but the empirical or theoretical understandings will be inadequate to permit the definition of a probability density function on this scale. Likewise, corporate and wider commercial decision-making is often reduced to questions of bottom-line profitability or shareholder value on a simple monetary scale, yet the complexity of the operating environment prohibits confident assignment of different probabilities to the different increments on this scale. Under such conditions of uncertainty, the relative likelihoods of a well defined set of outcomes are problematic. As a result, although the options under appraisal may be broadly characterized, they cannot be ranked even in relative terms.

Both risk and uncertainty, in the strict senses of these terms, require that different possible outcomes be clearly characterized and subject to measurement. The problems with such assumptions were discussed in the previous section. The multidimensionality, complexity, and scope of the different forms of environmental risk and the different ways of framing and prioritizing these risks can easily render the characterization of outcomes ambiguous.[12,13] This may be so even where there is relatively high confidence in understandings of the likelihood that at least some form of impact will take place This condition of ambiguity is shown in the top right corner of Figure 2. In addition to the case of energy impacts shown in Figure 1, further examples of ambiguity lie in the institutional assumptions around food safety regulation, the selection of hazard categories and vectors in chemical risk assessment, and in defining the notion of environmental harm in the regulation of genetically modified crops.

Where these difficulties of ambiguity are combined with the problems of uncertainty and compounded by the prospect of unknown unknowns beyond the scope of appraisal, we face a condition formally defined as *ignorance* (bottom right corner of Figure 2).[14–16] This applies in circumstances where there is not only no basis for assigning probabilities (as under uncertainty), but where the definition of a complete set of outcomes is also problematic. In short, recognition of the condition of ignorance is an acknowledgement of the possibility of surprise. Under such circumstances, not only is it impossible to definitively rank the different options, but it is difficult to even characterize them. Under a state of ignorance (in this strict sense), it is always possible that there are effects (outcomes) that have been entirely excluded from consideration. Past examples of the importance of this condition are evident in high-profile cases such as stratospheric-ozone depletion by chlorofluorocarbons, the links between bovine spongiform encephalopathy in cows and variant Creutzfeldt-Jakob disease in humans, and the emergence of recognition of the endocrine-disruption mechanism in chemicals regulation. These are all examples where the problem lay not so much in the determination of likelihoods, but in the anticipation of the very possibilities themselves. At crucial moments in their regulatory history, these were surprises.

It is quite normal, even in specialist discussion, for the full breadth and depth of such issues to be rolled into the simple concept of risk (and sometimes uncertainty), thus seriously understating the difficulties involved. To avoid confusion between the strict definitions of the terms *risk* and *uncertainty* as used here, and their looser colloquial usages, the term *incertitude* can be used to subsume all four subordinate conditions.[17] Either way, it is the formal concepts of ignorance, ambiguity, and uncertainty—rather than mere risk—that best describe the salient features of regulatory decision-making in areas such as energy technologies, toxic chemicals, and genetically modified organisms. The crucial point is that intractable uncertainties, ambiguities, and ignorance are routinely addressed in the regulatory appraisal of technology simply by using the probabilistic techniques of risk assessment. This treatment of uncertainty and ignorance as if they were mere risk effectively amounts to what the economist Friedrich von Hayek dubbed (in his Nobel acceptance speech) "pretence [sic] at knowledge."[18] Far from displaying a respect for science in regulatory appraisal, the effect of such scientistic oversimplification is to ignore and undermine the scientific principles on which risk assessment itself purports to be based. Given the manifest inapplicability—in their own terms—of probabilistic techniques under uncertainty, ambiguity, and ignorance, this is a serious and remarkable error. The self-contradictions in aspirations to a science-based approach reliant on quantitative risk assessment (noted in the last section) are further underscored.

Why is it that pursuit of (and claims to) the definitive authority of science-based approaches continues to be so prominent in regulatory appraisal? It seems that the elegance and facility of probabilistic calculus has had a seductive effect on many risk analysts and their sponsors. This may be understandable, yet it is also curious. Despite the intractability of the condition of ignorance, there is no shortage of operational, tactical, and strategic alternatives to reliance on probabilistic methods. Indeed, it is in full recognition of the inadequacy of risk assessment in addressing uncertainty, ambiguity, and ignorance that we find the real

justification and imperative for adopting newly emerging precautionary approaches.

PRECAUTION: THE PRACTICAL RESPONSE

The nature of precaution

The precautionary principle is becoming an increasingly prominent feature of the regulatory debate on environmental risks and of national and international legislation.[19–23] Though subject to a variety of definitions and interpretations, a truly precautionary approach acknowledges the difficulties in risk assessment by granting greater benefit of the doubt to the environment and to public health than to the activities that may be considered to threaten these things.

In essence, *precaution* involves the application of principles that "prevention is better than cure";[24] that "irreversible effects should be avoided,"[25] that options offering simultaneously better economic and environmental performance ("no regrets") should always be substituted,[26] that appraisal should take place at the level of production systems taken as a whole;[27] and that attention should be extended to the intrinsic value of non-human life in its own right (a "biocentric ethic").[19] In effect, this translates to a certain humility about scientific knowledge and an acknowledgement of the complexity and variability of the real world. It implies recognition of the vulnerability of the natural environment and living organisms, the prioritizing of the rights of those who stand to be adversely affected, and the placing of the levels of proof and burdens of persuasion in regulatory appraisal so as to favor the interests of risk avoidance rather than risk toleration.[21] It requires scrutiny of claims to benefits and justifications as well as risks and costs, with full accounting of the available alternatives.[6] In short, a precautionary approach involves the adoption of long-term, holistic, and inclusive perspectives in regulatory appraisal.

A host of instruments and measures are proposed in different contexts as embodying the precautionary principle or as means to implement a precautionary approach in risk management.[23] Naturally, there are no hard and fast distinctions between conventional and precautionary practices. The range of practices lies on a continuum, with details varying from case to case. This discussion, however, focuses on the general way in which precaution offers a series of direct responses to the practical and theoretical problems discussed so far in relation to risk assessment. The practical relevance of these "elements of precaution" is illustrated in cases drawn from a recent detailed empirical study for the EEA.[1]

Humility

The first key element concerns the need to maintain greater humility in the face of the many sources of uncertainty, ambiguity, and ignorance often displayed in risk assessment. Claims to complete or otherwise definitive knowledge can impede recognition of potential surprises, such as those associated with the development of stratospheric ozone depletion as a consequence of chlorofluorocarbon (CFC) use,[28] the unforeseen reproductive effects associated with the pharmaceutical diethylstylboestrol (DES) in the daughters of patients,[29] or the anti-fouling agent tributyltin (TBT) in marine animals.[30] In such cases, greater caution over the robustness of the available knowledge might have led to earlier recognition of the associated problems.

One way to address this is to focus more attention on relatively easily recognized properties of chemicals, such as their persistence, bioaccumulative potential, and mobility, as well as their hazardous potential for carcinogenic, mutagenic, and reproductive impacts, in contrast to waiting years for the knowledge about dose-response relationships that comes with such long latent period impacts as cancer in humans or damage to ecosystem services. Some of these indicators of the hazardous potential of chemicals become more significant once their impacts become evident. For example, there are difficulties in reversing impacts of such persistent and bioaccumulative substances, such as polychlorinated biphenyls (PCBs) and TBT, once the evidence of their impacts becomes clear. In giving greater weight to these more intrinsic properties in risk assessments, there is less danger of the misplaced certainties that can arise from the absence of direct evidence of harmful impacts. Another important response lies in shifting the levels of proof employed in the interpretation of science in the regulatory appraisal and moving the burden of persuasion away from those who wish to tolerate a risk and toward those who wish to avoid it.[1] Transcending all of these measures, there is the need to simply discard the hubristic language and thinking often associated with risk assessment, whereby unknowns are systematically neglected. The examples above illustrate that in denying the importance of surprise in regulatory appraisal, the wider social management of risk can become over-confident and over-exposed to the consequences.

Research and monitoring

Another way to make regulatory appraisal less vulnerable to the shortcomings of risk assessment is to make greater provision for (and place greater reliance on) the dedicated monitoring of occupational, public, and

ecosystem health. Rather than relying on theoretical models or narrow, relatively simplistic, and artificial laboratory-based testing, this can make policy more responsive to manifest harm in the real world. This would likely have made a considerable difference in mitigating the serious ecological effects of widespread use of the electrical insulators PCBs[31] and in anticipating the adverse consequences of routine use of antimicrobials in livestock management.[32]

Likewise, more strenuous efforts can be made to conduct research into outstanding questions or anomalies in our understanding of particular hazards. A failure to engage in active strategies of scientific enquiry played a significant role in compounding exposure to the species-jumping cattle disease bovine spongiform encephalopathy (BSE).[33] By enhancing both scientific research and environmental and health monitoring, we can hope to significantly reduce our exposure to uncertainty and ignorance.

Completeness

Broadening the scope of regulatory appraisal to include a wider range of possible mechanisms and effects and a greater variety of scientific disciplines would further mitigate uncertainty and ignorance. In the past, as exemplified in cases such as DES[29] and the engine anti-knocking agent methyl tert-butyl ether (MTBE),[34] regulation has systematically neglected consideration of indirect, cumulative, additive, complex, and synergistic effects. The regulatory response to BSE was characterized by undue reliance on the specialist community of veterinary scientists, rather than public health professionals.[33] Likewise, the broadening of the scope of regulatory appraisal can help ensure that attention is focused on conditions as they apply in the real world, rather than those embodied in hypothetical models—such as assumptions that chemicals like PCBs might realistically remain contained in "closed systems."[31] In all these ways, extending the scope of appraisal offers a direct means to mitigate ignorance.

Participation

The logic of broadening the regulatory appraisal process extends beyond just the inclusion of different scientific disciplines. By appraising the full range of interested and affected parties, we can hope not only to further mitigate ignorance, but also to accommodate the intrinsic ambiguities in the framing of risk science. The histories of asbestos,[35] benzene,[36] and PCBs[31] provide examples that communities of workers are aware of health effects well before they are recognized by specialist disciplines. Likewise, it may be local people who first become sensitized to the effects of complex mixtures of chemicals in the environment, as in the case of the Great Lakes.[37] Workers can also provide vital insights into real-world conditions, such as those in slaughterhouses crucial to the development of the BSE issue.[33] Finally, the BSE[33] and antimicrobials[32] cases also illustrate how greater consideration of the cultural values of consumers and ordinary citizens concerning certain industrial practices (like the feeding of ruminants on meat from their own species) may sometimes assist in reducing exposure to certain risks.

Comparing the pros and cons of potential substitutes

Perhaps more importantly, the regulatory appraisal process can be extended to consider the benefits and justifications of a range of policy options. As shown in the case of the marine antifoulant TBT,[30] the use of CFCs as refrigerants,[28] the medical use of X-rays,[38] and the automobile engine anti-knocking agent MTBE,[34] the scope of regulatory appraisal tends to be restricted to examination of the acceptability of individual products on a case-by-case basis, without reference to the range of other means to deliver the same goods or services at lower risk. All these products turned out to be much more readily substituted than initially thought, but the potential substitutes were simply not considered in risk regulation. A similar situation applies in the cases of products such as asbestos,[35] PCBs,[31] and benzene,[36] where the narrow scope of regulatory appraisal also contributed to serious long-term neglect of viable alternatives. By giving systematic consideration to the benefits and justifications of a range of different options at an early stage, we may avoid being locked in to harmful technologies and so foster more beneficial forms of innovation.

Precautionary technology strategies

Technology policy offers a final series of broad responses to uncertainty, ambiguity, and ignorance. Although these involve risk-management issues, they also require inclusion of new considerations in regulatory appraisal. In short, rather than focusing entirely on efforts to characterize the intractable problems of ambiguity and ignorance, these involve focusing attention directly on the potential solutions. General properties of technological trajectories, such as flexibility, reversibility, resilience, robustness, and adaptability, all offer ways to become less exposed to ambiguity and less vulnerable to ignorance.[1,39] Perhaps even more important are the merits of diversity across a range of options. After all, common sense tells us that when we don't know what we don't know, we don't put

all our eggs in one basket! Diversification also offers a way to accommodate the divergent interests and values associated with ambiguity.[40]

All the case studies cited here offer examples where premature commitments were made to particular technological pathways, without considering the ease with which society might withdraw from these commitments should adverse surprises arise. By devoting greater attention to these general features of technological strategies from the outset in regulatory appraisal—and at the earliest stages in the innovation process—we can attempt to reduce these problems. Either way, persistent preoccupation with the sufficiency of probabilistic methods—and their supposed "sound scientific" status—seems to neglect these crucial issues.

SCIENCE AND PRECAUTION IN RISK APPRAISAL

Thus far, we have reviewed the practical, methodological, and theoretical difficulties in conventional science-based risk assessment. By distinguishing the key elements of alternative precautionary approaches to regulatory appraisal, we see that precaution offers a direct response to the challenges of uncertainty, ambiguity, and ignorance. We briefly illustrated the practical relevance of these approaches through a series of documented cases. Now we can quickly review one of this article's central themes: To what extent does conventional risk assessment, based on the use of probabilistic techniques, warrant exclusive claim to science-based or "sound scientific" status? In what sense is a precautionary approach somehow in tension with this scientific aspiration?

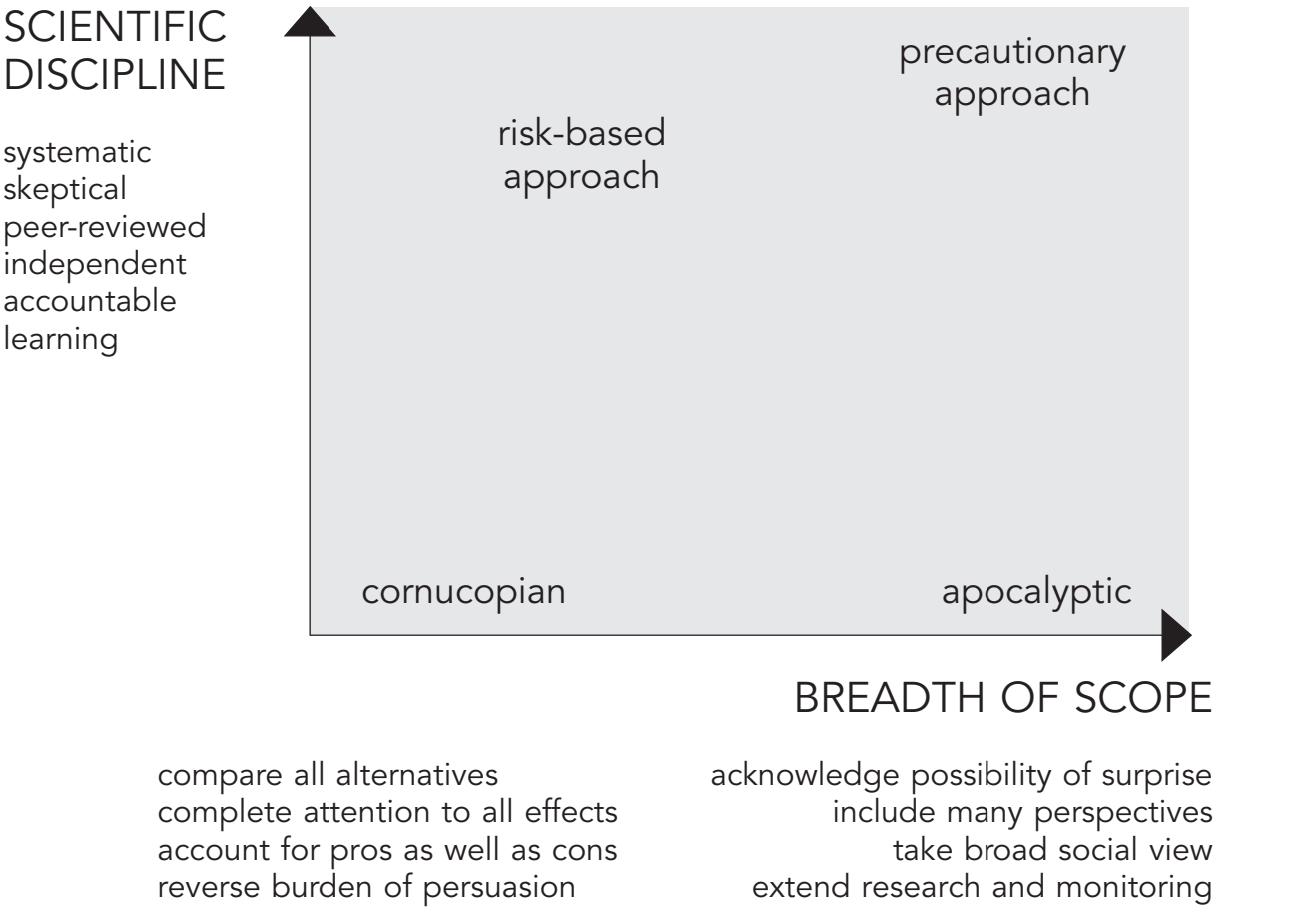
To begin this analysis, we need to clearly characterize *science* and *precaution* in the context of decision-making on environmental and human health risk. Drawing on a wide literature,[39] a series of idealized attributes can be identified to characterize the essence of a scientific approach to regulatory appraisal. In short, scientific appraisal should be transparent in its argumentation and substantiation, systematic in its analytical methods, skeptical in its treatment of knowledge claims, subject to peer review, independent from special interests, professionally accountable and continually open to learning in the face of new knowledge. These aspirations may not always be realized, but they represent fundamental, and relatively uncontroversial, principles guiding any science-based approach to regulatory appraisal.

The key elements of a precautionary approach to regulatory appraisal, on the other hand, are characterized by a different set of criteria. These relate to the institutional and procedural breadth of the regulatory process. Broad-based appraisal displays humility in its acknowledgement of the limits to the available knowledge; includes attention to research and monitoring alongside theoretical models and laboratory tests; extends attention to a more complete array of indirect causal mechanisms for harm; provides for participation by a full range of interested and affected parties; addresses the pros and cons of a variety of alternative options; and considers general features of technological commitments.

Figure 3 provides a graphic display of the emerging relationship between risk assessment and precautionary approaches in regulatory appraisal. It represents these two sets of attributes as dimensions in a space of possible approaches to regulatory appraisal. Of course, the broad/narrow and the scientific/unscientific dichotomies shown in this figure are highly stylized and simplified. However, the general picture displayed in Figure 3 is at least richer and more realistic than any one-dimensional dichotomy between science and precaution. Combined, the two dichotomies generate a fourfold array of idealized permutations. The adoption of a narrow regime in appraisal, without reference to scientific understandings or disciplines, might be described as a permissive position (lower left in Figure 3). Taken to an extreme, this would amount to an entirely uncritical, "anything goes" approach to the regulation of technology, such as that associated with caricature "cornucopian" visions of technological progress.[41] Likewise, a broad-based regime might be similarly unscientific (lower right in Figure 3). The resulting restrictive position might be associated with a caricature "apocalyptic" vision of technology. In the extreme, it would lead to a paralysis under which no new technological innovation that offends in the slightest respect would ever be approved for deployment. The crucial point here is that neither the permissive (cornucopian) nor the restrictive (apocalyptic) positions would be subject to challenge or reversal by the scientific disciplines associated with the vertical axis.

However, Figure 3 also illustrates the grounds for considering broad-based precautionary approaches to regulatory appraisal in some senses more scientifically well founded than conventional risk assessment (top right in Figure 3). These considerations arise simply because certain aspects of breadth are themselves matters of scientific discipline. All else being equal, the inclusion of a broader range of relevant bodies of knowledge is more, rather than less, scientific. It is hardly scientific to deny the existence or relevance of the challenges of uncertainty, ambiguity, or ignorance. For reasons discussed earlier in this article, any claim

Figure 3. The relationships between science and precaution



(or implication) that risk assessment can address these challenges must itself be unscientific. In this context, precaution can be considered to have a more robust claim to the status of "sound science" than conventional narrow risk assessment.

PRACTICAL WAYS FORWARD

The final question posed at the outset of this article concerns the feasibility of "broadening out" regulatory appraisal in the fashion suggested here. It may initially seem rather ambitious to argue that the regulation of risks should routinely extend to such a broad range of complex issues. How can any practical approach to regulatory appraisal incorporate humility, completeness, participation, and the systematic consideration of the pros and cons and strategic properties of a range of options, while also respecting the basic attributes of scientific rigor identified in Figure 3?

Much has been written about this, in a variety of fields. The business of developing practical ways to address the imperatives of precaution is a burgeoning and creative field.[1,6,8,13,20,21,39] Although there is obviously no panacea, and the appropriate response will vary from context to context (including the scale and nature of the activities concerned), one final example may illustrate just one way in which risk appraisal could be broadened out to address these considerations. Multicriteria mapping (MCM) employs techniques adapted from decision analysis.[42,43] Along with many other examples, MCM involves iterative open-ended appraisal of an unlimited set of policy or technology options under an unconstrained array of evaluative criteria. Performance is characterized under each perspective on a numerical rating scale, with explicit attention to a wide range of pessimistic and optimistic assumptions. Criteria priorities are represented by numerical weightings. Specialized computer software generates graphic representations of option perform-

ance and permits comprehensive sensitivity testing, addressing key aspects of social contingency and potential surprise. Institutional ignorance is addressed by including different bodies of knowledge and societal ignorance by allowing explicit attention to properties like flexibility and portfolio diversity.[40,43] The technique can address issues of principle as well as trade-offs. It can be employed in individual interviews or small group settings to characterize different stakeholder viewpoints.

Figure 4 illustrates the types of results obtained from such an exercise. Based on the appraisal of genetic modification strategies in UK agriculture, each chart shows an appraisal of the relative performance of six different options for the production of oilseed rape (comprising, from top to bottom, organic farming, integrated pest management, conventional intensive farming, and three different genetic modification strategies). The 10 diverse viewpoints are grouped according to whether they represent government, industry, public interest, or academic perspectives. The horizontal scale indicates overall performance, good (low risk) to the right, poor (high risk) to the left. The individual perspectives are not aggregated. The effect is to graphically convey the full implications of the ambiguities due to divergent institutional and disciplinary perspectives and the uncertainties due to different assumptions.

Although like risk assessment, MCM harnesses relatively transparent quantitative methods, these are used in a qualified "conditional" fashion to explore and map the consequences of subjective values and perspectives rather than to prescribe as "objective" the consequences of a particular set of assumptions. MCM focuses attention pragmatically on clear orderings of options generated under each perspective. Common ground can readily be identified, yielding conclusions that are all the more robust for being founded on detailed consideration of dissenting views. Yet, because no one prescription is made, this is achieved without sacrificing an appropriate degree of humility concerning the problems of ambiguity and ignorance. The freedom permitted in choosing and defining options, criteria, weightings, framing assumptions, and pessimistic and optimistic scenarios, addresses the intrinsic complexity, contingency, and open-endedness in the social appraisal of risk.

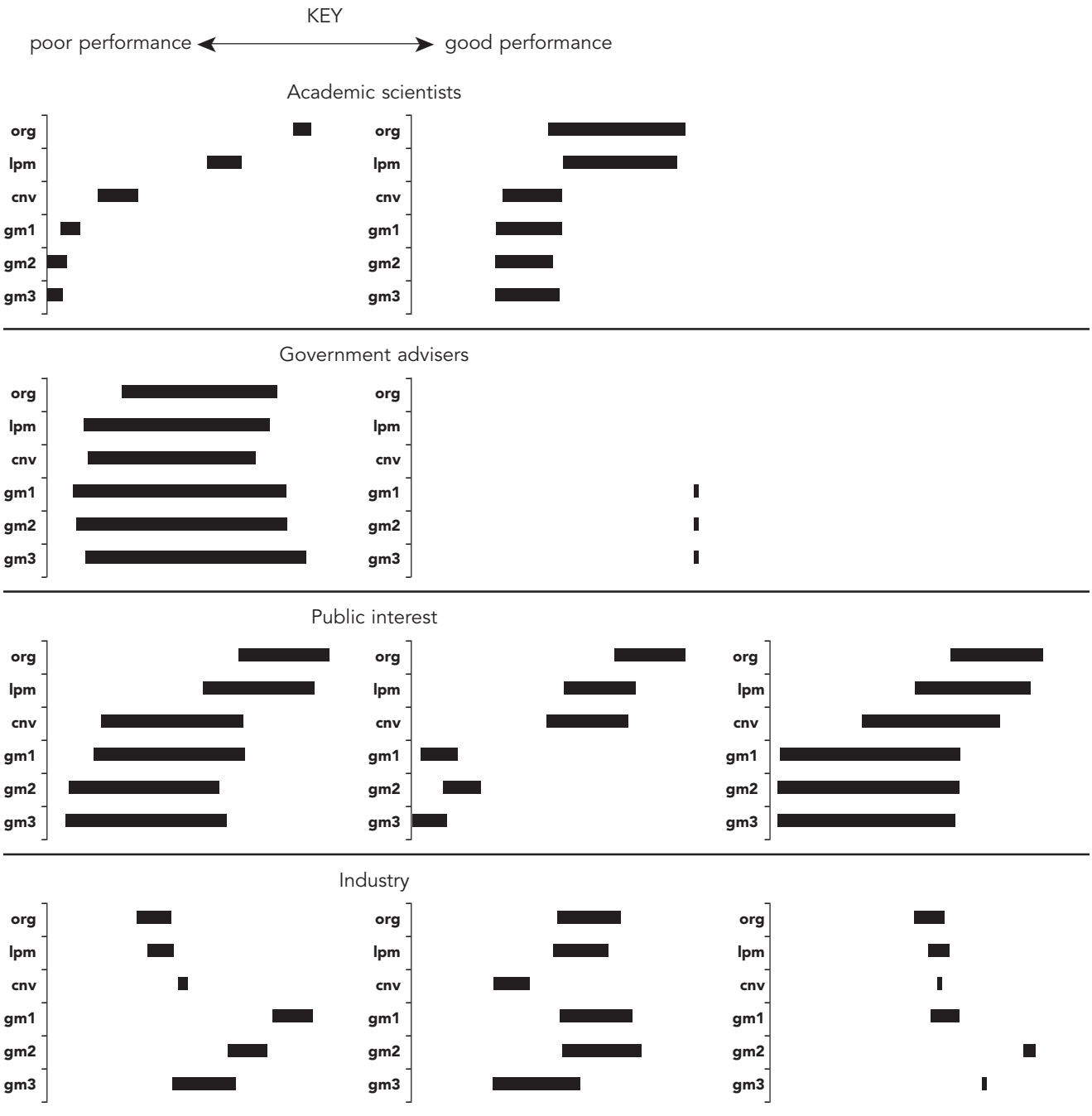
A technique like MCM, or one of the other approaches mentioned above, embodies greater humility than risk assessment in that it acknowledges (in the form of criteria selection, definition, and weighting) the intrinsic subjectivity and consequent ambiguity in appraisal, represents its results in a conditional form (without aggregating across divergent perspectives), and allows for the expression of uncertainty alongside risk. It is, in principle, more complete in scope because it can be applied to the consideration of an unlimited array of possible impacts, without methodological restrictions of the kind typically found with monetary or mortality metrics. It is inherently based on participatory engagement by a range of interested and affected parties. It is based on the comparative appraisal of a series of options, addresses the pros and cons of a variety of alternative options, and considers general features of technological commitments. In short, an approach such as MCM can be claimed to address—at least in principle—all the key features of a broad-based precautionary approach in a form that can be practically implemented in a realistic way.

CONCLUSION

This article has seriously questioned the frequent assertion that precautionary approaches to risk appraisal are somehow less scientific than conventional risk assessment. Indeed, a precautionary approach's greater breadth of scope and attention to a greater diversity of information and knowledge could be considered more scientifically robust than the relatively narrow and uncertainty-suppressing tendencies of so-called science-based approaches like cost-benefit analysis and risk assessment. The ostensible precision of conventional risk assessment can often conceal enormous ambiguity, thus both undermining policy effectiveness and infringing some of the basic principles of rational choice on which such science-based approaches are founded.

At first sight, the key requirements of a precautionary approach may seem somewhat daunting. Themes like humility over science, increased completeness of scope, attention to pros and cons, consideration of a range of alternatives, involving a diversity of disciplines and perspectives, and greater emphasis on research and monitoring may seem to raise challenging operational and resource questions. But the practical example of MCM shows that, in principle at least, there is no reason to consider such aspirations unworkable, or even unduly onerous. In the end, the real value of more precautionary approaches to risk appraisal will lie in the benefits of encouraging more deliberate processes in the social choice of technology, resulting in less risky technologies, identified and deliberately fostered at an earlier stage in the innovation process.

Figure 4. Divergent views of risks of different agricultural options



NOTE: Each chart shows the ranges in option performance rankings on an arbitrary subjective linear scale, running from low performance on the left to high performance on the right.

org = organic farming

ipm = integrated pest management

cnv = conventional intensive cultivation

gm1 = genetic modification with segregation and labelling

gm2 = genetic modification with monitoring

gm3 = genetic modification with voluntary controls

REFERENCES

1. Gee D, Harremoës P, Keys J, MacGarvin M, Stirling A, Vaz S, Wynne B, editors. Late lessons from early warnings: the precautionary principle 1896–2000. Copenhagen: European Environment Agency; 2001.
2. Holdren J. Energy hazards: what to measure, what to compare. Tech Review 1982;4:32-9, 74-5.
3. Stirling A. Limits to the value of external costs. Energy Policy 1997;25:517-40.
4. Byrd D, Cothern C. Introduction to risk analysis: a systematic approach to science-based decision-making. Rockville (MD): Government Institutes; 2000.
5. Shrader-Frechette, K. Scientific method, anti-foundationalism, and public decision-making. Risk: Issues in Health and Safety 1990;1:341-63.
6. O'Brien M. Making better environmental decisions: an alternative to risk assessment. Boston: MIT Press; 2000.
7. Wynne B, editor. Risk management and hazardous waste: implementation and the dialectics of credibility. Berlin and New York: Springer-Verlag; 1987.
8. Ashford N. A conceptual framework for the use of the precautionary principle in law. In: Raffensperger C, Tickner J, editors. Protecting public health & the environment: implementing the Precautionary Principle. Washington: Island Press; 1999. p. 198-206.
9. Bezembinder T. Social choice theory and practice. In: Vlek C and Cvetkovitch D. Social decision methodology for technological project. Dordrecht: Kluwer; 1989.
10. Arrow K. Social choice and individual values. New Haven: Yale University Press; 1963.
11. Funtowicz S, Ravetz J. Uncertainty and quality in science for policy. Amsterdam: Kluwer; 1990.
12. Aspects of this are referred to as "indeterminacy" in: Wynne B. Uncertainty and environmental learning: reconceiving science and policy in the preventive paradigm. Global Environmental Change; 1992. p. 111-27.
13. Stirling A. Risk, uncertainty and precaution: some instrumental implications from the social sciences. In: Berkhout F, Leach M and Scoones I, editors. Negotiating environmental change: perspectives from social science. Cheltenham: Edward Elgar; 2002.
14. Loasby B. Choice, complexity and ignorance: an inquiry into economic theory and the practice of decision-making. Cambridge: Cambridge University Press; 1976.
15. Smithson M. Ignorance and uncertainty: emerging paradigms. New York: Springer; 1989.
16. Wynne B. Uncertainty and environmental learning, p. 111-27.
17. Stirling A. Risk at a turning point? J Risk Research 1998;1;97-110.
18. von Hayek F. New studies in philosophy, politics, economics and the history of ideas. Chicago: Chicago University Press; 1978.
19. O'Riordan T, Cameron J. Interpreting the precautionary principle. London: Earthscan; 1994.
20. Fisher E, Harding R, editors. Perspectives on the precautionary principle. Sydney: Federation Press; 1999.
21. Raffensberger C, Tickner J, editors. Protecting public health and the environment: implementing the precautionary principle. Washington: Island Press; 1999.
22. Renn O, Klinke A. Risk evaluation and risk management for institutional and regulatory policy, a study conducted under the auspices of an ESTO project on technological risk and the management of uncertainty. Stuttgart: Centre for Technology Assessment in Baden-Wurttemburg; 1999.
23. O'Riordan T, Jordan A. Reinterpreting the precautionary principle. London: Cameron May; 2001.
24. Tickner J. A commonsense framework for operationalizing the precautionary principle. Proceedings of the Wingspread Conference on Strategies for Implementing the Precautionary Principle; 1998 Jan 23–25; Racine, WI.
25. Jackson T, Taylor P. The precautionary principle and the prevention of marine pollution. Chemistry and Ecology 1992;7:123-34.
26. Dovers S, Handmer J. Ignorance, the precautionary principle and sustainability. Ambio 1995;24:92-7.
27. Ashford N. An innovation-based strategy for the environment and for the workplace. In: Finkel A, Golding D, editors. Worst things first: the debate over risk-based national environmental priorities. Washington: Resources for the Future; 1996.
28. Farman J. Halocarbons, the ozone layer and the precautionary principle. In: Gee D, Harremoës P, Keys J, MacGarvin M, Stirling A, Vaz S, Wynne B, editors. Late lessons from early warnings: the precautionary principle 1896–2000. Copenhagen: European Environment Agency; 2001. p. 76-83.
29. Ibarreta D, Swan S. The DES story: long term consequences of prenatal exposure. In: Gee D, Harremoës P, Keys J, MacGarvin M, Stirling A, Vaz S, Wynne B, editors. Late lessons from early warnings: the precautionary principle 1896–2000. Copenhagen: European Environment Agency; 2001. p. 84-92.
30. Santillo D, Johnston P, Langston W. Tributyltin (TBT) antifoulants: a tale of ships, snails and imposex. In: Gee D, Harremoës P, Keys J, MacGarvin M, Stirling A, Vaz S, Wynne B, editors. Late lessons from early warnings: the precautionary principle 1896–2000. Copenhagen: European Environment Agency; 2001. p. 135-48.
31. Koppe J, Keys J. PCBs and the precautionary principle. In: Gee D, Harremoës P, Keys J, MacGarvin M, Stirling A, Vaz S, Wynne B, editors. Late lessons from early warnings: the precautionary principle 1896–2000. Copenhagen: European Environment Agency; 2001. p, 64-75.
32. Edqvist L, Pedersen K. Antimicrobials as growth promoters: resistance to common sense. In: Gee D, Harremoës P, Keys J, MacGarvin M, Stirling A, Vaz S, Wynne B, editors. Late lessons from early warnings: the precautionary principle 1896–2000. Copenhagen: European Environment Agency; 2001. p. 93-100.
33. van Zwanenberg P, Millstone E. Mad cow disease 1980s–2000: how reassurances undermined precaution. In: Gee D, Harremoës P, Keys J, MacGarvin M, Stirling A,

Vaz S, Wynne B, editors. Late lessons from early warnings: the precautionary principle 1896–2000. Copenhagen: European Environment Agency; 2001. p. 157-67.
34. von Kraus M, Harremoes P. MTBE in petrol as a substitute for lead. In: Gee D, Harremoës P, Keys J, MacGarvin M, Stirling A, Vaz S, Wynne B, editors. Late lessons from early warnings: the precautionary principle 1896–2000. Copenhagen: European Environment Agency; 2001. p. 110-25.
35. Gee D, Greenberg M. Asbestos: from magic to malevolent mineral. In: Gee D, Harremoës P, Keys J, MacGarvin M, Stirling A, Vaz S, Wynne B, editors. Late lessons from early warnings: the precautionary principle 1896–2000. Copenhagen: European Environment Agency; 2001. p. 52-63.
36. Infante P. Benzene: an historical perspective on the American and European occupational setting. In: Gee D, Harremoës P, Keys J, MacGarvin M, Stirling A, Vaz S, Wynne B, editors. Late lessons from early warnings: the precautionary principle 1896–2000. Copenhagen: European Environment Agency; 2001. p. 38-51.
37. Gilbertson M. The precautionary principle and early warnings of chemical contamination of the Great Lakes. In: Gee D, Harremoës P, Keys J, MacGarvin M, Stirling A, Vaz S, Wynne B, editors. Late lessons from early warnings: the precautionary principle 1896–2000. Copenhagen: European Environment Agency; 2001. p. 126-34.
38. Lambert B. Radiation: early warnings; late effects. In: Gee D, Harremoës P, Keys J, MacGarvin M, Stirling A, Vaz S, Wynne B, editors. Late lessons from early warnings: the precautionary principle 1896–2000. Copenhagen: European Environment Agency; 2001. p. 31-7.
39. Stirling A. On science and precaution in the management of technological risk. An ESTO Project Report. Report to the EU Forward Studies Unit, IPTS, Sevilla, 1999 May. Report No.: EUR19056 EN. Available from: URL: ftp://ftp.jrc.es/pub/EURdoc/eur19056en.pdf
40. Stirling A. Diversity and ignorance in electricity supply investment: addressing the solution rather than the problem. Energy Policy 1994;22:195-216.
41. Cotgrove S, Duff A. Environmentalism, middle class radicalism and politics. Socio Rev 1980;28:333-51.
42. Stirling A. Multicriteria mapping: mitigating the problems of environmental valuation? In: Foster J, editor. Valuing nature: economics, ethics and environment. London: Routledge; 1997. p. 186-210.
43. Stirling A, Mayer S. Precautionary approaches to the appraisal of risk: a case study of a genetically modified crop. Int J Occup Environ Health 2000;6:296-311.