Critical Components of Uncertainty Communication in Life Cycle Assessments of Emerging Technologies

Nanotechnology as a Case Study

Sheetal Gavankar, Sarah Anderson, and Arturo A. Keller

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Summary

Because of their recognition as a comprehensive tool of environmental assessments and their increasing use by governments and industries, life cycle assessments (LCAs) are positioned to be prominent sources of mass media information on new products and technologies. The LCA studies underlying media reports are often viewed by nonexperts after the initial reporting. However, uncertainty is rife in early assessments of emerging technologies, and LCA's ability to inform environmental opinions and decisions is limited without the accompanying communication on uncertainty. Though approaches to the technical aspects of uncertainty analysis in LCA are available in the literature, those on communicating that uncertainty, in ways that are cognitively accessible to the nonexperts, are still lacking despite their highlighted importance across various disciplines. With the focus on communication, this article uses the existing literature to derive five criteria for making uncertainty communication accessible to a nonexpert audience. Then, LCAs on engineered nanomaterial (ENM) and ENM-enabled products, as a case study of emerging technologies where uncertainties abound, are reviewed for whether they meet these five criteria. The study concludes with recommendations for communicating uncertainty in LCAs in order to enhance their role as decision- and public opinion–informing assessments.

Introduction

Because of their recognition as a comprehensive tool for environmental assessments and their increasing use by governments and industries, life cycle assessments (LCAs) are positioned to be the prominent sources of information for nonexpert audiences on new products and technologies. Compared to risk assessments, the presence of LCAs in public communication is limited currently, but examples, such as LCAs on diapers (Mirabella et al. 2013; Weisbrod and Hoof 2011), paper versus plastic bags (Post 2007), California high-speed rail (Chester and Horvath 2010; Guardian 2010), passenger transportation infrastructure (Chester and Horvath 2009; NYT 2009; BBC 2009), and the Prius (Reuters 2007; Inquirer 2007; Spinella 2007), show the growing presence of LCAs in nonacademic media. The LCA studies underlying media reports are often viewed by nonexperts after the initial reporting. For example, following the BBC (BBC 2012), *Guardian* (BBC 2012; Guardian 2012) and *Wall Street Journal* (WSJ 2013) reporting on an LCA of electric vehicles, the underlying LCA study (Hawkins et al. 2013) was accessed multiple times from the website of the *Journal of Industrial Ecology*.

Address correspondence to: Sheetal Gavankar, Bren School of Environmental Science and Management, 2400 Bren Hall, University of California, Santa Barbara, CA 93106-5131, USA. *Email*: sgavankar@bren.ucsb.edu

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Uncertainty information in LCA results is critical in supporting environmental decisions (US EPA 2003; UNEP 2011). One of the first discussions on the taxonomy of uncertainty in LCAs proposed uncertainty as parametric, model, and scenario uncertainty as well as spatial and temporal variability (Huijbregts 1998a, 1998b). In parallel, Weidema and Wesnæs (1996) applied the pedigree method to address LCA data quality and reliability based on the NUSAP (numerical unit spread assessment pedigree) approach by Funtowicz and Ravetz (1990). This framework was later applied within the ecoinvent database framework (Frischknecht et al. 2004), enabling its widespread application in the field of LCA. More recently, Henriksson and colleagues (2013) proposed that the NUSAP and pedigree approach adopted in current LCA practices capture only *unrepresentative uncertainty* and propose a way to capture *representative uncertainty* whereby dispersion from inherent uncertainty, spread and unrepresentativeness will be incorporated in the input parameters (Henriksson et al. 2013).

Although these and other approaches to the technical aspects of uncertainty analysis in LCA are available (Lloyd and Ries 2008; Ciroth et al. 2004; Huijbregts et al. 2001; Weidema 2000; Weidema and Wesnæs 1996; Henriksson et al. 2013; Williams et al. 2009; Lenzen 2005), strategies that draw on existing social science research for cognitively accessible communication of uncertainty to nonexperts (not just in LCA, but also in the realm of science communication in general) were lacking until recently (Frewer 2004; Friedman et al. 1999; Kuhn 2000; Miles and Frewer 2003; Satterfield et al. 2013; Wilsdon 2004; Zehr 2000; Friedman et al. 1999; Moss and Schneider 2000; Pidgeon et al. 2011). From the social science literature on uncertainty communication, we derive five criteria for effective communication of uncertainty to a lay (or nonacademic) audience: that uncertainty be reported, context be provided, scenarios be developed where quantitative methods cannot be used, common language describing subjective probabilities be developed, and the uncertainty information be physically accessible.

This study investigates whether the reporting of uncertainty in LCAs of emerging technologies meets these criteria using 15 LCAs of engineered nanomaterial (ENM) and ENM-enabled products (henceforth, nano-LCAs) as a case study. By employing a modified version of the Walker-Harremöes (WH) matrix of uncertainty (Walker et al. 2003), we assess how well the five communication criteria are met. Accordingly, we loosely follow the definition and classification of uncertainty provided by Walker and colleagues (2003, 5), who define uncertainty as "any departure from the unachievable ideal of complete determinism" and use the common typology of uncertainty that encompasses parametric, model, and scenario uncertainty (Van Zelm and Huijbregts 2013; Funtowicz and Ravetz 1990; Huijbregts 1998a, 1998b).

Although there is room for improvement in reporting uncertainty in ways that meet the first three criteria, the LCAs we study generally report uncertainty, provide some context, and develop scenarios. However, most of the uncertainty is reported in the text, limiting its accessibility. Each of the limitations we describe in meeting these four criteria can be overcome by continued attention to improving uncertainty communication on the part of LCA practitioners. The more difficult problem to overcome is that researchers are unlikely to use common language in capturing the overall uncertainty in their assessment. Thus, we conclude by proposing qualitative ways of capturing the overall uncertainty of the assessment. Our proposal is derived from the pedigree approach (Weidema and Wesnæs 1996), which itself is based on the NUSAP approach proposed by Funtowicz and Ravetz (1990) and general recommendations from the Intergovernmental Panel on Climate Change (IPCC) (IPCC 2010). Such a presentation is meant to complement, not replace, a more technical and quantitative analysis of uncertainty in the assessment.

Life Cycle Assessments and Nonexpert Audiences

Academic studies and National Science Foundation (NSF) reports indicate a steady increase in the coverage of science and scientific assessments in the mass media over the past several years (Pellechia 1997; Weitkamp 2003; NSF 2002–12). From the 1990s to the early 2000s, NSF surveys show that the number of media articles resulting from journal articles quadrupled, from around 23,000 to approximately 125,000 (NSF 2006). Surveys also indicate increasing reliance by journalists on peer-reviewed articles and reports, rather than press releases and personal communications with experts (Painter and Bundy 2010). Also, there is an increasing trend for accessing peer-reviewed literature online when the issues are of public interest (Peterson and Merino 2003; NSF 2012). This trend reflects the overall increased reliance on the Internet for scientific issues (Brossard and Scheufele 2013). Science bloggers, who frequently cite peer-reviewed documents, are rapidly supplementing, probably even replacing, the traditional mass media as the public's source of scientific information (NSF 2012). For example, the blogging community has reported academic LCAs on biofuels (Schwark 2012; Lowe 2013), electric vehicles (Taylor 2013; Heinze 2013), as well as a commercial LCA on Levis (Arora 2011).

Uncertainty is a characteristic feature of proactive assessments, such as LCAs, that typically do not have adequate data or mature models. To boost the credibility of the message and prevent misinterpretation, social science scholarship has shown that uncertainties need to get communicated in a manner that is literally and cognitively accessible to the nonexpert audience (Friedman et al. 1999; Kuhn 2000; Wilsdon 2004; Zehr 2000; Giles 2002; IPCC 2010; EC 2004; SIRC-ASCoR 2011). Failing to adequately communicate uncertainty, a common practice in the past, can be detrimental to the credibility of the assessment because it increases public distrust in the motives of researchers, risk regulators, and scientific advisors (Frewer 2004; Miles and Frewer 2003; Wilsdon 2004). In recent years, there has been more-open communication on uncertainty in the scientific assessments of climate science, nuclear science, genetically modified crops, or nanotechnology (Pidgeon 2008). However, scientists' technical communication of uncertainty is often not well understood by the nonexperts (Suleski and Ibaraki 2009). Scientists' familiarity with the issues can impede their ability to communicate with people outside their field and, particularly, with lay people and policy makers (Pidgeon et al. 2011). With informed, but nonexperts increasingly accessing LCAs, it is important to systematically assess how LCAs currently communicate uncertainty and whether that comports with empirically derived criteria for effective communication.

Criteria for Communication of Uncertainty to Lay Audiences

Social science research, particularly in communication, public policy, and psychology, offers empirically validated criteria for cognitively accessible communication of uncertainty to a nonexpert audience. Simple acknowledgement of uncertainty, particularly that resulting from lack of information, is perhaps the most central component of uncertainty communication and serves as our first (if obvious) criterion for effective uncertainty communication (Doble 1995; Zehr 2000; Frewer 2002). Scientific assessments from earlier years routinely failed to acknowledge incomplete information (Frewer and Salter 2002). Though researchers believed, at the time, that lay people could not assimilate or did not value such information, social science research has now shown that lay people not only can conceptualize uncertainty (Frewer 2002), but also its acknowledgement is shown to boost the public's trust on the assessment and on the organization (Kuhn 2000). This is because uncertainty analysis is viewed as an effort on the part of researchers to provide transparency about limits to their capacity to assess the reality (Painter and Bundy 2010; Zehr 2000). Conversely, lack of acknowledgement of uncertainty erodes the trust in the assessment as well as the assessor. When adequate data are available for statistical analysis, quantification of variability (uncertainty) is expected.

The second criterion for effective uncertainty communication is that uncertainty needs to be provided with the context of the issues it is affecting (Satterfield et al. 2013). When scientific assessments also affect socioeconomic, cultural, or policy issues and become matters of public debate, uncertainty analysis without consideration of the social, economic, and ethical issues is insufficient (Casman et al. 1999; Morgan 1998). When context is not originally provided by the researcher, it might be provided by the media and interest groups in a phenomenon called framing (Kuhn 2000; Morgan et al. 2001; Scheufele and Nisbet 2007). Maximum distortion or framing of scientific assessments as a result of uncertainty happens when assessments have implications for society's lifestyle (SIRC-ASCoR 2011; Scheufele and Tewksbury 2007; Scheufele and Lewenstein 2005). Additionally, European Union (EU) REACH guidelines on science and scientific assessment communication explicitly advise researchers to "take a stand" and "be prepared to discuss social and ethical issues" in their scientific assessments as part of uncertainty communication (SIRC-ASCoR 2011).

As uncertainty deepens, that is, as it moves away from statistical variability and toward epistemic uncertainty as a result of lack of information, scenarios need to be considered for several different parameterizations and alternative sets of outcomes (Höjer et al. 2008; Walker et al. 2003). These scenarios comprise the third criterion for effectively communicating uncertainty. For example, in the case of LCAs on emerging technologies, the uncertainty deepens as the assessment that began with the laboratory process moves toward assessing the commercial scale impact based on the laboratory process data. In these situations, providing plausible scenarios is important for scientific communication where the future course of the subject matter is uncertain. Also, when multiple scenarios are presented, relative probability assignments are desirable so that less-likely scenarios are not afforded equal consideration with more-likely scenarios (Painter and Bundy 2010; Moss and Schneider 2000). Often, scientists are reluctant to provide likelihood information on scenarios, fearing the label of subjective judgment (Moss and Schneider 2000; Giles 2002; Painter and Bundy 2010), but the absence of likelihood information on the scenarios allows groups to use whichever scenarios fit their agenda.

When lack of data prevents the employment of standard statistical techniques, researchers should use subjective probabilities to describe their results (Weiss 2003; Moss and Schneider 2000). This approach is used in screening-level toxicity assessment and clinical trials when adequate data are not available (Giles 2002). The audience perceives uncertainty analysis as a way to consolidate the decision maker's confidence in the results and recommendations (Rosqvist 2003; Maxim and van der Sluijs 2011). Community-wide common language and a scale to express uncertainty can provide a common platform to the researchers and enhance the usefulness of the assessment for policy and public opinion formation (IPCC 2010). The type of common scale proposed in this fourth criterion has also been proposed in resolving legal disputes where generalists untrained in scientific assessments—judges, juries, government officials, company managers, and the general public—must evaluate the merits of the scientific assessments when they are presented as supporting documents or proofs (Weiss 2003). When that is the case, subjective assessments of uncertainty using shared language are essential.

Finally, communication of uncertainty should be accessible, because perceived trustworthiness increases with the ease of access to critical information (Mitra et al. 1999). To a lay reader, uncertainty expressed in the abstract or conclusion is more accessible than uncertainty expressed in other sections of a document. This study explores the ease of access to uncertainty information with the maintained assumption that the information needs to be physically accessible with relative ease before it becomes cognitively accessible to lay people. The following section assesses whether these criteria—that uncertainty be reported, context be provided, scenarios be developed where quantitative methods cannot be used, common language describing subjective probabilities be developed, and the uncertainty information be physically accessible—are met in LCAs on nanotechnology.

Case Study: Uncertainty Communication in Life Cycle Assessments

The framework of LCA is used to systematically assess the environmental impact of a product system or service over its entire life cycle (Guinée et al. 2002). According to the International Organization for Standardization (ISO), this framework has four main stages: goal and scope definition; inventory analysis; impact assessment; and interpretation (ISO-14044 2006). At the first stage of goal and scope definition, the product(s) or service(s) to be assessed are defined in terms of functional unit and/or reference flow, which determine the unit of assessment and comparison. This is also the stage where the boundaries and scope of the assessment are determined. In the next stage of inventory analysis, the input (energy and raw materials used) and output information from the product or service system under assessment are connected to the elementary flows (extractions and emissions) from the environment according to the earlier defined functional basis. Then, the environmental impacts of the elementary extractions and emissions are assessed for various impact categories, such as global warming and eco-toxicity, and interpreted. The process of LCA is iterative; it is often repeated when the first round identifies the areas that need a more enhanced assessment.

Because LCAs of emerging technologies must necessarily communicate uncertainty, this article focuses on emerging technologies. In order to keep the nature of uncertainty relatively constant, the selection was limited to one type of technology.

Selection of Nanotechnology as a Case Study

LCAs on ENMs and/or ENM-enabled products were chosen as case study candidates to assess the communication of uncertainty in LCAs on new technologies. They offer a current example of an emerging technology, yet a reasonable number of LCAs have been published that can be used to assess the reporting of uncertainty. An Institute for Scientific Information Web search with key words LCA, nano* and names of various ENMs, and subsequent manual screening yielded 15 LCA studies on ENM and ENM-enabled products, a complete or near complete set of LCAs on ENM and related products as of the time of this study (Gavankar et al. 2012; Hischier and Walser 2012; Keller et al. 2013). We refer to these as nano-LCAs in the remainder of this article.

The Instrument and Coding Methodology

We use the WH matrix that was introduced as a heuristic tool to capture "systematic treatment of uncertainty in model-based decision support" (Walker et al. 2003, 5) to capture the location, level, and nature of uncertainty acknowledged in nano-LCAs, but expand it to account for other aspects of uncertainty communication. The WH matrix has been used to keep track of uncertainties in studies on the level of knowledge of ENM risks (Grieger et al. 2009), fishery science-policy interface (Dankel et al. 2011), soil carbon in ecosystems (Jandl et al. 2011), and water management (Refsgaard et al. 2007). A report by the International Council of Mining and Metals (ICMM) on metal risk assessment has used the WH matrix as an aid in keeping track of the possible locations of the most (policy) relevant uncertainties (ICMM 2007).

The original WH matrix (Walker et al. 2003) provides guidelines on uncertainty communication in decision-informing assessments for several types of audiences along three main dimensions: location, level, and type of uncertainty (figure 1). Location describes where the uncertainty is located within a given model. It can be in the context, model, inputs, parameters, or outcome. The context, as defined by Walker and colleagues (2003), refers to the external reasons behind the choice of the system boundaries, as well as formulation of the problem influenced by those boundaries. Under this definition, "uncertainty about the external economic, environmental, political, social, and technological situation forms the context for the problem being examined" (Walker et al. 2003). Model structure reflects how uncertainty is captured in the mathematical relationships illustrated in the model. In LCAs, these could be assumptions on substitutions, possible supply-chain routes, and the consequential nature of processes, among others. The technical model, as defined by Walker and colleagues (2003), implies computer implementation and software shortcomings or errors. In the case of LCAs, different softwares employ different methodologies (e.g., in the handling of allocation) that eventually contribute to the study's collective uncertainty. Uncertainty can also be located in input data resulting from the constants used in the model (e.g., characterization factors for impact assessments), the system data over which the researcher has no control (e.g., life cycle inventory), or the more controllable process data (e.g., direct energy and raw material inputs). Finally, model outcome uncertainty is the collective uncertainty from all the locations, which is propagated though the model and is reflected in the resulting estimate.

As described by Walker and colleagues (2003), uncertainty at each location can range from statistical variability at one end to recognized ignorance at the other, with scenarios in between. Uncertainty is also of two different types (nature): epistemic uncertainty and variability uncertainty. We use the term variability to indicate the quantities that are inherently variable and need mean, variance, skewness, and other moments for their proper presentation. In contrast, epistemic uncertainty arises as a result of lack of information.

According to this classification, statistical uncertainty represents variability that can be adequately captured with statistical techniques. Scenario uncertainty is present when various outcomes are possible, but exact mechanisms leading to those outcomes cannot be modeled statistically. Walker and colleagues (2003, 12) note that a transition from statistical uncertainty to scenario uncertainty happens at the point where a "change occurs from a consistent continuum of outcomes expressed stochastically to a range of discrete possibilities." Recognized ignorance is when the uncertainty is so deep that

<table>
<tr><th colspan="2" rowspan="2">LOCATION</th><th colspan="3">LEVEL</th><th colspan="2">NATURE</th></tr>
<tr><th>Statistical Variability</th><th>Scenario uncertainty</th><th>Recognized ignorance</th><th>Epistemic uncertainty</th><th>Variability uncertainty</th></tr>
<tr><td>Context</td><td>Boundary conditions</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td rowspan="2">Model</td><td>Model structure</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Technical (Software)</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td rowspan="2">Inputs</td><td>Driving forces</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>System data</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td colspan="2">Parameters</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td colspan="2">Model outcomes</td><td></td><td></td><td></td><td></td><td></td></tr>
</table>

Figure 1 The Walker-Harremoës (Walker et al. 2003) matrix to account for location and type of uncertainty.

not enough information is available to capture the mechanism and functional relationships under study and that the scientific basis for developing scenarios is weak. Unrecognized ignorance (i.e., unknown-unknown) is omitted from this matrix because it indicates total ignorance, which cannot be assessed.

Thus, the WH matrix provides well-tested guidelines for adequate uncertainty characterization in model-based scientific assessments aimed to inform decisions and opinions. It captures two of the criteria for uncertainty communication described in the earlier section, namely, the acknowledgment and contextualization of uncertainty. To capture the remaining three, namely, likelihood discussion for scenarios, researcher's subjective assessment of uncertainty, and ease of accessibility of information, an extension of this matrix is necessary.

As illustrated in figure 2, the horizontal extension comprises three sections, each accounting for a component not captured by figure 1. The matrix in figure 1 is not modified vertically, that is, its rows are the same as those in figure 2. The first section of figure 2 accounts for whether or not any likelihood was provided for scenarios in the LCAs at any location. The second section captures researchers' comments on how uncertainty at various locations and levels affected results. The last section accounts for the ease of access to information at each location. This section has five columns representing five possible places—abstract, introduction, results, figure, and other text—within the LCA study where uncertainty information can be found. Thus, together, figures 1 and 2 capture the five critical criteria for effective communication of uncertainty.

A binary coding was used, where "1" represents communication of uncertainty at a given location and level, and "0" represents the absence of such communication. Each nano-LCA study had its own set of the two tables. The values for each cell were then summed for all studies to assess the five criteria across the set of 15 LCAs. Thus, the maximum attainable score for a given cell in the summary table is 15. The maximum attainable score for each column is 105 (= 15 LCAs * 7 locations of uncertainty). Likewise, in the summary table corresponding to figure 2 (provided in the Supporting Information on the Web), the maximum score for each column under "Ease of Access to Information" is 105. The columns under "Researcher's Belief" and "Scenarios" from figure 2 have a maximum attainable score of 15 because the location specificity is not considered.

Results and Discussion

The coding methodology allows assessment of the degree to which each of the five criteria for effective communication of uncertainty to a lay audience is met. The first criterion is acknowledgment of uncertainty. Considering the technological immaturity and data scarcity on various aspects related to ENMs and ENM-enabled products at the time of these LCAs (Gavankar et al. 2014) one would expect more discussion on reducible uncertainty than statistical analysis. This expected dominance of reducible uncertainty in the LCA discussions on uncertainty is captured in figure 3. Here, each of the 15 studies was reviewed for whether it addressed uncertainty resulting from lack of information in the six locations identified in figure 1. If all of the 15 studies addressed epistemic uncertainty in all the six locations, the maximum score would be 105. The figure shows that epistemic uncertainty was addressed at most locations by most of the studies and has a score of 55. Collectively, reducible epistemic uncertainty is acknowledged seven times as often as nonreducible variability. This also reflects the discussion in the studies on steps that can be taken to reduce uncertainty in the subsequent assessments when the processes mature.

The overall dominance of epistemic uncertainty reflects the emerging nature of nanotechnology; however, the total of 55, vis-à-vis the maximum attainable 105 in figure 3, indicates room for improvement in the acknowledgement of uncertainty. Figure 3 also shows that there is minimal discussion of the accumulated uncertainty affecting model outcomes. This is another area of improvement revealed by this study, because addressing how epistemic uncertainty is likely to affect model outcome is crucial for the decision- and opinion-informing role of the LCAs. There is also no discussion on uncertainty resulting from the selection of software. The studies mention what database and software they use, but a discussion on how these choices

LOCATION		SCENARIOS		RESEARCHER'S SUBJECTIVE ASSESSMENT OF UNCERTAINTY		EASE OF ACCESS TO INFORMATION				
		w/ likelihood discussion	w/o likelihood discussion	Discussion on how uncertainty at various locations, level and nature affected results		Abstract	Intro	Results	Figure	Other text
Context	Boundary conditions	(Location specificity not assessed)	(Location specificity not assessed)	(o or 1)	(Adjacent column on the left was used to keep count of the LCA that had discussion. This column was used to note the details of the discussion. Location specificity not assessed)					
Model	Model structure									
	Software/ Technical									
Inputs	Driving forces									
	System data									
Parameters										
Model Outcomes										

Figure 2 Expanded section of Walker-Harremoës matrix to account for the three additional components of uncertainty communication: scenario likelihood; researcher's subjective assessment of uncertainty; and ease of access to information.

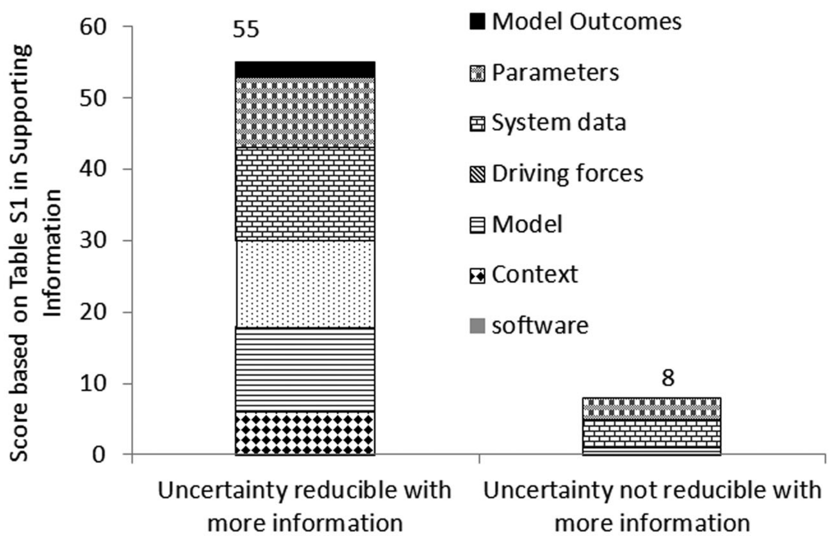

Figure 3 Epistemic uncertainty (which is reducible with more information) and statistical uncertainty (which is reducible with process control, but not with more information) acknowledged at different locations in the life cycle assessments (LCAs) on nanotechnology. Discussion on reducible uncertainty is more dominant in the LCAs related to nanotechnology.

affect their results is missing. This is perhaps because of an implicit assumption that most LCAs use similar software (such as GaBi and SimaPro) and databases (such as ecoinvent), and thus software related uncertainty is somewhat common across studies. Because discussion related to uncertainty resulting from software is completely missing from all the studies, there is no presence of this category also in any of the other charts of this study.

The second prominent recommendation from the social science literature is contextualization of uncertainty. Figures 3 and 4 show that contextual uncertainty (which is about the external economic, environmental, political, social, and technological situation) is one of the least addressed topics in the nano-LCAs. This could be because of two reasons: (1) controllable system data are the basis for LCA, and the ISO methodology does not encourage consideration of economic, social, or ethical issues and (2) not all LCAs may need social, political or economic contextualization. But some, especially those closer to the public's lifestyle, do need it. However, given the emphasis on contextualization by communication studies, it would be beneficial to the LCA community to be cognizant of this recommendation as applicable. An example of such contextualization

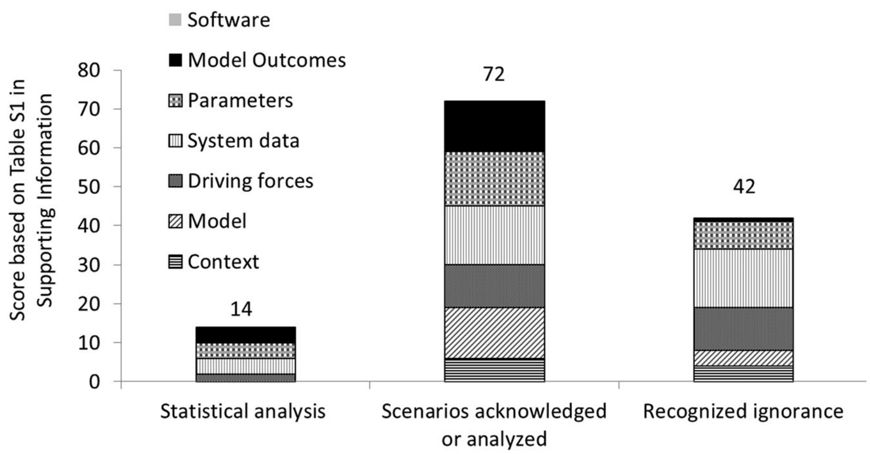

Figure 4 Scenarios are the preferred way to address a deeper level of uncertainty inherent in the assessments of engineered nanomaterial (ENM) and ENM-enabled products.

can be seen in the nanosilver T-shirt study by Walser and colleagues (2011), where the researchers discuss nanosilver manufacturing in the context of the policy and legal framework. Figure 4 also provides insights into how uncertainty was addressed. It shows that uncertainty was predominantly captured either in scenarios or was simply recognized as ignorance. Also, statistical analysis was not a preferred means of uncertainty analysis, and this was likely because of the higher level of epistemic uncertainty. Figure 4 also highlights the preference toward scenarios for addressing uncertainty in nano-LCAs and that epistemic uncertainty at multiple locations was addressed, or at least acknowledged, in scenario analysis. However, no study provided any discussion on the likelihood information on scenarios. This may be a result of the current practices of presenting the LCAs, rather than from limitations of each individual study.

Acknowledgment of the deepest uncertainty is captured as recognized ignorance. The dominance of scenarios over recognized ignorance in figure 4 indicates that though uncertainty is too deep to be characterized by statistical technique, it is probably *not* deep enough that likelihoods for the scenarios cannot be estimated. This leads to the recommendation that, whenever possible and as applicable, likelihood or ranking of scenarios needs to be part of uncertainty discussion in the LCAs.

Results on the fifth criterion—accessibility of uncertainty information—are illustrated in figure 5. Uncertainty communication is mainly present in the text, and prominent places for communication to lay audiences, such as the abstract, introduction, conclusion, and figures, feature much less discussion of uncertainty. This suggests that discussion of uncertainty is not as easily accessible within the text to a nonexpert audience.

Finally, 10 of 15 studies had some discussion either summarizing uncertainty or providing caveats or suggesting improvements in the results with more data. However, lack of uniformity in these various forms of summaries made it difficult to compare even the studies with similar subject matter on the basis of uncertainty in the assessment. Moreover, these recapitulations were not structured enough to provide an indication of the researchers' confidence in the results and recommendations. Hence, although we kept track of whether or not the studies summarized their uncertainty, we did not assess them further on any dimension.

Bridging the Gap

Over the last four decades, social science research has identified the challenges faced by scientists in communicating technical content to nonexperts (Pidgeon et al. 2011). Uncertainty communication is a necessary component of effective communication in light of the changing audience for LCAs. Our case study on nano-LCAs found that important aspects of uncertainty communication are inadequately presented in the current LCA practices in emerging technologies.

These findings can be broadly separated in two groups according to the ease of their remediation. The gaps related to increased level of acknowledgment, contextualization, likelihood information on scenarios, and easier access to information can be addressed by individual researchers relatively easily within the realm of current practices.

On the other hand, bringing uniformity to the summary and providing some level of confidence in the results will need community-wide agreement. We propose a two-part standardized presentation to communicate researchers' beliefs regarding the overall uncertainty in the study.

Because graphical presentations aid communication of information, we propose figure 6, which we call the "Uncertainty Diamond," as a primary tool for communicating researchers' belief on overall uncertainty. Climate scientists have used similar four-axes plots (called a radar plot) to show the sources of uncertainty in their studies (Giles 2002; Moss and Schneider 2000) with axes more appropriate for climate science. The four axes represent the uncertainty dimensions critical for credible and decision- and opinion-informing communication to nonexperts. The left axis represents epistemic uncertainty resulting from lack of information, and the right axis accounts for statistical variation in the process. The uncertainty resulting

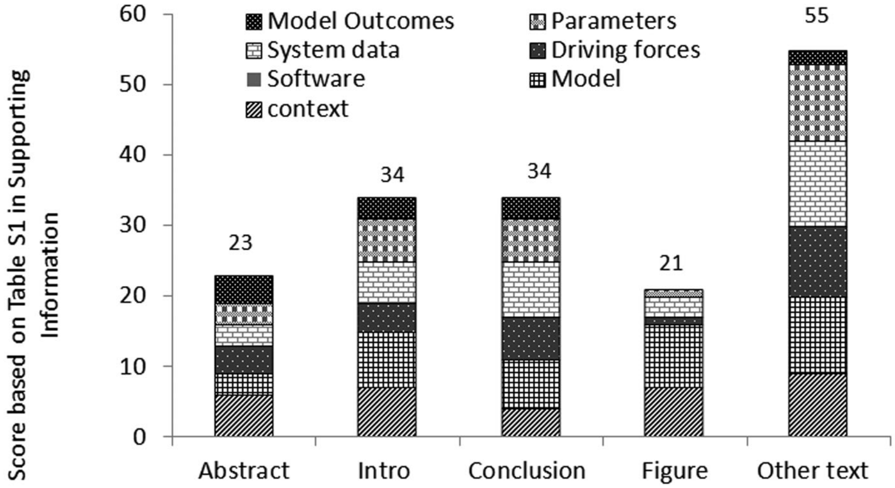

Figure 5 Uncertainty is communicated mainly in the text.

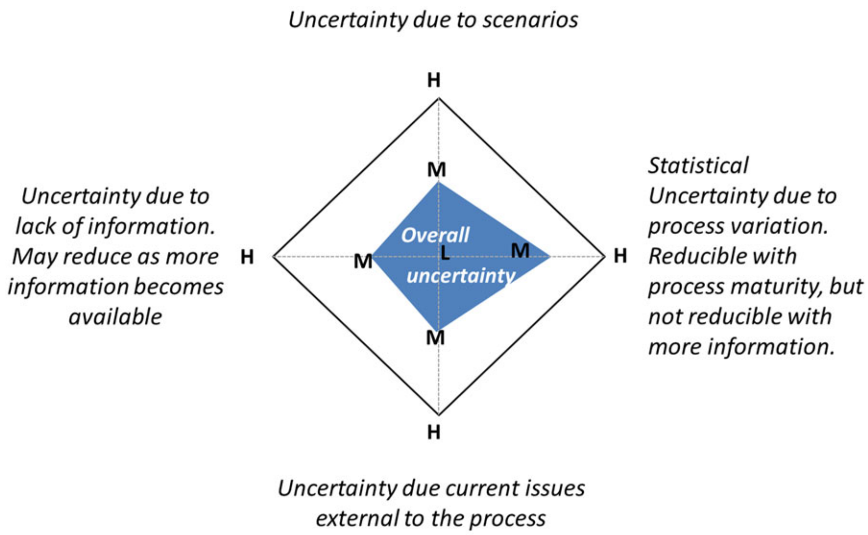

Figure 6 Proposed Uncertainty Diamond for communicating researchers' judgment on overall uncertainty. A larger inner solid diamond indicates higher uncertainty. L = low; M = medium; H = high.

from scenarios is presented by the top axis, and uncertainty resulting from the issues external to the process is on the bottom axis. Each axis can be assigned with a low, medium, or high level of uncertainty. We leave the assignment of low-medium-high to the discretion of the researcher, but a general recommendation for the same provided in figure 7. We recommend that the low-medium-high levels of statistical uncertainty be guided by the size of the error bar and the acceptable variability norms of the subject matter. The levels of uncertainty resulting from lack of information should be guided by whether and how it can be accounted for in the assessment. Similarly, the levels for scenario uncertainty should be guided by whether they are rich enough to be ranked or not. The uncertainty resulting from external issues should be guided by the effect these issues have on the scope and system boundary of the assessment.

The advantage of the Uncertainty Diamond is that multiple aspects of uncertainty can be presented effectively, in that it conveys more information than a single number or word and yet is less cumbersome than placing all uncertainty aspects in one hypercube. Given the qualitative nature of this presentation, the calibration for the exact points between the two extremes is neither desired nor expected. Rather, this diamond is a tool for the researchers to communicate their qualitative judgment on various uncertainty aspects in their study.

Additionally, we propose figure 8 as an accompanying presentation to figure 6. A similar matrix is part of the IPCC recommendation for uncertainty presentation in climate studies (IPCC 2010). The IPCC matrix has "experts' agreement on data" and "evidence supporting data" as two dimensions that are more suitable for a topic in climate science. Instead, we propose "reliability of data" and "completeness of data" as two data-quality dimensions, the importance of which is already established by the pedigree matrix currently used to indicate the quality of data used in LCA studies. The reliability measure

	Low	Medium	High
Statistical Uncertainty	Dictated by the size of the error bar in the statistical analysis, and the "permissible variability" conventions of the topic at hand.		
Uncertainty due to Lack of Information	Can be accounted for or captured with tools such as sensitivity analysis within the current assessment set-up	May need to modify the model or assumptions of assessment to account for information gaps	Cannot be modeled. Borders with ignorance
Uncertainty due to Scenarios	Adequate scientific bases are available for scenarios to be designed and ranked	Enough information is available for scenarios to be designed, but they cannot be ranked	Not enough information is available for developing consistent scenarios
Uncertainty due to External Issues	May not affect the current scope and system boundary of the assessment	May affect the current scope and system boundary of the assessment	Will affect the current scope and system boundary of the assessment

Figure 7 General recommendations for assigning low-medium-high on the Uncertainty Diamond.

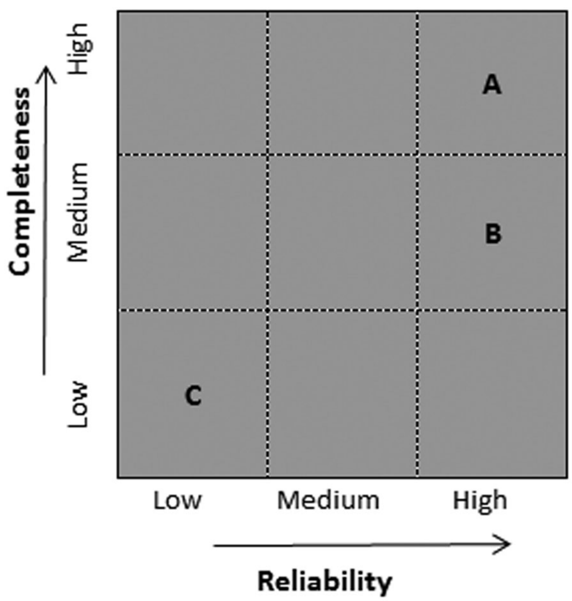

Figure 8 Proposed matrix for data quality assessment accompanying figure 6. The scores limited, medium, and high can be assigned to the dimensions of reliability and completeness according to their scores generated for the pedigree matrix by Weidema and Wesnæs (1996).

relates to the sources, acquisition methods, and verification procedures used to obtain the data, and completeness relates to the representativeness of data (Weidema and Wesnæs 1996; Frischknecht et al. 2004). The scores limited, medium, and high can be assigned to these dimensions according to their scores generated for the pedigree matrix. The scores of 1 and 2 can be limited, with the score of 3 as medium and the scores 4 and 5 as high. The pedigree matrix provides a final aggregated number for multiple dimensions, which works well for technical and reporting purposes, but makes the dimensions of data quality invisible to the reader. The pictorial presentation in figure 8 can be more informative for, and better understood by, a nonexpert. Accordingly, the lower-left corner "C" represents the lowest and the upper-right corner "A" represents the highest quality of data assessed according to these two dimensions. It will be valuable to provide this type of data-quality assessment for critical data points in the LCAs of emerging technologies where data are not only inadequate, but also come from various sources. In an LCA study where the researcher wants to represent the uncertainty in different impact categories or multiple inputs parameters, both can be presented with one matrix (figure 8).

Last, a comparison between the LCAs on the newer system and more conventional/established system may be desired. In this case, the two LCAs are likely to have different levels of uncertainty as a result of the maturity level of the systems, accessibility of data, and other reasons. Such a comparison will be more informative if the uncertainties in both the assessments are made transparent. A technical treatment of uncertainty in these cases can be supplemented with the figures 6 and 8 for the environmental assessment of each system in order to communicate a broad-base comparison of uncertainty.

Conclusion

When compared against the social science recommendations, the results from this study indicate that though uncertainty, especially deeper-level epistemic uncertainty, is acknowledged in nano-LCAs in general, the discussion is mostly centered around fixed parameters and input data. Scenarios seem to be the preferred way of addressing epistemic uncertainty, but none came with likelihood information.

Moreover, uncertainty-related discussion is mostly in the text, and the lack of structure in the recapitulation does not provide a sense of researchers' judgments of overall uncertainty.

Thus, this study indicates that the communication of uncertainty in LCAs of emerging technologies falls short on a few key principles of good communication. Researchers should move toward better reporting of uncertainty, including offering context and assigning likelihoods to scenarios whenever possible. These practices have the advantage of allowing the researcher to frame the conversation and place more weight on likely scenarios. In addition to continuing to quantify uncertainty, the LCA community would benefit from adopting more-standardized means of conveying the qualitative uncertainty assessments. We recommend the use of graphical presentation of uncertainty (especially when it cannot be captured with the statistical tools), as illustrated in figures 6 and 8, to present researchers' judgment on overall uncertainty and data quality. Together, these two figures more prominently place uncertainty communication to allow a nonexpert audience to better understand the level of uncertainty. With increasing use of LCAs by the media and nonexpert audiences, these practices will make uncertainty communication more accessible and improve the credibility of LCA researchers.

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About the Authors

Sheetal Gavankar is a Ph.D. candidate in Bren School of Environmental Science and Management at the University of California in Santa Barbara, CA, USA. **Sarah Anderson** is an assistant professor and **Arturo A. Keller** is a professor in Bren School of Environmental Science and Management at the University of California.

Supporting Information

Additional Supporting Information may be found in the online version of this article at the publisher's web site:

Supporting Information S1: This supporting information provides the populated table of the Walker-Harremoes matrix used to assess the reporting of uncertrainty in 15 nano-LCAs and their complete references.