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Quality in environmental science for policy: Assessing uncertainty as a component of policy analysis

Laura Maxim [a,*], *Jeroen P. van der Sluijs* [b]

[a] *Institut des Sciences de la Communication, CNRS UPS 3088, 20 Rue Berbier du Mets, 75013 Paris, France*
[b] *Copernicus Institute, Department of Science Technology and Society, Utrecht University, Budapestlaan 63584 CD, Utrecht, The Netherlands*

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ABSTRACT

The sheer number of attempts to define and classify uncertainty reveals an awareness of its importance in environmental science for policy, though the nature of uncertainty is often misunderstood. The interdisciplinary field of uncertainty analysis is unstable; there are currently several incomplete notions of uncertainty leading to different and incompatible uncertainty classifications. One of the most salient shortcomings of present-day practice is that most of these classifications focus on quantifying uncertainty while ignoring the qualitative aspects that tend to be decisive in the interface between science and policy. Consequently, the current practices of uncertainty analysis contribute to increasing the perceived precision of scientific knowledge, but do not adequately address its lack of socio-political relevance. The ‘‘positivistic’’ uncertainty analysis models (like those that dominate the fields of climate change modelling and nuclear or chemical risk assessment) have little social relevance, as they do not influence negotiations between stakeholders. From the perspective of the science-policy interface, the current practices of uncertainty analysis are incomplete and incorrectly focused.

We argue that although scientific knowledge produced and used in a context of political decision-making embodies traditional scientific characteristics, it also holds additional properties linked to its influence on social, political, and economic relations. Therefore, the significance of uncertainty cannot be assessed based on quality criteria that refer to the scientific content only; uncertainty must also include quality criteria specific to the properties and roles of this scientific knowledge within political, social, and economic contexts and processes.

We propose a conceptual framework designed to account for such substantive, contextual, and procedural criteria of knowledge quality. At the same time, the proposed framework includes and synthesizes the various classes of uncertainty highlighted in the literature.

1. Introduction

There are high stakes associated with uncertainty in science used to inform policy. Failure to consider scientific uncertainty at the interface between science and policy has led to numerous controversies with serious consequences (Keepin and Wynne, 1984; Van der Sluijs, 2002). Ignoring uncertainty by suggesting unwarranted scientific precision can have far-reaching effects. In addition to engendering public distrust in science for policy, and giving space for expression of

* *Corresponding author*. Tel.: +33 158 521 724; fax: +33 158 522 165.
E-mail addresses: laura.maxim@iscc.cnrs.fr (L. Maxim), J.P.vanderSluijs@uu.nl (J.P. van der Sluijs).

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conflicting power relationships, the quality of the scientific literature itself and the science-based regulatory debates can be influenced through non-critical propagation of (often preliminary) results presented as well-established facts. In some cases, this can even lead to a collapse of trust in science and its institutions. Overall, failure to consider uncertainty can negatively influence policy-making in the short term, via poorly informed decisions with potentially significant long-term environmental and health consequences.

In environmental science for policy there is increased awareness of the importance of evaluating uncertainty. Indeed, uncertainty assessment has been applied to a broad range of environmental issues including maritime management, maintenance management and software reliability, environmental and biological modelling, integrated assessment modelling, climate change modelling, water management modelling, chemical risk assessment, seismic hazard analysis, ecological risk assessment of Genetically Modified Organisms (GMOs), emissions inventories of greenhouse gases and air pollutants, environmental health impact assessment, environmental indicators, nuclear risks, and many other domains of environmental assessment (see Supplementary material).

Uncertainty is classified in substantially different ways in the literature. However, the vast majority of studies focus on quantifying uncertainty and analyzing its propagation in model calculations, while ignoring qualitative aspects. In real-life controversies, these qualitative aspects tend to be decisive in the interface between science and policy. By ignoring these key dimensions of uncertainty, many modern uncertainty analyses do not adequately fulfill their primary role: to illuminate public debate and inform decision-making processes.

The objective of this paper is to present a conceptual framework able to account for the quality of science for policy, for its relevance in a certain socio-economic and political contexts, and for the quality of the processes through which this knowledge is produced and used.

Sections 2 and 3 summarize an extensive literature study. We selected 79 references (briefly reviewed in the Supplementary material), from all of the papers on uncertainty identified in academic journal databases, that propose a typology of uncertainty related to production of scientific knowledge for environmental decision-making. In Section 4, we propose a conceptual framework for defining uncertainty along four axes: the dimension, the step in the knowledge lifecycle, and the nature and location of the research addressed. Finally, Section 5 discusses the relevance of our proposed framework to the existing literature.

2. Objectives of uncertainty analysis

In this section we briefly discuss six common functions of uncertainty analysis in science-policy interfaces, identified from the literature.

2.1. *Increase precision and identify knowledge gaps*

For most of the authors reviewed, uncertainty is synonymous with lack of knowledge; the purpose of uncertainty assessment is to improve knowledge accuracy (Rowe, 1994; IPCC, 2000). Uncertainty assessment therefore represents an opportunity for scientists, especially modellers, working in a policy context to check the quality of their own work (Rotmans and van Asselt, 2001; Walker et al., 2003; Van der Sluijs et al., 2003, 2008) and that of their colleagues. It should aim to bring scientific predictions increasingly closer to reality (Wandall et al., 2007, pp. 606). The final objective is to quantify and reduce uncertainty as much as possible and minimize the extent to which particular uncertainties affect conclusions (IPCC, 2000; Rotmans and van Asselt, 2001).

2.2. *Increase decision-maker's confidence in robustness of scientific results*

Policy-makers are the principal audience for most uncertainty analysts. Policy-makers do not appear to accord scientific data the credibility it deserves. An objective of uncertainty analysis is to consolidate "*the decision maker's confidence in the results and recommendations of risk assessment*" (Rosqvist, 2003, pp. 43).

But also, uncertainty analysis is an effort on the part of knowledge producers to provide more transparency about limits to their capacity to reveal truths (IPCC, 2000; EPA, 2001) or to provide a fully objective description of reality. Thus, for constructivists, scientists are responsible for revealing their own culturally determined subjectivity and assessing how robust their findings are in light of the remaining uncertainties.

2.3. *Improve stakeholder's and public's confidence in science*

In addition to increasing policy-makers' trust, systematic management of uncertainty is a recommended response to the "credibility crisis" in science for policy; this crisis has resulted from increased use of poorly validated computer models to advise scientific policy. Stakeholders and the public must represent, for post-normal science, an expanded community of peers, invited to discuss the quality of scientific evidence. This is because incomplete and provisional knowledge gives space to subjective choices and therefore to influencing decision-making and the societal power balance (Van der Sluijs, 2002). Without increased transparency and extensive quality control, false precision in science for policy can incite opposition to the role that scientists play in changing democratic relationships.

2.4. *Increase stakeholder's confidence in decision-making*

Inadequate articulation of uncertainties in environmental science for policy has contributed to inappropriate decisions and significant environmental and health damages. Levin (2006) proposes to address uncertainty as a means to increase the public and other stakeholder's confidence "*in the decision-making process as a whole because all parties would know that serious attempts at identifying all important uncertainties had been made*" (p. 853).

2.5. *Improve the quality of decisions*

Better understanding of uncertainty and of how the level of uncertainty influences action is a prerequisite for better decision-making (Rowe, 1994; Walker et al., 2003). Thus, uncertainty assessment is especially relevant when the potential consequences of an incorrect action are far-reaching. Understanding critical uncertainties "*is a crucial step to more adequate acknowledgement and treatment of uncertainty in decision support endeavors*" (Walker et al., 2003, p. 5).

2.6. Highlight the influence of science communication patterns on decision-making

Stakeholders and even scientists can strategically use scientific knowledge and uncertainty information, for example, by communicating only favourable scientific studies and ignoring or discrediting others. Thus, they can create "subjective uncertainty" (i.e. distrust in the existing knowledge) in decision-makers' understanding of the science (Maxim and Van der Sluijs, 2007; Oreskes and Conway, 2010). In this case, the aim of uncertainty analysis is to highlight the social and communication mechanisms involved, with the goal of informing the decision-making process.

3. Typologies of uncertainty in environmental science for policy

The classifications of uncertainty published in the literature are numerous, diverse, and difficult to compare. We limit our discussion here to those most frequently encountered. We structure the results of the literature study by distinguishing between the locations of uncertainty (within a conceptual and/or mathematical model) and its sources, in line with Walker et al. (2003).

3.1. Location of uncertainty in a model

3.1.1. Uncertainty related to the content of knowledge

The locations of uncertainty most often encountered in mathematical modelling are (EPA, 2001; Rotmans and van Asselt, 2001; Rosqvist, 2003; Van der Sluijs et al., 2003, 2008; Li and Wu, 2006):

- in model structure (practical limitations in describing complex relationships between variables or acquiring detailed information using measurements);
- in parameter uncertainty (certainty about the true value of the parameter);
- in conceptual uncertainty (ignorance about qualitative relationships between phenomena).

Several other locations of uncertainty also appear in the literature: in model input data, initial states, output data, assumptions, level of simplification, extrapolation and scaling algorithms, resolution (spatial or temporal) and boundaries, or in the technical equipment used in modelling (hardware, software and input data measurement instruments; see the Supplementary material for details).

In the chemical risk assessment domain, Wandall et al. (2007) identify several locations where knowledge is a poor fit to the reality it represents. What these authors call "bias" can arise while selecting the problem, developing and implementing the research protocol, choosing and implementing the study method, performing the experiment itself, collecting and recording data, analyzing data, or reporting and publishing results.

3.1.2. Uncertainty related to the process of knowledge production

In science for policy, it is essential to consider the social interactions that occur during the process of knowledge production. The procedural quality of knowledge was described by Cash and Clark (2001) in terms of effectiveness, and measured using three criteria: saliency, credibility, and legitimacy.

Clark and Majone (1985) use "critical criteria" for evaluating the process of using science in a policy context. These criteria can be assembled into four metacriteria: adequacy, effectiveness, value, and legitimacy.

Rosqvist (2003) focuses on the subjective reception of knowledge by decision-makers, and states that confidence in risk assessment results is determined by different, quality-based criteria: completeness, credibility, transparency, and fairness.

3.1.3. Uncertainty related to the context of knowledge production

Context refers to socio-economic and political influences on knowledge production. For Walker et al. (2003), context means identifying the boundaries of the real world to be modelled at the moment that the problem is framed.

Constructivist[1] approaches suppose that these contextual dimensions are inextricably embedded in the researchers' minds and therefore in the scientific knowledge itself. Van Asselt and Rotmans (2002), for example, focus on three socio-cultural perspectives – individualist, egalitarian, and hierarchist – that influence modellers' choices of inputs, parameters, structure, and equations.

Dunn (2002) opposes contructivism and states that science and its context can be completely separated. He recognizes that different stakeholders defend different ways of framing a problem, but affirms that it is possible and necessary to identify the best of these frameworks in order to ensure context validity.

3.2. Sources of uncertainty

3.2.1. Lack of knowledge

The source and forms of a knowledge gap are extremely diverse, and there is no consensus about how they should be classified. For example, Rowe (1994) distinguishes four forms of uncertainty: temporal (in past or future states), structural (related to complexity of the world), metrical (related to measurement), and translational (inherent ability of people to understand and interpret scientific knowledge). For Li and Wu (2006), uncertainty comes from simplification: identification and selection of the processes, relationships, and variables

[1] The constructivist view proposed by the Sociology of Scientific Knowledge (Jasanoff, Irwin, etc.) and the analysis of controversies (e.g. Nelkin) stresses the key role of by the societal context in which the knowledge is produced and used. However, we do not include this literature here, as our focus in this section is on papers that have proposed a typology of uncertainty.

that are considered most important, and from the translation of the selected processes and relationships into mathematics (i.e. model formulation).

A particular form of knowledge gap is imprecision in observations and measurements, which can be related to both the conceptual instruments used to approach the world (the methods) and to the precision of the measurement instruments (technical uncertainty). The first is often dealt with as uncertainty in model structure; the second, in model data and parameters (Walker et al., 2003).

3.2.2. *Variability*

Many authors identify variability, or the inherent randomness of natural systems, as a second source of uncertainty. Variability is not a property of knowledge but of the ''reality out there'' (e.g. variability between individuals inside animal or human populations) (Rowe, 1994; IPCC, 2000; EPA, 2001; Rotmans and van Asselt, 2001; Van Asselt and Rotmans, 2002; Van der Sluijs et al., 2003, 2008; Walker et al., 2003; Hayes et al., 2006; Li and Wu, 2006). According to Li and Wu (2006), analysis of natural variability in data is the most frequent type of uncertainty analysis. Natural variability is compounded by socio-economic variability (Rowe, 1994; Rotmans and van Asselt, 2001; Van Asselt and Rotmans, 2002; Walker et al., 2003), i.e. value diversity, human behavior, technological surprises, and social, economic, and cultural dynamics. However, the literature provides no criterion to clearly differentiate between variability and uncertainty (EPA, 2001; Hayes et al., 2006).

3.2.3. *Expert subjectivity*

Walker et al. (2003) shows that even mathematical models usually contain subjective elements. For example, modellers often make assumptions about what characteristics of the relevant reality should be included in the model system, or about the most appropriate theoretical framework for expressing relationships in the model. However, Walker et al. (2003) do not draft criteria for assessing the subjective dimension of uncertainty, considering it implicitly addressed in the uncertainty assessment. Their framework has been updated by Van der Sluijs et al. (2003, 2008), who refer to several cognitive biases that can lead to expert subjectivity, e.g. overconfidence, anchoring and adjustment, availability, representativeness, satisfying, interests (motivation), unstated assumptions, and coherence. Expert subjectivity in model assumptions has been treated by Kloprogge et al. (2011), who developed a pedigree matrix to address epistemic (general and discipline-bound) and non-epistemic (socio-political and practical) values.

Wandall et al. (2007) proposed an original approach. They highlight, in addition to expert subjectivity, expert conflict of interest or even fraud. Claxton (2007) reviewed the growing conflict of interest literature and identified three sources: financial, philosophical, or professional.

3.2.4. *Communication patterns*

Linguistic typologies of uncertainty refer to the relationship between the properties of the message emitted and those of the message received. Levin et al. (2004) classify linguistic uncertainty as: uncertainty in content (leading to inexact propositional content), epistemic (the degree of belief assigned to a proposition), conditional (the truth of one statement is conditional on the trust in another), and inferential (logical inference).

Maxim and Van der Sluijs (2007) distinguished several forms of linguistic uncertainty within a communication itself: lack of reliability (selective use of references from the available scientific knowledge), lack of robustness (ignoring criticism), ignorance of knowledge produced by other stakeholders, lack of relevance of the arguments to the issue under debate, logical circularity of the discourse, and lack of legitimacy of the sources of information used. This kind of uncertainty is similar to the translational uncertainty described by Rowe (1994).

In communication, word choice is as important as the content of the message. Hayes et al. (2006) distinguish between ambiguity (lack of clarity about the intended meaning of a word), context dependence (failure to specify the context), underspecificity (overly general statements), and vagueness (words allow borderline cases of consequences of a risk). Ambiguity can be removed through the use of linguistic conventions on the meaning of words. Communication of scientific knowledge must be structured according to its particular user, who is characterized by factors like interest, capacity, and openness (Cash and Clark, 2001).

Fig. 1 represents several ways in which different authors represent the problem of scientific knowledge in the context of decision-making. Some view incomplete or erroneous knowledge (i.e. far from the objective reality) as problematic in sociopolitical situations. For others, the problem lies with knowledge that is produced under the influence of subjectivity and socio-economic objectives (e.g. when the production process is not fair, transparent, or adequately credible). Finally, some see both of these characterizations as problematic (''uncertain'') knowledge (e.g. the problem lies with knowledge that is influenced by socio-economic objectives that cause it to diverge from the objective reality). We have represented the different sources and locations of ''problematic knowledge'' (also called ''uncertainty'' or, in this paper, ''low quality knowledge'') as objects that can be defined along two axes – distance from the objective reality, and how knowledge is embedded in subjectivity and socio-economic value loading. The size of the circles indicates the approximate frequency of that kind of ''problematic knowledge'' in the literature.

4. Conceptual landmarks for an inclusive framework

The first conclusion of this extensive literature study is not new: in environmental science for policy, there is neither commonly shared terminology nor full agreement on a typology of uncertainties.

Based on this finding, Rotmans and van Asselt (2001), Van Asselt and Rotmans (2002), Walker et al. (2003) and Van der Sluijs et al. (2003, 2008) have successively built on previous classifications by adding structure and homogeneity in addressing uncertainties. However, these frameworks remain incomplete because:

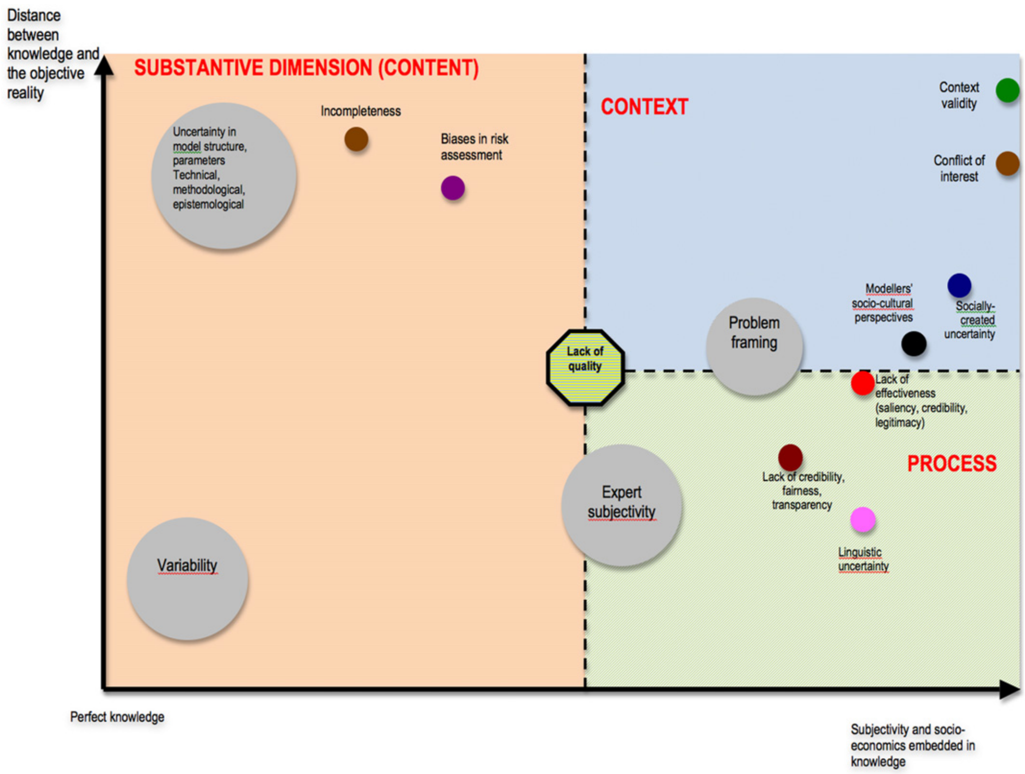

Fig. 1 – Representations of several locations and sources of "problematic knowledge" in the literature.

- they take the perspective of the "producer" of uncertainty analyses, implicitly assuming that the message about uncertainty does not change when it is communicated between the producer (e.g. the modeller) and the final user (e.g. the decision-maker). This ignores the difference between the criteria that scientists, policy-makers, stakeholders, and the public use for judging the relevance of knowledge for decision-making (Maxim and Van der Sluijs, 2007). In any communication process, the messages emitted and received are not identical. Ignoring this impacts the ultimate success of uncertainty communication (Jager, 1998).
- they do not specifically address important aspects of uncertainty: those related to the process (see Section 3.1.2) and to communication (see Section 3.2.4). However, both influence stakeholder and policy-maker's perceptions of knowledge quality. If the purpose is to increase confidence in scientific results, these two aspects must also be addressed.

Here, we go a step further. We aim to extend the typologies of Walker et al. (2003) and Van der Sluijs et al. (2003, 2008) by including the missing aspects identified in the literature. We adopt the approach to uncertainty proposed within the realm of post-normal science; going beyond "lack of knowledge" by focusing primarily on the issue of "quality". Lack of knowledge is only a part of lack of knowledge quality, and not necessarily the most important part.

We include the location and the nature dimensions of uncertainty identified by these authors, but we omit "level" – the third dimension – because not all the classes in our Table 1 can be measured using the scale of levels of uncertainty proposed in the two papers cited. Below, we use the same definition of "model" as Walker et al. (2003), including both the conceptual and the mathematical meanings of the word.

Our framework is based on two conceptual landmarks:

- the steps of what we call the "knowledge production cycle";
- the different dimensions along which all knowledge is produced and used.

The *knowledge lifecycle* consists of several *steps*:

- problem framing;
- knowledge production;
- knowledge communication from authorities to stakeholders, or knowledge-based communication between stakeholders.

In terms of the "knowledge production cycle", our approach considers knowledge quality assessment as a part of the policy analysis[2]. It is important to specify that when we talk about "quality", we do not refer to knowledge that exists within the scientific community on a subject but to the scientific knowledge used in a decision-making process. This distinction is important because general scientific knowledge is never fully or faithfully used in decision-making (see examples in Section 4) and is sometimes not used at all (e.g. the case of asbestos). Low quality of knowledge for policy can therefore arise not only from the fact that scientists have not yet produced "perfect knowledge" of a subject, but also from the

[2] Concepts from policy analysis can be very helpful in understanding the role of scientific uncertainty in policy-making. For example, in policy analysis, the step of problem identification and framing is well identified and addressed (Dery, 1984).

Table 1 – Analytical framework for assessing the quality of environmental science for policy.

Uncertainty nature /location	Problem framing		Knowledge production		Knowledge communication and use	
	Nature of uncertainty	Location of uncertainty	Nature of uncertainty	Location of uncertainty	Nature of uncertainty	Location of uncertainty
			Technical	Model input (data)	Preciseness	Reporting of study outcomes
			Methodological	Model parameter		Reporting of uncertainty information
				Model structure		
Substantive	Epistemological	Assumptions, system boundaries		Model output		
				Technical model implementation (hardware and software bugs)		
			Epistemological	Data management and storage (Database)		
Contextual	Regulatory	Regulatory rules of knowledge production	–	–	Socio-economic	Relevancy for the different scales, stakeholders, socio-economic stakes and option of action
	Socio-economic	Assumptions				
Procedural	Transparency, inclusiveness, fairness	Access to information	Competence	Expert competence regarding the subject addressed	Transparency	Uncertainty assessment available
		Opportunities given to stakeholders/the public to participate		Expert field and research experience regarding the subject addressed		Public communication of scientific results
		Representativeness and role of different stakeholders		Knowledge validation (e.g. through peer-review)		
	Operational	Financial, time and human resources available	Linguistic	Vocabulary		
			Legitimacy	Conflict of interest, biasses	Linguistic	Clarity of the vocabulary used (e.g. lack of ambiguity, hedging)
	Competence	Relevancy of lay knowledge	Value-ladeness	Interpretation of the existing literature or of the results obtained	Legitimacy	
		Expert competence regarding the subject addressed		Choice of the literature sources used		Conflict of interest, biasses
		Expert field and research experience (e.g. number of papers in peer-reviewed journals) regarding the subject addressed				
	Legitimacy	Conflict of interest, biasses				

Note: This table does not aim at being exhaustive regarding the locations and natures of knowledge quality, because these tend to differ from case to case and cannot be exhaustively covered to arrive at a one-size-fits-all framework.

ways in which existing knowledge is understood, communicated, and used.

The second axis of describing uncertainty (lack of knowledge quality) to arise from the considerations above, refers to three dimensions:
- *substantive* (the content of the knowledge itself);
- *contextual* (the context of knowledge production or use, i.e. "when and where" knowledge is framed, produced, communicated or used, and in which socio-economic and political conditions);
- *procedural* (the processes of how knowledge is framed, produced, communicated, or used).

The methods and tools for addressing knowledge quality differ depending on the dimension.

The main purpose of our classification is to highlight procedural and contextual dimensions as full components of knowledge quality that must be specifically addressed on the same level as technical, methodological, and epistemological components. This is because there is a discrepancy between the objectives given to uncertainty analysis used to increase stakeholder and policy-maker's confidence in scientific and decision-making quality and the current conceptual framings of uncertainty used for doing so.

Scientific knowledge of good substantive quality can have a poor contextual quality (e.g. developing good scientific knowledge on viruses in a context where a decision is needed regarding chemical contamination); in this case, knowledge would not lead to better decision-making. Another situation occurs when inadequate contextual rules of knowledge production lead to the production of substantively low quality knowledge (e.g. technically inexact or methodologically unreliable; see our example on Gaucho® in Section 4).

The contextual and procedural dimensions differ in scale. The context changes at long time scales and high political levels, and therefore cannot be easily influenced at the level of each new situation of knowledge production (e.g. an expert committee conducting a government-commissioned risk assessment of a substance). Process is more easily influenced (e.g. through the choices of an expert committee or the allocation of human and financial resources).

4.1. *The substantive dimension*

4.1.1. *Problem framing*

Problem framing requires that system limits be defined, that indicators and parameters for describing the system be chosen, and that causal relationships between these parameters be defined. This process can be influenced by both the concepts and theories available for framing the problem (epistemological quality), by the values and interests of the scientist, and by the socio-economic and political context in which the research is conducted.

Epistemological quality is relevant for the substantive dimension, as it determines the quality of assumptions used to describe the observed aspect of reality (see Table 1). The socio-economic and regulatory influence is relevant to the contextual dimension (see Section 4.2.1), and value-ladenness is relevant to the procedural dimension, as it can be relevantly addressed through robust processes (see Section 4.3.1).

Problems with epistemological quality (the substantive dimension) can be dealt with by addressing the content of the knowledge (quantifying limits and producing more knowledge).

4.1.2. *Knowledge production*

In this step, the technical dimension refers to the numerical imprecision of data – which can arise from limitations of the measurement instruments and techniques, from limitations of the hardware and software used for storing data, from calculating or running models, and from the ordinary variability of repeated measures associated with the randomness of natural phenomena.

The methodological dimension concerns the relevance (regarding the specific characteristics of the problem) and the scientific robustness of the method chosen for producing the knowledge (e.g. its validation through peer-review or through standardization).

The epistemological dimension refers to our ignorance or limits to our ability to understand the world. In knowledge production, this dimension can influence such things as the interpretation of experimental results or the relationships between variables included in a model.

4.1.3. *Knowledge communication*

The quality of knowledge that a decision-maker receives can be related either to the quantity (i.e. completeness) or quality (e.g. misleading textual and logical patterns of the language, knowledge that is inadequate for the user's needs) of the information communicated by the knowledge producer. Examples include underreporting, selective communication, and ambiguity.

4.2. *The contextual dimension*

The socio-economic and regulatory contexts influence both problem framing and knowledge use. Three aspects are important for judging the contextual quality of knowledge:
- the regulatory framework's relevance to the best state of scientific knowledge;
- the influence of socio-economic factors on problem framing;
- the relevance of the available knowledge to the decision problem.

4.2.1. *Problem framing*

Regulation can be a source of knowledge of low substantive quality, as it can impose a certain set of constraints on knowledge production or on the use of the available knowledge (e.g. standardized tests, and risk assessment protocols). Indeed, regulations change much more slowly than scientific knowledge; regulations are often a compromise between many objectives, some scientific but others economic, social, political, or practical.

Quality assessment of the contextual dimension should specify the status of the current regulatory-imposed rules of knowledge production compared to the best available scientific knowledge. Being aware of "regulatory-induced" lack of quality is important not for transforming science as the absolute standard for policy, but for staying aware of potential regulatory failures and of opportunities offered by the progress of science; in our opinion, this awareness can lead to better decisions.

As well, science for policy is influenced by current social and economic priorities, partially shaping the assumptions made when a problem is framed. This should also become transparent through quality assessment, at least to prevent the inappropriate use of knowledge in other socio-economic contexts in which it is irrelevant.

4.2.2. *Knowledge communication and use*

Qualities of knowledge intended to inform decision-making will differ depending on how and by whom the problem requiring a decision is framed. Therefore, relevance of knowledge to its use should be assessed along different scales (e.g. local, regional, and continental), socioeconomic stakes (e.g. child mortality, and income losses), stakeholders (e.g. NGOs, and industry), and options for action (e.g. ban, and limit uses).

4.3. *The procedural dimension*

How and by whom knowledge is produced can significantly influence both the substantive quality, and the confidence of certain stakeholders and policymakers in the final results. As most environmental controversies demonstrate, stakeholder's perception of the quality of knowledge is influenced by elements like conflicts of interest for the researchers, or the political stakes of the institutions employing them.

4.3.1. *Problem framing*

The boundaries of the ''system'' as well as the indicators and parameters chosen for describing it depend significantly on ''who'' defines the problem and ''how'' this is done. The legitimacy of the problem framing process depends on the procedures for including stakeholders. Stakeholders can make a valuable contribution to knowledge production, but a careful balance is needed between scientific work and stakeholder involvement. As Ravetz (2007, p. 277) highlighted: ''*in less popular fields, there might be fewer than a dozen people who are fully competent to assess the quality of each other's work*. [. . .] *quite subtle gaps in a mathematical argument* might vitiate a whole proof! There is no possibility that an untrained person would have anything to contribute to such a process of research and assessment''.

Operational constraints such as financial and human resources, or withholding of institutional support (e.g. to whistleblowers) often play a major role in determining the quality of the problem framing.

4.3.2. *Knowledge production*

When research is interdisciplinary, which is generally the case in science for policy, linguistic aspects can play an important role in communication between scientists from different disciplines. Misunderstanding and lack of boundary concepts lead to ''patchy'' research results that fail to reflect the full range of relevant characteristics of the problem.

The substantive quality of knowledge strongly depends on expert competence, including the expert's relevant research and field experience. Specialists with published articles in peer-reviewed journals on the specific subject addressed by an expert committee (Bisphenol-A) can reach conclusions than oppose generalists of the same discipline (toxicologists) (Beronius et al., 2010). This is not related to ''lack of knowledge'', but to the fact that different specialists have different abilities to identify the relevant quality details.

4.3.3. *Knowledge communication*

The discursive formulation of the scientific evidence reflects the power game, because stakeholders are aware that the ''winning definition'' of an environmental problem will influence the policy-maker's decision, and will affect the distribution of the costs and benefits of the environmental problem among those concerned.

Involuntary communication failures can be solved by better structuring the available knowledge, or by implementing standard linguistic and learning procedures.

But when discursive tactics are voluntary, they introduce confusion that can prolong the debate and generate a state of facts that favors a given stakeholder (e.g. selective use of the available data to argue in favor of a specific idea).

In this case, rules of good practice in communication of scientific knowledge can be established, such as rules for writing risk assessment reports that could include complete analysis of views from dissenting scientists. Quality assessment can also make these communication patterns transparent, and consequently improve decision-maker's awareness of the reasons for the stakeholder's discourse.

Another important element influencing the user's ''perception'' of scientific knowledge relates to problem structuring. Users and scientists do not have the same knowledge or needs; scientific knowledge communication should be adapted to the characteristics of the recipient.

4.4. *The interplay between substantive, procedural, and contextual dimensions in knowledge quality assessment: examples*

4.4.1. *The risks of Gaucho® for honeybees*

We first sketch the controversy that emerged over side effects of a new class of insecticides, the neonicotinoids (Maxim and Van der Sluijs, 2007). In France, the insecticide Gaucho® (active substance: imidacloprid, the most widely used neonicotinoide insecticide) was banned in 1999 for use in sunflower seed-dressing and in 2004 for use in maize seed-dressing, due to emerging concerns regarding risks to honeybees. However, during the first risk assessment in the 1990s neither Bayer (the producer) nor the ministerial expert committee that assessed the marketing dossier submitted by Bayer had identified such risks.

It was later determined that the knowledge submitted by the company and that produced by the expert committee led to an incorrect decision, i.e. marketing authorization of the insecticide for sunflower and maize seed-dressing. Not even suspicion of a lack of knowledge quality was highlighted during that initial risk assessment (pre-damage). The obvious inadequacies of the knowledge (massive omissions in the risk assessment dossier would have been noticed if the dossier's knowledge quality had been addressed) became evident later (post-damage). Why, then, did not the company or the expert committee highlight any quality issue? Our argument is that procedural and contextual factors either created low quality knowledge (e.g. regulation imposed the use of risk assessment methods that were inadequate for the nature of the risk assessed) or allowed the lack of knowledge quality to go unnoticed (e.g. experts on the committee did not have the relevant competence or enough time to critically review the knowledge).

Several aspects of substantive lack of quality, that existed in the original company's risk assessment but were not ‘‘seen'' by the expert committee, were later highlighted by researchers from outside of Bayer:

- the method chosen for the risk assessment was inadequate for evaluating the risk associated with systemic seed-dressing insecticides, because it did not suit the pattern of exposure; the producer originally used a risk assessment method appropriate for acute toxicity linked to sprayed insecticides but the effects of prolonged exposure to systemic insecticides are mainly chronic. The long-term effects on honeybees of different ages, and on the hive as a whole (‘‘super-organism''), were also not considered in the original risk assessment.
- the detection and quantification limits used by Bayer during its first risk assessment were too high for the small quantities of insecticide present in pollen and nectar (technical lack of quality); insecticide presence, therefore, went unnoticed.
- well-established methods for assessing sub-lethal effects were not developed (epistemological lack of quality).

The methodological lack of quality mentioned above was created by the ongoing regulation of pesticide risk assessment, created for the previous generation of pesticides (sprayed) but not appropriate for the new one (seed-dressing). However, the company respected this regulation in getting its insecticide approved for the market; in this case regulation was a source of methodological lack of quality. It is not possible to identify either the source of uncertainty or possible solutions for improving knowledge quality without accounting for the contextual aspect, as in quantitative uncertainty analysis.

The expert committee that reviewed the knowledge submitted by Bayer for marketing the insecticide included only one bee specialist, and the relevant honeybee sub-group was not consulted until very late – after the controversy had already begun. Furthermore, the expert's workload was heavy and did not allow in-depth study of the risk assessment dossiers. Unavoidably, there was only a limited assessment of the quality of the knowledge.

The procedural approaches can also generate low-quality scientific results that potentially support specific political objectives. This low scientific quality is due to a lack of political ability or willingness to use the best available scientific knowledge, rather than lack of knowledge. Thus, in 1997–1998, the French General Directorate for Food of the Ministry of Agriculture (DGAL) demanded analyses of Gaucho® in sunflower using ‘‘the lowest detection limit possible'', but ‘‘without going below 0.01 mg/kg'' (10 ppb). For the 1998 programme DGAL noted that ‘‘it is not useful to try to work with the lowest detection limits''. This detection limit corresponded to the characteristics of the Bayer method: inverse chromatography in liquid phase and UV detection. Bayer representatives also participated in the committee charged with building the research protocol. At the time that the DGAL made this demand, CETIOM (Technical Interprofessional Centre for Metropolitan Oleaginous Plants) had already estimated that detection limits much lower than 10 ppb (about 1.4 ppb) were necessary for finding imidacloprid in nectar. Such concentrations well below the detection limit of the Bayer method were later shown to cause sub-lethal effects, such as disorientation of honeybees, and are thus of key relevance for adequate risk assessment. They are also relevant to understand the risks of chronic exposure, which is a key issue in toxicity of neonicotinoide insecticides in honeybees.

Communication patterns can take advantage of another phenomenon, which is unrelated to lack of knowledge but can nevertheless lead to the promotion of low quality knowledge in the political arena. Perceived knowledge quality can be different from that expressed by specific scientists. During the debate on Gaucho®, some stakeholders implied contradictory scientific results, insufficient for decision-making, when communicating to the public. Indeed, selectively using existing science can create the impression in non-specialists (like policy-makers) that the existing knowledge is not adequately robust (Maxim and Van der Sluijs, 2007). In these cases, there is a discrepancy between the high quality of scientific knowledge, accepted by research specialists in the subject, and the level of quality declared in some stakeholder's discourses. Communication patterns should therefore be included in the assessment of knowledge quality in a political context, because different stakeholders, with different levels of understanding and different stakes, use that knowledge.

When extended to other situations, the case of Gaucho® shows that a **process** of knowledge production (e.g. knowledge produced by someone who is not a specialist of the subject, or who has conflicts of interest) or its context (e.g. a regulatory procedure) can lead to creating or ignoring substantive uncertainty, and therefore render the available knowledge inadequate for the decision-making process. For Gaucho®, the available knowledge was incorrectly considered to be of high quality (for decision-making) in the 1990s, because procedural and contextual factors concealed important quality failures from decision-makers.

4.4.2. *The risks of Bisphenol A (BPA) for human health*

BPA is another relevant case for highlighting the role of the procedural and contextual dimensions in the quality of knowledge produced in a political context. In this case, again, the contextual dimension significantly influenced the ability to correctly assess the toxic properties of BPA. Indeed, the regulatory risk assessment requirements are apparently inadequate for grasping the particularities of the dose-effect pattern of BPA. Furthermore, regulation favored GLP studies over non-GLP published scientific evidence, disadvantaging the latter and indirectly lowering the scientific quality of the final knowledge produced (Borell, 2010; Myers et al., 2009).

Beronius et al. (2010) nicely show that the procedural framing of the expertise can significantly influence the risk assessment result, to the point that results can depend on the identity of the experts participating in the process.

Studying different risk assessment reports, these authors show that results vary from ''there is no risk to any part of the population'' to ''there is a risk to the entire population''. They showed that differences in the conclusions were mainly influenced by expert judgment on the significance of low dose effects; some considered them relevant, while others rejected them. Therefore, the composition of the expert committees and the rules established for how these experts interact while evaluating the available knowledge are of major importance.

Based on the idea that decision-makers should be aware of the best available knowledge, we consider that the processes and the context should be analyzed as part of the knowledge quality assessment, as these dimensions have the capacity to contribute to:

- using low quality scientific knowledge in decision-making, despite the fact that higher quality scientific knowledge exists;
- strategically creating perceived lack of quality, in contrast to the actual state of knowledge;
- hiding the existing lack of knowledge, major omissions in research design, or other quality failures.

There are currently no well-established approaches for assessing the quality of the knowledge production process or context. Research is needed to compare the decisional quality of knowledge produced following different process framings and contexts (along the components highlighted in Table 1 and possibly others that we have not identified).

5. Discussion and conclusions

Recognition of the controversial nature of decision-making about complex environmental issues initially led to discussions about the role of uncertainty. Assessing uncertainty becomes necessary for addressing the credibility of the scientific approaches used in a decision-making context (Van der Sluijs, 2002). However, many research developments in the field of uncertainty assessment seem to underappreciate this key, societal function of addressing scientific uncertainty; research has become increasingly ''positivistic'', to produce a (false) impression of ''certainty about uncertainty'' (see also Van Asselt and Rotmans, 2002).

Our literature study shows that, of the six objectives assigned to uncertainty analysis identified in Section 2, the vast majority of present practices focus exclusively on one, i.e. improvement of the precision of scientific knowledge and identification of gaps in knowledge.

This comes from the hypothesis that ''complete knowledge'' also means ''full trust''– a well-known assumption about the attitude of decision-makers and society towards science. However, trust includes a scientist – policymaker – stakeholder relational dimension linked to communication patterns, issues of legitimacy, influence networks, and value systems associated with knowledge production and use; these factors depend on the regulatory and socio-economic context, and on who participates in or is excluded from the process.

Our framework is comprehensive enough to incorporate the existing frameworks preferred by various disciplines while also acknowledging the strong points of other typologies identified in the literature. Further, it could promote structured opportunities for collaboration between researchers from the natural and social sciences working in different fields such as communication sciences, environmental sciences, and policy analysis.

Some kinds of uncertainties seem to be preferred or better accepted than others. Smithson (2008) notes, for example, that many people prefer probabilistic uncertainty to ambiguity. The methods of uncertainty assessment and communication will have to go beyond the idea of ''producing uncertainty assessments and transmitting them to policy-makers'' in order to better accommodate the end-user of these assessments, with his/her unique preferences and capacity for understanding.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.envsci.2011.01.003.

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Laura Maxim's research focuses on developing methods and tools for knowledge quality assessment in situations of environmental controversy. Her training in both natural and social sciences favors an interdisciplinary approach to her main interest centre, i.e. the analysis of how scientific knowledge and uncertainty change contemporary socio-economic and political relationships.

Jeroen van der Sluijs leads the research cluster Energy and Global Change: Dealing with Risks and Uncertainties, within the Department of Science Technology and Society at Utrecht University. He develops conceptual work on uncertainty in model-based environmental risk assessment, along with methodologies that facilitate better management of uncertainty, quality, plurality, and value judgments in risk and integrated environmental assessment.