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Communicating scientific uncertainty in advice provision to decision-makers: Review of approaches and recommendations for UK Statutory Nature Conservation Bodies

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Executive summary

Context

This report presents the findings from a review of approaches to the communication of uncertainty in the context of advice to decision-makers. The review was carried out to support the work of the Joint Nature Conservation Committee (JNCC) and other Statutory Nature Conservation Bodies (SNCBs). SNCBs should articulate and present scientific uncertainty in their advice in ways that facilitate informed, transparent, proportionate and robust decision-making. The overarching objective of this study was to generate recommendations of approaches that could be used to communicate scientific uncertainty to regulators of marine industries in the UK. It has aimed to contribute to greater consistency and proportionality in the manner in which SNCBs communicate their scientific advice to regulators, in the context of plans and projects examined by the latter.

State of the art

There has been a growing call within academic and regulatory circles for greater and better communication of uncertainty to decision-makers: uncertainty should be part of the information and advice given to risk managers. However, the literature on *how* uncertainty should be communicated and *what impact* that communication has on decision-makers is ambiguous. The evidence for or against some ways of communicating uncertainty as opposed to others remains limited and is inconsistent. This study has built on the few robust findings that one can find in the literature, while having regard also to the more tentative findings and the untested proposals that have been published.

Methodology

The study's methodology involved desk research, interviews, and a consultation of the UK's marine regulators. A rapid review of the existing literature was carried out at first to identify relevant approaches and guidance to the communication of scientific uncertainty. This review produced a long list of approaches, from which three sources were selected for in-depth investigation. They were:

1. The Food and Environment Research Agency's (FERA) Uncertainty Table
2. The Dutch Environmental Assessment Agency's (PBL) guidance on Uncertainty Assessment and Communication
3. The Department for Environment, Food & Rural Affairs' (DEFRA) guidance on the *Plant Health Risk Register*

The tools for uncertainty communication presented in each of these three sources were evaluated against their potential use by SNCBs. The evaluation of approaches was broken down into criteria and each assessment was illustrated using a traffic light system. Examples of use within a [fictional] marine regulation context were also developed, to illustrate how each approach might be implemented in SNCB advice. The findings were compiled into a Findings note, which was sent to relevant marine regulators for review. The feedback received from regulators was then reviewed before the finalisation of this report.

Key Findings

The three sources selected for in-depth review presented the following tools for communicating uncertainty:

- The Uncertainty Table Tool
- The Progressive Disclosure of Information (PDI) approach

- Pedigree charts
- Uncertainty proxy scores
- Uncertainty ranges
- Uncertainty ratings
- Box plots
- Mapping
- Kite charts

The Uncertainty Table aims to provide a comprehensive picture of the uncertainties of a particular issue, while integrating some of the findings and recommendations from the scientific literature on uncertainty communication. The PDI approach is also a tool that helps organise the communication of uncertainties overall, as well as of any other information that can be communicated in advice, or in other contexts (e.g. to structure the information in a newspaper article). The other tools identified are rather illustrative in the sense that they can be used to graphically represent uncertainty information that can also be presented verbally or numerically. As such, they are tools that can enhance the clarity of communication. They do not offer a framework for communicating uncertainty, and are more likely to be of use occasionally.

ICF's assessment of these tools against their potential use by SNCBs indicated that the PDI approach, Pedigree Charts, and Uncertainty Table were the most promising of the tools reviewed.

The PDI approach in particular scored high across criteria. It is highly relevant to SNCBs' work and presents a structured approach, sufficient level of detail underlying uncertainty, a combination of qualitative and quantitative elements and the flexibility to incorporate a graphical/visual representation.

The Uncertainty Table would also be appropriate for communicating uncertainty in a wide range of cases, where outcome quantification is possible. For those cases, it can provide a tool that usefully combines qualitative and quantitative expressions of uncertainty. It can also account for the interdependencies between uncertainties, and includes information on the direction and scale of the uncertainties' impact on the risk assessment.

Amongst options in the visual representation of uncertainty, Uncertainty proxy scores and Box plots presented a simple yet informative illustration which could usefully complement text. Box plots and radar or kite charts appeared to be the most suitable to represent the types of uncertainty SNCBs frequently come across. Uncertainty proxy scores and uncertainty ranges may also be applied to the uncertainties dealt by SNCBs.

Recommendations

With regard to the communication of uncertainty, it is recommended that SNCBs:
- structure further the communication of uncertainty using the PDI;
- prevent misunderstanding of uncertainty information by linking verbal expressions of uncertainty to numerical scales; and
- invest in training to engage staff and develop better uncertainty communication practices.

With regard to research on uncertainty communication, it is recommended that SNCBs:
- test alternative formats of uncertainty communication in controlled settings;
- ground uncertainty terms in empirical evidence; and
- consistently and regularly collect and review feedback from regulators for continuous improvement.

Contents

1 Introduction

This report was commissioned to ICF by the JNCC to explore existing tools, approaches and frameworks for communicating uncertainty in the context of advice to decision-makers, and, on that basis, to draw recommendations for the JNCC and other Statutory Nature Conservation Bodies (SNCBs).

This section introduces the background to the study, its objectives, and the state of the art in communicating scientific uncertainty.

1.1 Background to the study

The work of the SNCBs as regulatory advisors to decision-makers should be understood in the context of the UK legal and policy framework for the marine environment. This is a complex framework that has evolved incrementally over the past century. Today, it is heavily influenced by a range of national, European and international laws and agreements.

Marine nature conservation is principally delivered through protected area site designation and management. As well as species protection through designated sites, certain species may also be afforded protection outside of designated sites. These include species listed in Annex IV of the European Habitats Directive, under The Wildlife & Countryside Act (1981), as well as those identified as Biodiversity Action Plan species.

Development or other activity in or near to protected areas is required to undergo tests provided for in the relevant European or national nature conservation legislation. For example, activities in or near Natura 2000 sites are assessed via Habitat Regulations Assessments (HRAs) and Habitats Regulation Appraisal in Scotland; activities in or near Marine Conservation Zones (MCZs) are assessed via Marine Conservation Zone assessments and Marine Protected Areas assessments in Scottish waters. More broadly, when development is being considered at a strategic level, environmental impacts are considered through the use of Strategic Environmental Assessment (SEA), Licencing Rounds for certain plans and programmes (e.g. Oil and Gas Licencing Rounds); and Environmental Impact Assessment (EIA) for specific project proposals (e.g. oil and gas installations, offshore wind applications). A proposal may have to undergo EIA, as well as the relevant designation-specific assessment.

A number of decision-makers are responsible for marine planning and licensing decisions in the UK. This includes, but is not limited to, the Marine Management Organisation (MMO), the Department for Business, Energy and Industrial Strategy (BEIS), the Department of Agriculture, Environment and Rural Affairs (DAERA), the Department for Environment, Food and Rural Affairs (DEFRA), the Crown Estate and Crown Estate Scotland, Natural Resources Wales (NRW), the Planning Inspectorate (PINS) and Marine Scotland (MS).

It is the responsibility of the applicant to supply sufficiently high-quality information to allow licencing and other decisions to be made. Applicants may seek advice from SNCBs in advance of undertaking their assessments. In turn, decision-makers draw on advice from SNCBs to help determine whether an assessment satisfies the relevant tests in the European or national nature conservation legislation.

To assess whether these plans and projects satisfy the requirements set in European or National nature conservation legislation, the SNCBs may rely on a wide range of available evidence. The assessment of the plan/ project’s impact may involve modelling to explore how ecosystems might evolve on the basis of the activity proposed, as well as other parameters. The evidence informing the SNCBs’ advice may be qualitative or quantitative.

As with any assessment of impact, the assessments that SNCBs carry out are built on imperfect and partial evidence: data may be limited or it may be outdated. Sometimes an issue may not be documented in any detailed manner, in which case expert views may be sought instead, or assumptions made. Advice may be required at short notice preventing a full review of the evidence available. Such imperfect or incomplete knowledge base constitutes uncertainty. Uncertainty can take many forms and result from many factors. It is an element the SNCBs' have to consider in their advice provision and should therefore be communicated to decision-makers alongside other elements of the SNCB's assessment.

This study has explored potential frameworks that the SNCBs could use in order to communicate such uncertainty more clearly and more consistently to decision-makers in a marine protection context.

1.2 State of the art

There has been a growing call within academic and regulatory circles for greater and better communication of uncertainty to decision-makers (e.g. Arvai 2014; Kasperson 2014; Fischhoff & Davies 2014; EFSA 2016): uncertainty should be part of the information and advice given to risk managers. Consistently and appropriately communicating uncertainty plays an important role in ensuring transparency and establishing trust. Attempts to diminish or ignore information on uncertainty have been linked to losses of trust in public institutions (Jensen 2004).

However, the literature on *how* uncertainty should be communicated and *what impact* that communication has on decision-makers is ambiguous. While some principles have been outlined in the literature, these are mostly based on logic rather than empirical evidence. The evidence for or against some ways of communicating uncertainty as opposed to others remains limited and is inconsistent (e.g. EFSA 2016; Lees *et al* 2016). As such, it does not provide a firm direction for risk assessors or risk communicators: the field of uncertainty communication research is still nascent, therefore the correspondent literature provides generally only tentative findings.

While risk information enables decision-makers to consider whether to act or not (e.g. deliver a permit to an applicant or not; Heimann 1998), various contributors have argued that communicating uncertainty expands the range of choices decision-makers face. It may allow them to go beyond binary choices and consider other, intermediary options. For example, knowing the distribution of the risks may enable decision-makers to distribute risks between different areas, or populations (of humans, fauna, *etc*) (Fischhoff & Davis 2014; also Arvai 2014).

The literature has demonstrated that communicating uncertainty impacts on risk perceptions. However, the scale and direction of that effect varies. Studies have shown that providing uncertainty information could heighten the perceived risk, which may be a function of the level of 'science literacy' (i.e. the extent to which recipients of the information understand that uncertainty is inherent to scientific work; Johnson & Slovic 1995) and cultural dispositions (which some authors discuss in terms of 'tolerance towards uncertainty'; van Dijk *et al* 2008).

However, experimental work carried out by ICF on behalf of the European Food Safety Authority (EFSA) and involving actual decision-makers has not found conclusive evidence that risk perceptions evolved significantly after sharing information on the uncertainty attached to a risk assessment (Etienne *et al* 2018). To some extent, changes to risk perceptions is a desirable, or "normal" consequence of communicating uncertainty: as an element of the risk assessment, uncertainty alongside other elements from the assessment should contribute to shaping the perceptions of risk managers. Some of the evidence, however, indicates that communicating too much uncertainty information could generate undue concerns and negatively affect confidence in the authority communicating the information (van Kleef *et al* 2009). Much depends on the audience, to which the communication should be tailored (Leung *et al* 2016; Wardekker *et al* 2008).

It is well established that the format uncertainty is presented in influences interpretation. Various studies have considered the meaning lay people ascribed to probabilities attached to an outcome, depending on whether these probabilities were formulated strictly in a qualitative manner (e.g. “very likely”, “likely”, “very unlikely”), in percentages (e.g. “20% chance”, “40% chance”, “between 50 and 80% chance”), or in a combination of the two (e.g. “likely” (60% chance)”) (Ho *et al* 2015; Budescu *et al* 2014; Jenkins & Harris 2018). These studies show that verbal expressions of uncertainty are generally liable to be interpreted in a variety of ways.

However, the use of numerical values may also contribute to a false sense of precision. The advice emerging from this research is that uncertainty should be formulated by a combination of verbal terms and numerical ranges (Budescu *et al* 2012), while the lexicons used by risk assessors should be evidence-based, to ensure that their meaning is attuned to the understanding of the intended audience, and in the context in which those terms are used (Ho *et al* 2015).

This advice is based on very robust research, which was initially all carried out in the context of climate science research (e.g. Budescu *et al* 2012), but has then also been applied to at least two other fields (Ho *et al* 2015; Jenkins *et al* 2018). It has been followed by some institutions such as the Intergovernmental Panel on Climate Change (IPCC) and the United Nations Environment Programme (UNEP), and the JNCC in its Evidence Quality Assurance Guidance.[1]

Other challenges to the communication of uncertainty to decision-makers that have been identified in the literature include:

- Difficulties in achieving a balance in communicating uncertainty in scientific understanding in a way that is scientifically robust and yet does not undermine the power of the main messages (Fischhoff & Davis 2014).
- Addressing the needs of different stakeholders as they come from a range backgrounds and have varying levels of understanding of the science behind the advice provided. They may also use the information differently (Wardekker *et al* 2008).
- Differences in the terminology and language used by scientists on one side and policy-makers on the other, while scientists’ communication skills are often lacking (Leung *et al* 2016).
- Mismatch between the long-term context in which uncertainty is frequently framed and the short-term nature of policies and policy cycles (Wardekker *et al* 2008).

1.3 Study objectives

SNCBs should articulate and present scientific uncertainty in their advice in ways that facilitate informed, transparent, proportionate and robust decision-making. The overarching objective of this study was to generate recommendations of approaches that could be used to communicate scientific uncertainty to regulators of marine industries in the UK. As a consequence, the study has aimed to contribute to greater consistency and proportionality in the manner in which SNCBs communicate their scientific advice to regulators, in the context of plans and projects examined by the latter.

[1] http://jncc.defra.gov.uk/pdf/jncc_EQGN_1_BiasandUncertainty.pdf

To help achieve these overarching objectives, the study's specific objectives were to:

- review current approaches used across a variety of disciplines that communicate / present scientific uncertainty and its possible consequences to decision-makers;
- consider stakeholder views; and,
- provide recommendations for the SNCBs to consider in their work going forward.

The next section presents the methodology followed in the study in order to achieve these objectives.

2 Methodology

The project involved three main steps: data gathering, analysis and consultation with regulators.

2.1 Data gathering

The research team collected information on current approaches to communicating scientific uncertainty, in the manner outlined below.

At first the research team **familiarised** itself with the work of SNCBs. It collected insights from SNCBs on their experience of communicating with regulators of marine activities, through a number of short interviews. Regulator feedback collected by SNCBs before the project began was also reviewed, alongside examples of advice and relevant case material provided by the SNCBs.

A **rapid review of evidence** was carried out, based on an online search for relevant content in academic publications, guidelines on risk assessment and uncertainty communication, publicly available reports and online resources available from various organisations and practitioners. Suggestions provided by marine regulators, collected by the SNCBs before the project began, were also included in the review. The outcome of this effort was a long list of 26 approaches, toolkits and methods for communicating uncertainty.

More **in-depth research** was carried out on three sources from the initial long list that were identified as the most relevant ones in consultation with SNCBs. This involved additional desk research as well as telephone calls and written correspondence with authors of the sources and the organisations implementing the approach. This helped to complete any outstanding gaps in information around the various tools and approaches, clarifying uncertainties around their practical applications, as well as providing examples and any emerging feedback from users on the effectiveness of the approach. The selected sources are:

1. The Food and Environment Research Agency's (FERA) Uncertainty Table
2. The Dutch Environmental Assessment Agency's (PBL) guidance on Uncertainty Assessment and Communication
3. The Department for Environment, Food & Rural Affairs' (DEFRA) guidance on the Plant Health Risk Register

2.2 Analysis

Information on the shortlisted approaches and tools was recorded and assessed against the following criteria:

- Issue relevance – Is the approach applicable to SNCBs' advice on marine nature conservation?
- Regulatory relevance – Does the approach present uncertainty in a manner that is appropriate for the UK regulatory context?
- Scope – Can the approach be applied across various issues, industries, by both SNCB advisors and regulators?
- Feasibility – What are the feasibility constraints of the approach (technology, systems, expertise, *etc*)?
- Feedback – Has the approach been applied by one or more organisations/ institutions and what results or lessons emerged as a result?
- Competing goals – Does the approach recognise and account for competing priorities?

- Communicability – Can the information be transmitted and interpreted by end users (i.e. decision-makers) easily?
- Sufficiency – Does the approach cover all the important aspects without assuming much implicit knowledge or require users to look for clarification elsewhere?
- Adaptability – Does the approach allow for the identification of changes in knowledge, regulatory context or policy context? Does it tolerate adjustments to the advice as a result of these changes?

In order to facilitate comparison between the different approaches and tools, a score was assigned to each of them on a scale of 1-3 for each criterion. This score summarised the extent to which the approach or tool fulfilled the criteria requirements (1 – Only fulfils the criterion to a small extent, 2 – Fulfils the criterion to some extent, 3 – Considerably fulfils the criterion). A summary table (see page 26, Table 5. Summary table) of the approaches and their evaluation scores against the criteria listed above was produced as a result. A traffic light system was used so that the table can easily convey the strengths and weaknesses of each approach against the criteria.

2.3 Consultation with regulators of marine industries

The findings were summarised in the form of a Findings note. The Findings note also included an illustrative example for each approach identified, developed using a combination of elements from actual examples of SNCB advice and fictional elements. The example for each approach contained uncertainty on a fictional offshore windfarm development. This was chosen because (i) assessments of offshore windfarm projects represent a very sizeable share of the SNCBs' advice to regulators, and (ii) the impacts of such projects are often uncertain.

Feedback on the Findings note was sought from regulators of the marine industries in the UK, using a feedback form submitted by email. The feedback was then reviewed and incorporated into the present report. Regulators contacted for feedback were:

- BEIS
- The Crown Estate
- The Crown Estate Scotland
- DAERA
- DEFRA
- MMO
- NRW
- PINS
- MS

Responses were received from all regulators contacted, with the exception of DEFRA.

3 Findings

This section presents in detail the approaches or tools for communicating uncertainty that are outlined in the three sources that were selected as the most relevant ones for further analysis.

3.1 The Food and Environment Research Agency's Uncertainty table

3.1.1 Description

The Uncertainty Table Tool[2] was developed by FERA[3] to illustrate how different sources of uncertainty impact on a defined outcome. It offers two approaches, depending on whether outcomes are:

- quantitative – when the question asked relates to a specific number; or
- categorical – when the question asked calls for a 'yes' or 'no' answer.

The uncertainty information is presented in a tabular form. Each line of the table presents a different aspect of the evidence. All uncertainties are listed within this table, along with a judgement presented with a symbolic rating (such as +/- or arrows) indicating the estimated impact each uncertainty would have on the outcome were it to be resolved (in some scenarios, numerical or verbal expressions may be used instead of symbolic ratings). This judgment is likely to be a range (expressed, for example, as +/++ or -/+). Symbolic ratings are tied to a mathematical scale or, if this is not possible, defined verbally. The definitions of each symbol are presented alongside the table as a legend.

A concluding line in the table explains how the different elements of evidence interact with one another to influence the outcome and presents an overall judgment on the impact of the uncertainties on the defined outcome.

The conclusion from the table can then be included as summary headline conclusions, while more detailed information, including the table itself, can be presented in either the main body of the work or in an annex. More specifically, the guidance recommends the following:

- In the assessment's conclusion: "one sentence summarising the overall impact of uncertainties on the assessment outcome; 1-2 sentences outlining the major sources of uncertainty; plus a description of any uncertainties whose impact on the outcome could not be evaluated."
- In the main assessment report or as an annex: lists/tables plus supporting text as appropriate.

For uncertainties where the impact cannot be measured, the guidance recommends using Pedigree Analysis[4] (see Section 3.2), which assigns qualitative scores to characterise uncertainty or, preferably, presenting the information in narrative form. It also suggests that such uncertainties can be included within the table, and their impact can be judged as "?".

3.1.2 Illustrative example

Below is an illustration of how FERA's Uncertainty Table may be used in a relevant case of an offshore windfarm project to deliver SNCBs' advice.

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[2] https://secure.fera.defra.gov.uk/uncertaintytables/index.cfm
[3] FERA (2010) Development of a framework for evaluation and expression of uncertainties in hazard and risk assessment https://www.food.gov.uk/sites/default/files/676-1-1148_T01056_Final_Report_for_Web.pdf
[4] Pedigree analysis is a qualitative approach within the NUSAP (numeral, unit, spread, assessment, pedigree) system for evaluating uncertainty (Van der Sluijs *et al* 2005, in FERA 2010).

Assessment conclusion

The modelling used to determine both collision risk and thresholds is subject to a great deal of uncertainty, suggesting that actual collision rates could be either lower or higher than those indicated and that thresholds are likely to be lower than those indicated.

The main sources of uncertainty are the gaps in knowledge required to accurately inform the collision risk modelling and the propagation and potential magnifying of uncertainties at each step in the modelling process. The thresholds given, based on an approach to identifying population level thresholds, are subject to uncertainties in modelling but also do not take into account certain important negative external uncertainties. This means that actual thresholds are likely to be lower than estimates. Further details on the nature and impacts of uncertainty can be found within the Annex.

Annex

The following tables present some of the main sources of uncertainty in the modelling used to determine both collision risk and population thresholds for kittiwakes. A legend is included indicating the impact each uncertainty would have on the outcome of the model. Symbols are used to indicate the impact of the uncertainty, each corresponding to a percentage range presented in the legend. Where there is uncertainty around the direction or magnitude of the impact a combination of symbols is used to together indicate the range of impact, for example '↓/↑↑' below can be translated as 1.7-2.5% decrease in adult survival. Concluding statements consider the possible impact on the model outputs when all uncertainties have been resolved. The concluding judgment is not meant to simply add the lines of uncertainty together, as the impact of uncertainties may not combine in a straightforward way. Interdependencies between uncertainties, such as synergies between the impacts of uncertainties, are qualitatively assessed and reflected in the concluding judgment.

All judgements are approximate.

Table 1: Uncertainty in collision risk modelling for Kittiwake.

Uncertainty	**Impact**
Assigning flight height distributions: *Collision risk modelling is undertaken on the assumption that birds are always correctly assigned to their respective flight height bands.*	↓/↑↑
Flight height and observer error: *The flight height data for the development proposals is derived solely from boat-based survey work, so there could be associated observer error due to the difficulty of measuring flight heights at sea.*	↓/↑
Generic flight height distribution data: *The dataset used for this (Cook* et al *2012) has recently been re-analysed and errors have been identified. A revised version is due but 2012 figures were used in these calculations.*	↓/↑
Avoidance Rates (AR): *A 98% AR has been traditionally used in basic modelling.*	↓/↑↑
The populations considered are based on foraging ranges: *For each species of interest all colonies within foraging range of the development are selected.*	●
The size of the population is based on numbers from Seabird 2000: *This provides a known comparison point between colonies. However, there have been possibly significant changes in populations since this point in time.*	↓↓/↑
Area of foraging habitat available: *Assumes flat distribution of foraging birds, but there is insufficient reliable and detailed knowledge of distribution to make better judgments.*	↓/↑

Legend

Symbol	**Predicted decrease in adult survival (%)**
↓↓↓	1.3 – 1.5
↓↓	1.5 – 1.7
↓	1.7 – 1.9
●	1.9 – 2.1
↑	2.1 – 2.3
↑↑	2.3 – 2.5
↑↑↑	2.5 – 2.7

Wind farm and turbine parameters: *Amount of time turbines are operational, number of turbines, rotation speed all contribute to impact. Worst case scenarios were assumed.*	↓↓/●
The collision risk modelling is based on several assumptions, many of which are subject to uncertainty due to insufficient data or gaps in knowledge. Each step is subject to uncertainty and these uncertainties are propagated and potentially magnified through modelling. The uncertainties present suggest that although the predicted decrease in adult survival under this model is 2.0%, it could range anywhere from 1.4% to 2.6%.	↓↓↓/↑↑↑

Table 2. Uncertainty in threshold calculations.

Uncertainty	Impact
Thresholds have been set without considering the status of the population; whether it is increasing or declining. Consequently, thresholds for declining species, such as kittiwakes, should be treated with caution.	↓↓/●
The method used (to identify population level thresholds) allows for larger decreases in adult survival to be determined 'acceptable' for models which have higher variation or uncertainty.	↓/●
The calculations only address one form of anthropogenic mortality (wind farm impacts).	↓↓/↓
The calculations only address mortality during the breeding season.	↓
The population thresholds given based on this method are subject to uncertainties in modelling but also do not take into account certain important negative external uncertainties. This means that although the threshold predicted under this model is a 1.5% decrease in adult survival, the threshold incorporating these uncertainties is likely to be between a 0.7% and 1.3% decrease in adult survival.	↓↓↓/↓

Legend

Symbol	Threshold for decrease in adult survival (%)
↓↓↓	.7 – .9
↓↓	.9 – 1.1
↓	1.1 – 1.3
●	1.3 – 1.7
↑	1.7 – 1.9
↑↑	1.9 – 2.1
↑↑↑	2.1 – 2.3

3.1.3 Performance against set criteria

This sub-section presents ICF’s assessment of the Uncertainty Table against all criteria.

Issue relevance

FERA’s Uncertainty table is **applicable to any type of quantitative estimate or measure**. It is suitable for characterising any of the following types of uncertainty:

- Measurement uncertainty, including accuracy, precision and detection/ reporting limits.
- Sampling uncertainty (variability and bias).
- Other study quality and design issues, including inconsistency of results across multiple studies, ambiguity and inadequate reporting.
- Variability between individuals in the population under assessment.
- Relevance of the data to assessment scenario, and the use of surrogate data.
- Uncertainty about experts' judgements, including differences between experts.

The approach can be used for uncertainties that relate to different contexts or framings of a given problem. Separate tables can be produced for each sub-question and then combined in a table that looks across the evidence to provide an overarching conclusion.

Feedback from SNCBs and regulators indicated that quantitative measures may not always be appropriate to the types of uncertainty dealt with by SNCBs.

Regulatory relevance

The Uncertainty table was developed initially for use by the Committee on Toxicity of Chemicals in Food, Consumer Products and the Environment (COT), however it has not been used within the context of their work. A version of it has been used by the European Food Safety Authority (EFSA) in its scientific opinions, which are delivered in the context of several different EU regulatory frameworks.

By providing a guide to the identification of all sources of uncertainty and their qualification in the context of the risk assessment, the uncertainty table can help advisors to regulatory bodies satisfy the requirements of case law, in that they should demonstrate all areas of potential doubt have been explored.

Scope

Uncertainty tables are applicable to situations where there are multiple sources of uncertainty and where uncertainty can be measured quantitatively. If the impact of an uncertainty cannot be measured quantitatively, it may be appropriate to include other expressions of uncertainty (e.g. Pedigree analysis or narrative). If the sources of uncertainty are limited in number, the table might also not be the most appropriate method for detailing such uncertainties.

Feasibility

FERA has developed free software to assist users of this tool. However, uncertainty tables can be developed without using this software. SNCBs should be able to use and incorporate uncertainty tables in their advice, assuming it is appropriate to the context of their work. Some training may be advised, especially if users are uncomfortable with the idea of quantifying uncertainties.

Feedback

The informal feedback that FERA has collected from decision-makers who have used the table has been generally positive. Other feedback received on this tool has been mixed, which appears to reflect the different sensitivities of potential users with regard to the principle of uncertainty communication, and particularly with the use of numerical values to quantify uncertainty.

Competing goals

The table does not explicitly recognise or illustrate trade-offs or competing priorities. By design it addresses uncertainties associated to a single question. However, tables can be produced for all relevant questions or framings of a single question and summaries can then be included in a final concluding table. The guidance suggests that consideration should be given to "how the uncertainties combine, taking account of any dependencies between them" (FERA 2010). Relevant commentary can be included in the narrative accompanying the symbol.

Communicability

The table provides an indication of uncertainty accompanied by a legend defining the symbols used, either quantitatively or qualitatively. There are different opinions on whether it is appropriate to quantify uncertainties where knowledge is low. Some argue that it can lead to a false sense of accuracy (this was echoed in comments from some UK regulators). Others suggest that quantification is less likely to be subject to misinterpretation than verbal expressions of uncertainty. The latter view is supported by empirical research (see Ho *et al* 2015). The use of symbolic representations is intended to avoid both the imprecision of verbal representations of uncertainty and the excessive precision of numerical representations.

Some UK regulators commented that the use of both symbols and ranges in the table might add unnecessary complexity. The use of ranges and narrative alongside these may be preferable. One regulator also suggested that the communicability of the table could be improved by moving the concluding statement to the top of the table.

Sufficiency

The table provides information on:

- the sources of uncertainty;
- the direction of the uncertainty; and,
- the scale of the impact that resolving the uncertainty would have on the response to the question examined.

As such it implements one of the recommendations from the literature on uncertainty communication: "Specify the various sources of uncertainty underlying key events and outline their nature and magnitude, to the degree that this is possible" (Budescu *et al* 2012:8).

The level of detail in the table can vary on the basis of the user's preferences, although trade-offs exists in terms of the formats in which the information is provided, as discussed above. This tool is suitable for communicating quantifiable uncertainties and may not be sufficient for the overall communication of uncertainty in cases where outcomes are difficult to quantify. In such cases, additional tools could be used (e.g. Pedigree Analysis).

Adaptability

Each source of uncertainty is addressed in turn. Each individual aspect of uncertainty is assessed for its impact on the final outcome. Therefore, any changes can be applied transparently and their impact on the overall impact assessment documented. Changes to the regulatory or policy context may require reframing the question examined and therefore making more extensive changes to the uncertainty tables.

Gaps

The study has not found extensive evidence of the table's use and there is therefore limited feedback available on how it addresses the needs of users, both advice providers and those they provide advice to.

3.1.4 Synthesis

The uncertainty table presents numerous advantages:

- It can accommodate the types of uncertainty dealt with by SNCBs in their regulatory advisory role.
- It applies to situations where there are multiple sources of uncertainty and uncertainty can be measured quantitatively.
- It is easily developed and revised.

- It provides synthesised information on:
    - the sources of uncertainty;
    - the direction of impact of the uncertainty on the risk assessment; and
    - the scale of impact of the uncertainty on the risk assessment.
- It should be easily understandable by end users when presented with text summarising the information as well as a clearly understandable legend.
- It has been tested by EFSA with positive initial feedback.

However, this approach is not fit for all types of uncertainty that SNCBs deal with and will need to be complemented by other tools when uncertainties are difficult to quantify.

3.2 The Dutch Environmental Assessment Agency’s guidance on Uncertainty Assessment and Communication

3.2.1 Description

This guidance document was developed by the Dutch Environmental Assessment Agency (Planbureau voor de Leefomgeving or PBL).

It offers a range of tools for communicating uncertainty:

- The **Progressive Disclosure of Information (PDI)** approach presents uncertainty information in ‘layers’. 'Outer' layers are those most likely to be read by everyone: they are headline conclusions. 'Inner' layers are sections, such as the Annex, that are likely to be read and used by more technical audiences. Layering the information is intended not only to provide uncertainty information that is complete and understandable to different audiences within a single text. It also aims to clarify uncertainty information by presenting it in different forms throughout the text. The approach provides a table to detail how different aspects of uncertainty are communicated at each level. The table can then be used to coordinate the communication of uncertainty between different authors and ensure that information is presented consistently across layers.
- **Pedigree charts** are tools for illustrating 'deep uncertainties', such as disagreement between experts. Pedigree Charts illustrate the degree to which the evidence can be measured on certain distinct measures (such as proxy, methodological rigour, biases, *etc*.

Each approach is illustrated with an example in the next section.

3.2.2 Illustrative example

PDI Tool

The following table is intended not as a communication tool, but instead as a guide to help the authors determine how and where to communicate uncertainty within the different layers of advice, while maintaining consistency. The table can be filled out beginning with the inner-most layer (from the bottom), listing all of the uncertainties identified in assessment that are relevant for the scope of the communication. Moving toward the outer layers, the most important uncertainties can be identified and summarised.

Table 3. The uncertainty information recorded in this table can then be inserted into the appropriate section of the advice.

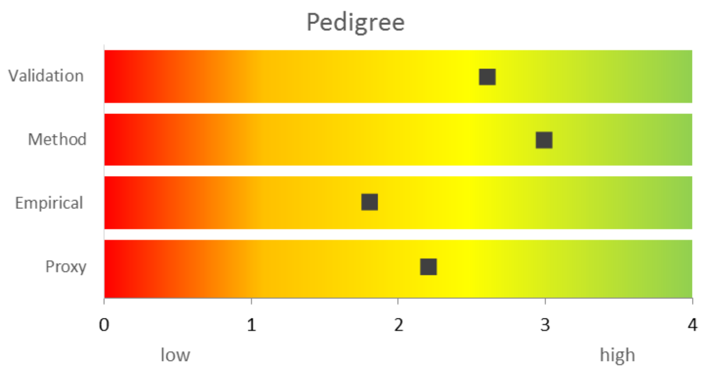
PDI Layer	Intended Audiences	Main messages	Main weaknesses in knowledge base	Implications of uncertainties	How uncertainty is dealt with
Key Advice [Outer layer] *This includes only the uncertainty information assessors deem* ***most important*** *to regulators.*	*Regulators, specialist readers such as NGOs and developers, general audience*	Methods to determine thresholds do not take into account several important factors, leading to uncertainties in calculations They should be viewed as indicative only and the precautionary principle should be applied.	Both the collision modelling and threshold calculations are subject to significant uncertainty. The threshold calculations, in particular, do not take into account several important factors, such as other forms of anthropogenic mortality, mortality outside of the breeding season and whether populations are declining.	Uncertainties in the threshold calculations imply that actual thresholds are likely to be lower than estimates. If populations encounter any additional forms of anthropogenic mortality, then thresholds will be exceeded.	The precautionary principle is recommended due to the uncertainty present in threshold calculations.
Appendix A Introduction [Middle layer] *This includes* ***more detail*** *on the relevant uncertainties, including numerical representations. This would also be an appropriate location for*	*Regulators, specialist readers such as NGOs and developers*	Threshold calculations are indicative only, as they do not take into account several important factors and are subject to a high degree of uncertainty. The collision modelling is also subject to uncertainties at several points and these uncertainties are potentially propagated	There are several uncertainties present in the collision modelling. These include potential inaccuracies in flight height data and distribution, doubts on the applicability of a 98% avoidance rate and gaps in the knowledge of population sizes and wind farm and turbine parameters. The threshold calculations have been set without considering the status of the population, whether it is increasing or declining. The thresholds also only address one form of anthropogenic mortality (wind farm impacts) and only address mortality during the breeding season.	The uncertainties present imply that the collision risk could be significantly higher (170%) or lower (30%) of estimates. The uncertainties in threshold calculations imply that actual thresholds are likely to be much lower, up to 30% of those listed.	In light of the uncertainties, in particular the negative uncertainties in threshold calculations, the precautionary principle is recommended.

pedigree analysis *or* ***graphical representations***.		and magnified through the modelling.			
Appendix A Main body [Inside layer] *This layer contains the* ***most detail*** *on all relevant uncertainties. Expressions of uncertainty within this section should be numerical wherever possible and jargon is permissible.*	*Regulators (May also be of interest to developers and NGOs)*	The collision modelling is based on several assumptions, many of which are subject to uncertainty due to insufficient data or gaps in knowledge. Each step is subject to uncertainty and these uncertainties are propagated and potentially magnified through modelling. The thresholds given based on the method used are subject to uncertainties in modelling but also do not take into account certain important negative external uncertainties.	<u>Uncertainties in collision modelling</u> • Assigning flight height distributions: *Birds may not always be correctly assigned to respective flight height bands.* • Flight height and observer error: *Data solely derived from boat-based observer work.* • Generic flight height distribution data: *Errors have been identified in dataset used.* • Avoidance rates: *It is unclear whether a 98% AR is suitable for the model used.* • Size of the population is based on numbers from Seabird 2000. • Area of foraging habitat available: *Assumes flat distribution of foraging birds.* • Wind farm and turbine parameters: *Worst case scenarios were assumed.* <u>Uncertainty in threshold calculations</u> • Thresholds have been set without considering the status of the population; whether it is increasing or declining. • Method allows for larger decreases in adult survival to be determined 'acceptable' for models which have higher variation or uncertainty. • The calculations only address one form of anthropogenic mortality (wind farm impacts). The calculations only address mortality during the breeding season.	The uncertainties present imply that the collision risk under this model could be anywhere from 30% to 170% of estimates. Actual thresholds may be between 30% and 80% of the threshold estimates provided using this method.	• A revised version of the flight height distribution data is expected, which will resolve some uncertainties. • There is ongoing research to review seabird avoidance rates, which will help establish whether the 98% avoidance rate is transferable to the model being used. • In light of the uncertainties, in particular the negative uncertainties in threshold calculations, the precautionary principle is recommended.

Pedigree chart

The pedigree chart below is intended to illustrate the underpinning of evidence based on expert opinions. As part of the uncertainty assessment, experts are asked to rate the evidence based on the listed elements (Validation, Method, Empirical basis, Proxy) on a 0-4 scale, as defined below for two of the elements. 'Validation' refers to how the evidence and methods have been tested over time; 'method' refers to whether the methodology used is considered to be best practice; 'empirical basis' refers to what extent the evidence is based on observed data rather than theoretical understanding; and 'proxy' refers to how well the evidence is representative of the entity in question. Other elements can be used, depending on context and the nature of uncertainties.[5] The pedigree chart illustrates the average of that rating. It provides the same information as the kite and radar charts illustrated in Section 3.3.2 and is illustrating the same [fictional] data set.

Table 4. Pedigree chart.



Score	Proxy	Empirical basis
4	An exact measure of the desired quantity	Controlled experiments and large sample direct measurements
3	Good fit or measure	Historical/field data; uncontrolled experiments; small sample; direct measurements
2	Well correlated but not measuring the same thing	Modelled/derived data; indirect measurements
1	Weak correlation but commonalities in measure	Educated guesses indirect approx. rule of thumb est.
0	Not correlated and not clearly related	Crude speculation

Source: Pedigree matrix for emission monitoring data [Available at: http://www.nusap.net/]

3.2.3 Performance against set criteria

This sub-section presents ICF's assessment of the PBL's guidance against all criteria.

Issue relevance

This method is used by the Dutch Environmental Assessment Agency, which works across sustainable development, energy and climate change, spatial planning, nature and biodiversity, among other areas. The method was initially developed for use in yearly environmental reports.

PDI is a universally applicable communication tool and could be applicable to a marine protection context.

Pedigree Charts are applicable anywhere there is uncertainty due to expert disagreement. They are therefore useful for communicating one specific type of uncertainty SNCBs might encounter.

[5] Other elements that have been used in pedigree analyses include: theoretical structure, data input, peer acceptance, colleague consensus, model structure, testing, source and set-up. It is important that whatever elements are used to describe the underpinning of evidence are clearly defined, and what constitutes the different scores within each element is also defined.

Regulatory relevance

The approach should be able to incorporate UK regulatory requirements despite being developed within the Dutch regulatory context. There are no specific regulatory requirements regarding the communication of uncertainty, but the method has been developed under the assumption that uncertainties and assumptions will be subject to political scrutiny.

By providing a guide to the identification of all sources of uncertainty and their qualification in the context of the risk assessment, the PDI approach can help advisors to regulatory bodies satisfy the requirements of case law that they should demonstrate all areas of potential doubt have been explored.

As suggested by one UK marine regulator, the addition of a column to the table highlighting the 'worst case' consequences of uncertainties would be helpful in ensuring regulatory relevance.

Scope

The guidance includes a checklist/questionnaire to determine what elements of uncertainty communication are relevant to any given project. The guidance and tools that would be suitable for communication vary on the basis of the outcome from the regulators questionnaire. It is therefore a flexible approach and one that should be easy to adjust and customise to different contexts and audiences.

The *PDI* approach allows the communicator to decide who the advice is for, and to build uncertainty communication (in layers) on that basis. The Guide to Communication includes hints and recommendations on the types of information appropriate to each audience and layer. PDI would be applicable to all contexts of SNCB advice.

Pedigree Charts are relevant to any contexts where deep uncertainties or expert disagreement play a role.

Feasibility

For the majority of the tools presented, no specific technical skills are required other than skills in generating graphical representations (for pedigree charts).

The *PDI* is fairly straightforward but can become complex depending on the number of uncertainty elements incorporated. The PBL advised that the PDI has been the most successful aspect from the guidance. SNCBs and UK marine regulators expressed concern that the use of the table could be overly time-consuming and this might lead to inconsistent implementation. Accompanying such a method with training and guidance and implementing it in proportion to the uncertainties under consideration could help. One regulator also noted how similar the PDI approach was to the manner information is already presented in SNCB advice, therefore providing additional structure by implementing the PDI would be beneficial.

Pedigree Charts are simple to produce, as long as the relevant data is available.

Feedback

Feedback on the approach has generally been positive, although it was not used consistently in the Netherlands in the first years after it was developed. Implementing the guidance as a whole has been seen as possibly too time-consuming for use in every study /

advice carried out.[6] A training programme in uncertainty assessment and communication was initiated following the publication of the guidance, and this was considered to have a bigger impact on the improvement of uncertainty communication than the guidance itself.

Competing goals

The guidance recommends that before uncertainty communication is developed, one should ask how the problem is framed and which contextual factors are included/excluded. The method recognises the possibility of competing priorities from the outset.

Communicability

The *PDI* approach is meant to facilitate communicability by presenting different levels of information in distinct layers. As such readers can decide to stop at any point or continue reading the document to access the more detailed information they understand. Through PDI, uncertainty can be communicated in multiple forms. This repetition contributes to a better understanding of uncertainty and makes it more likely that readers will notice this information.[7] SNCBs and UK marine regulators indicated that including key advice in the outermost layers would be particularly helpful. Similarly, specifically including information on the implications of uncertainty and how uncertainty is dealt with would also be helpful. One UK regulator suggested that adding an element that linked the communication of uncertainty between different layers would be useful, so that further details on particular aspects could be quickly located within the document.

The study team identified one source suggesting that *Pedigree Charts* are easily understood and preferred by policy makers (Wardekker *et al* 2008). However, no other user feedback has been identified. It could be argued that Pedigree Charts require translation and explanation in order to be appropriately used by policy makers.

Sufficiency

The *PDI* tool, as illustrated above (section 2.2.2), lists the uncertainties (source and nature), what their implications are for the assessment and how they are being dealt with in the analysis. As such it encourages advisors to provide sufficient uncertainty information to regulators.

Pedigree Charts indicate the source and extent of uncertainty (for those uncertainties where they are relevant). Feedback from UK regulators indicated that it did not explain or illustrate the sources of uncertainty as well as other tools or approaches.

Adaptability

As uncertainty information is dispersed throughout the text and presented in different forms, it could be challenging to adapt communications to new information. The message should remain consistent, however. The approach recommends the use of a table, as illustrated

[6] The reader should note, however, that the guidance addresses both assessment and communication, therefore this comment may apply to other aspects of the guidance than just the uncertainty communication elements.

[7] Verbal presentations of uncertainty are to be included in the outer layers, intended for more general audiences. Communication within these layers should also avoid jargon. Numerical presentations are more appropriate for inner layers. However, the guidance also recommends that verbal representations should be defined and tied to a scale (offering the IPCC scale as an example and echoing findings published in the scientific literature, as discussed in the state of the art section) and this should be clearly indicated within the text. Information can be included in boxes within the main text, with the understanding that many readers will ignore boxes, so important information should always also be included within headline conclusions. Graphical representations of uncertainty can be helpful, but usually require additional explanation for readers to make sense of them. They should therefore be carefully considered before use.

earlier, so as to detail how each aspect of uncertainty is communicated at different levels. If one aspect changes, therefore, that table would help ensure that uncertainty information is amended at each relevant level.

Gaps

There is limited evidence on the use of Pedigree charts.

3.2.4 Synthesis

The PBL approach can best be described as a selection of approaches and tools in uncertainty communication, rather than as an approach.

PDI and Pedigree Charts would apply in the context of uncertainties dealt with by the SNCBs. Several guidance documents have been developed by the PBL to support users in selecting and applying the most appropriate tool to match their communication needs. Although the guidance was developed within the Dutch regulatory framework, the PDI approach and Pedigree Charts are flexible approaches that make them applicable in the UK context. The PDI approach provides also a structure to the organisation of uncertainty information within the advice, which resembles that which can be found in the advice SNCBs provide to UK marine regulators. As such it can contribute to structuring further and improving the overall consistency of uncertainty communication across SNCBs.

The PDI approach encourages advisors to provide sufficient information on the source, nature, and impact of the uncertainty on the risk assessment. It can be used in conjunction with Pedigree Charts, as it describes a layered approach for identifying and layering information in a way that will reach the intended audience.

However, due to the multiple layers of information involved, the PDI may be a more resource intensive approach especially in cases where adjustments to the information may be required.

3.3 The Department for Environment, Food & Rural Affairs' Plant Health Risk Register guidance

3.3.1 Description

The Department for Environment, Food and Rural Affairs (Defra) has considered several potential approaches that would allow the communication of uncertainty within the Plant Health Risk Register (PHRR). The risk register provides scores on likelihood, spread, impact, value at risk and an overall relative risk rating for plant pests. This illustrative example focuses on a selection of approaches for communicating uncertainty that were considered by the PHRR.[8] With specific reference to plant health risks, the guidance explores the following three tools:

- **Uncertainty proxy scores** provide a single score on a pre-defined scale, indicating how well-known the issue is.
- **Uncertainty ratings** based on monetised impact integrate the information on uncertainty with monetised impact calculations, showing the potential range and likelihood of associated costs.

[8] From the range of approaches reviewed by the PHRR, only those that were deemed appropriate in the context of advice provided by SNCBs to regulators are included. The approach chosen by the PHRR is not amongst these.

- **Uncertainty ranges** illustrate uncertainty as the range around the relative risk rating score.

Furthermore, the guidance recommends the use of **radar and kite charts** to express 'deep uncertainties', notably the level of agreement or disagreement among experts. By asking experts to rate evidence based on different elements (such as proxy, methodological vigour, validation *etc*), it places a rating on the evidence that also shows where and to what extent there is agreement or disagreement.

Finally, the guidance includes details on different types of mapping that can be used to illustrate uncertainty that is geographically dispersed. The guidance highly recommends **box plots** as default graphical representations of uncertainty.

3.3.2 Illustrative example

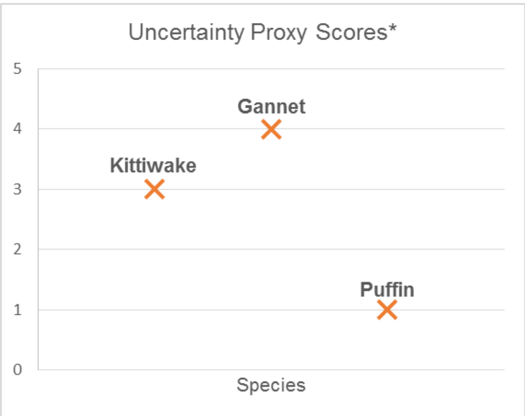
Several tools presented in the guidance rely on the existence of an overall risk score, to which uncertainty proxy scores, ranges, or ratings can be articulated. Since SNCBs do not tend to produce such a score in their risk assessments, these tools are of limited use in the context of SNCB advice and could not be used to communicate the impact of the uncertainty on the risk assessment. In order to illustrate these tools in the context of SNCB advice, they were adapted to fit the sort of advice that SNCBs produce.

Uncertainty Proxy Score

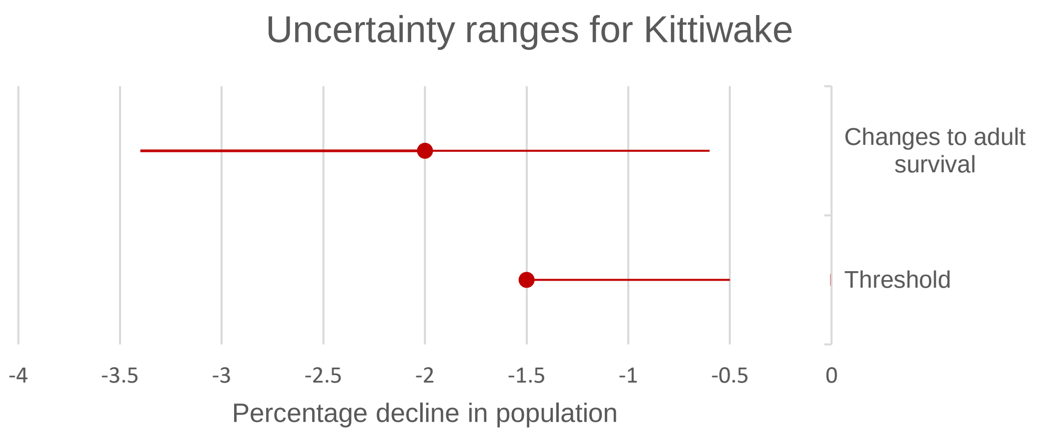
For the PHRR, proxy scores are ratings of the amount of literature published on a given pest to indicate its overall known-ness. Rather than looking at literature published on specific species, SNCBs could instead base such a score on the **amount of available relevant information.** The scale here is set as 0-5, with 0 representing no knowledge and 5 representing a strong knowledge base with little uncertainty. In the PHRR, the scale is sent as percentages out of 100%, but a smaller scale is used here to avoid seeming overly precise.

In this example:

- The advice indicates that there is a decent amount of recent information available on **kittiwake** population numbers but little information available on how they interact with windfarms, leading to a rating of 3.
- **Gannets** have been subject to a Population Viability Analysis (PVA) conducted recently and a very detailed population count, indicating a high level of knowledge. However, the lack of knowledge on how they interact with windfarms leads to a rating of 4.
- For **puffins**, there is a large amount of uncertainty due to the inherent difficulty of assessing this species, which means one needs to calculate impact based on proxy species. This leads to a rating of 1.

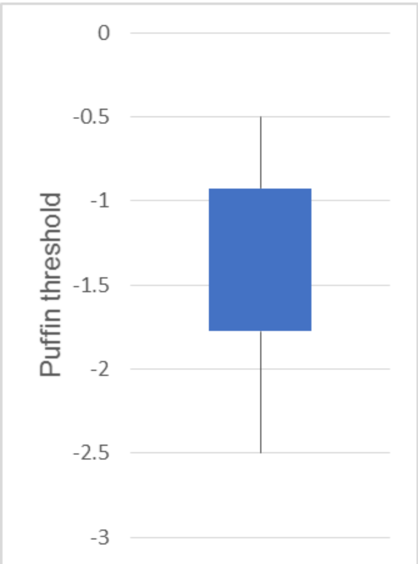


Uncertainty ranges



This chart uses a collision risk model and threshold figure for kittiwakes on site and presents a (fictional) range of uncertainty around that number based on the uncertainties in modelling.

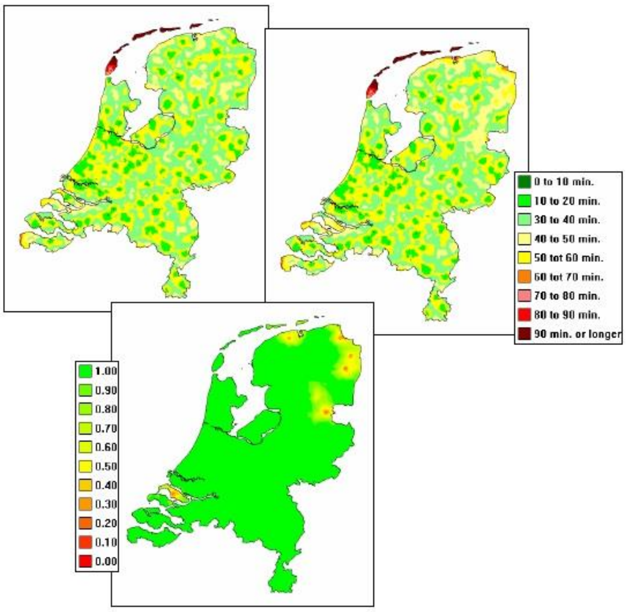
Box plots



This example of a box plot uses the figures given for the likely potential range for a puffin population reduction threshold based on a fictional dataset of threshold estimates, where the grey line indicates the minimum and maximum thresholds (-2.5% and -.5% respectively). The blue box illustrates the middle 50% of the data and the median is -1.4%.

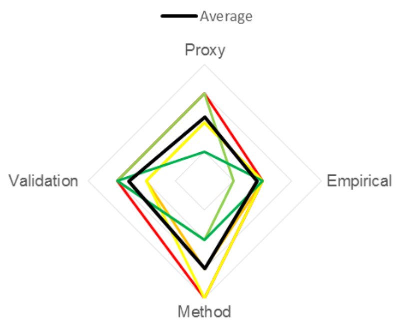
Mapping

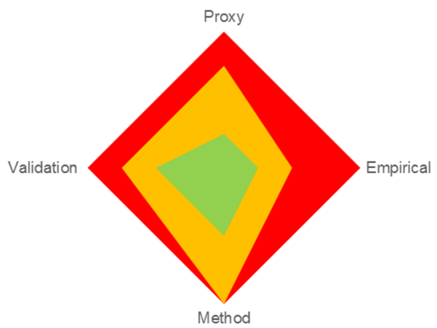
Difference maps could be used to illustrate the differences between the model predictions at different locations. The following example is meant to illustrate ambulance driving times in different scenarios, with the above two maps illustrating the scenarios and the map below showing where the two maps differ. Green indicates that the scenarios are identical at that location and red indicates extreme difference. Difference maps can be used to highlight what areas spatially are subject to the highest degree of uncertainty.



Source: Visser et al *(2006) Guidance for uncertainty assessment and communication: Checklist for uncertainty in spatial information and visualising spatial uncertainty.*

Radar and kite diagrams





The above diagrams illustrate [fictional] expert assessments of the method used above in identifying population level thresholds. Such diagrams could be amended to include other aspects for consideration more specific to the method itself. Each aspect is given a rating by an expert on a 0-4 scale. The radar diagram indicates how each expert ranked each aspect of the method and represents each with a different coloured line. The average of all is represented by a black line. The kite diagram on the right indicates the minimum (green) and maximum (amber) ratings across all experts and the remaining area is red. The size of the amber area therefore illustrates the extent of disagreement among experts. Visually, the greener the chart is, the stronger the underpinning of each parameter. The redder the chart, the weaker the underpinning of each parameter.

3.3.3 Performance against set criteria

Issue relevance

Uncertainty proxy scores and *uncertainty ranges* may be applied to the uncertainties dealt by SNCBs.

Box plots can be used to graphically represent likely ranges in contexts where this information is not subject to high variations in probability density.

Maps can be used to illustrate differential impacts. Difference maps, scenario maps, ensemble maps and grid maps are all suitable for different aspects of this. Feedback from UK regulators suggested that this is already used to some extent but would not be relevant to most forms of uncertainty encountered in their work.

Kite charts can be used to illustrate disagreements between experts.

Regulatory relevance

This approach was developed within the UK context specifically for the PHRR. It has not been developed to be compatible with regulatory requirements such as those the SNCBs need to abide to. The PHRR is under no regulatory obligation to report uncertainty.

Scope

The PHRR did not explicitly record information on uncertainty until very recently (December 2017), when it began including uncertainty information on a small number of pests. The approaches specific to the PHRR might be applicable to some contexts of SNCB advice, where uncertainty is based largely on how well-known certain elements are or where uncertainty can be quantified and numerical ranges can be illustrated.

Feasibility

There is limited information on the resource or expertise implications of these tools. Uncertainty ranges and proxy scores were trialled by DEFRA. Assessors concluded that the incorporation of uncertainty ranges, although an accurate and relevant description of uncertainty, were too time-consuming for use in what is intended to be a rapid risk assessment. The calculation of proxy scores was less resource-intensive and considered more proportionate to the goals of the risk register. Proxy scores were ultimately not used after tests indicated that the scores did not correlate with the risk assessors' own perceptions of uncertainty.

We can infer that box plots would be easily implemented, as they can be created from raw data using fairly straightforward tools. The same is true for kite charts for which online resources are also available. Maps might be more challenging to produce, however, and it is likely that additional software and training will be required.

Competing goals

Uncertainty proxy scores, *uncertainty ratings with monetised impact*, and *uncertainty ranges* present impact as a one-dimensional quantity, as they focus on the risk register score put out by the PHRR. They are intended to indicate cumulative uncertainty, rather than uncertainties specific to the individual elements used to calculate the PHRR's risk register score.

Box plots are used only to indicate the range of uncertainty and do not address competing priorities.

Kite graphs can be used to illustrate deeper uncertainties and can be used to show discrepancies between expert evaluations.

Mapping can be used to identify uncertainties in physical location and the extent of these uncertainties. It does not explicitly recognise trade-offs between competing goals.

Communicability

The guidance recommends that quantitative and graphical expressions of uncertainty should be preferred to qualitative scales (such as the IPCC scale) because the latter are liable to misinterpretation.

Feedback from UK regulators indicated that *proxy scores*, although insufficient by themselves, could provide a useful visual tool, alongside other more thorough explanations of uncertainty. *Uncertainty ranges* were also considered to be a potentially useful method for communicating uncertainty visually, although *box plots* were considered the best method for the same purpose. Both, however, are only applicable to areas where uncertainty is quantifiable.

Kite charts were generally preferred to pedigree charts (see Section 3.2.2) for representing uncertainty caused by disagreements in expert opinion, although regulators expressed concern that appropriately using and understanding such depictions would require some training and experience.

Sufficiency

The main intent of all the tools listed in the guidance is to illustrate how uncertainty impacts risk assessment. These tools rely on the existence of an overall risk score, to which uncertainty proxy scores, ranges, or ratings can be articulated. Since SNCBs do not tend to produce such a score in their risk assessments, these tools are of limited use in the context of SNCB advice and could not be used to communicate the impact of the uncertainty on the risk assessment.

Uncertainty proxy scores or *uncertainty ranges* that could be used in the context of SNCB advice would provide only a general idea of the extent of the uncertainty, without any information on the source of the uncertainty, the direction of its impact on the risk assessment, or how much resolving that uncertainty might impact on the risk assessment.

Graphical representations, including *box plots* and *maps*, can also indicate the extent and direction of uncertainty, but not the source. UK regulators indicated that such methods were therefore not appropriate as standalone methods, although they could be helpful visual aids in certain scenarios. *Kite diagrams* can be used to indicate the source and the extent of uncertainty where the cause of uncertainty is rooted in expert disagreements. However, they do not provide information on its impact on the risk assessment (neither direction nor scale of impact).

Adaptability

Uncertainty proxy scores, monetised impact, or uncertainty ranges are outcomes of the risk assessment process and could easily be amended as long as the underpinning risk assessment tools could themselves accommodate changes easily. Box plots and kite diagrams can be easily adapted. Box plots may no longer be applicable if new information leads to greater variations in probability density.

Gaps

As these approaches have not been used by the PHRR, there is limited evidence on their communicability. There is some evidence (Wardekker *et al* 2008) to suggest that graphical and numerical representations of uncertainty are more effective than narrative representations, but limited evidence as to how these approaches have been received by decision-makers.

3.3.4 Synthesis

Although the guidance for the PHRR was developed in the context of plant health, it presents a range of tools – box plots, maps and kite charts – which could be used in SNCB advice to regulators. Proxy scores are less likely to apply to SNCB advice. Graphical representations of ranges could be used for situations where such ranges can be quantified. It should be noted that these tools only offer alternative ways of graphically representing uncertainty and do not provide guidance on representing the sources of uncertainty, its overall impact, or where information should be presented. As such their potential to help structure the manner in which SNCBs communicate uncertainty to marine regulators is low. They rather are elements from a toolkit that SNCBs may occasionally draw from. While there may be benefits as a result of these occasional uses, they are not conducive to greater consistency in SNCB advice.

3.4 Summary of the findings

A range of tools has been identified through three different sources and assessed against a set of criteria defined to align with the objectives of the study and the SNCBs' needs. The assessment shows tools that are very different from one another.

FERA's Uncertainty Table aims to provide a synthetic and comprehensive picture of the uncertainties of a particular issue, while integrating some of the findings and recommendations from the scientific literature on uncertainty communication, including, to some extent, the combined use of verbal/ symbolic and numerical expressions to prevent misinterpretation.

The PDI approach is also a tool that helps organise the communication of uncertainties overall, as well as of any other information that can be communicated in advice, or in other contexts (e.g. to structure the information in a newspaper article). In the PBL guidance it is presented alongside propositions or findings from the literature on uncertainty communication.

The other tools identified are rather illustrative in the sense that they can be used to graphically represent uncertainty information that can also be presented verbally or numerically. As such they are tools that can enhance the clarity of communication (in the sense of initiatives such as the Clear Communication Index[9]). They do not offer a framework for communicating uncertainty, and are more likely to be of use occasionally.

This broad range reflects the diversity of practices present in the literature and found across organisations. Depending on the scientific field, target audience, as well as characteristics of the uncertainty, such as its source and impact, approaches to communicating uncertainty differed in the language, presentation and content provided.

The table below summarises the results of the assessment of each approach and tool against the criteria discussed in the previous section. This assessment cuts across evidence found in the literature and feedback received from organisations, SNCBs and regulators. It uses a colour-coded scoring system of 1 (low) to 3 (high) to indicate the extent to which the approach or tool fulfils the criterion (refer to the table legend). It further provides a breakdown of the different approaches and tools reviewed within each approach.

This assessment suggests that the PDI approach, Pedigree Charts, and Uncertainty Table perform better against the criteria, in particular in terms of communicability and sufficiency.

[9] https://www.cdc.gov/ccindex/index.html

The PDI approach as it is presented in the PBL guidance in particular scored high across criteria presenting a structured approach, sufficient level of detail underlying uncertainty, a combination of qualitative and quantitative elements and the flexibility to incorporate a graphical/visual representation.

Similarly, amongst options in the visual representation of uncertainty, Uncertainty proxy scores and Box plots presented a simple yet informative illustration which could usefully complement text.

With reference to tools and approaches focusing on the visual presentation of uncertainty, these tend to be specific to certain aspects of uncertainty (e.g. uncertainty maps) and will therefore be more or less relevant depending on the nature of uncertainty (e.g. in cases where there is geographical variation in uncertainty) and the needs of the audience. Regulators generally agreed that visual representations could be helpful but would not be appropriate as standalone methods in uncertainty communication.

As noted in the literature reviewed, different stakeholders will not only have different information needs and expectations but also varying skills and levels of understanding. Feedback received from regulators and SNCBs with reference to some of the more complex tools highlighted the importance of this consideration with some of them finding the tools less intuitive or easy to understand. Overall, simplicity in graphic representations was valued over complex charts incorporating multiple aspects or elements of uncertainty.

Linked to the above was a concern raised by stakeholders, as to the potential need to provide some form of training to users of these approaches. Although the majority of approaches and tools presented do not require specific technical skills there are some for which training would be beneficial to ensure clarity and consistency in the application of the approach or tool. For instance, a 2-day training programme was undertaken on the PBL guidance in the Netherlands, following initial feedback that the guidance was not being used in a structured way. The training programme, which involved two interactive afternoons, helped staff members get acquainted with the ideas and content of the approach. Being exposed to the material through training was reported to have improved staff's awareness on:

- the role and various aspects of uncertainty in studies that PBL researchers perform; and
- how to deal appropriately with uncertainties.

With regards to the *regulatory environment*, it is worth noting that any references in the literature were limited to guidance documents and good practices as drivers for better uncertainty communication. Across the approaches and tools reviewed regulatory relevance did not emerge as a concern, as the approaches did not tend to be overly prescriptive and could be adjusted to incorporate specific expressions or wording as dictated by legislation. However, as highlighted in the individual assessments, most of the tools would not be sufficient to communicate uncertainty to the extent required by regulators in their decision-making. Instead they could be useful components as part of a more comprehensive approach.

Overall, there was limited evidence around the practical applications of most of these approaches and tools, generating some uncertainty over their feasibility and communicability.

Table 5. Summary Table.

<table>
<tr><th rowspan="2">Organisation / Source</th><th rowspan="2">Approach / Tool</th><th colspan="9">CRITERIA</th></tr>
<tr><th>Issue relevance</th><th>Regulatory relevance</th><th>Scope</th><th>Feasibility</th><th>Feedback</th><th>Competing goals</th><th>Communicability</th><th>Sufficiency</th><th>Adaptability</th></tr>
<tr><td>FERA</td><td>Uncertainty Table Tool</td><td>2</td><td>3</td><td>2</td><td>2</td><td>2</td><td>2</td><td>2</td><td>3</td><td>2</td></tr>
<tr><td rowspan="2">PBL's Guide to Uncertainty</td><td>Progressive Disclosure of Information</td><td>3</td><td rowspan="2">3</td><td>3</td><td>2</td><td rowspan="2">2</td><td rowspan="2">3</td><td>3</td><td>3</td><td>2</td></tr>
<tr><td>Pedigree Charts</td><td>2</td><td>2</td><td>2</td><td>2</td><td>2</td><td>2</td></tr>
<tr><td rowspan="6">DEFRA Plant Health Risk Register</td><td>Uncertainty proxy score</td><td>2</td><td rowspan="6">2</td><td rowspan="6">1</td><td>3</td><td rowspan="6">1</td><td>1</td><td>2</td><td rowspan="6">1</td><td>3</td></tr>
<tr><td>Uncertainty ranges</td><td>2</td><td>2</td><td>1</td><td>3</td><td>2</td></tr>
<tr><td>Uncertainty ratings</td><td>1</td><td>1</td><td>1</td><td>2</td><td>2</td></tr>
<tr><td>Box plot</td><td>2</td><td>3</td><td>1</td><td>3</td><td>3</td></tr>
<tr><td>Mapping</td><td>2</td><td>1</td><td>1</td><td>3</td><td>2</td></tr>
<tr><td>Kite charts</td><td>2</td><td>3</td><td>2</td><td>2</td><td>2</td></tr>
</table>

1	2	3
Only fulfils the criterion to a small extent	Fulfils the criterion to some extent	Fulfils the criterion to a large extent

4 Conclusions

4.1 Discussion of the evidence

4.1.1 Discussion of the approaches reviewed in the context of the broader literature

The field of uncertainty communication research is nascent, and as such holds only few firm conclusions that practitioners can take forward. The tools and approaches reviewed in this study are representative of the current state of the literature.

On the one hand, they are attuned to the literature's calls for greater transparency about uncertainty from the part of risk assessors when they communicate their advice to their audiences (e.g. Arvai 2014; Kasperson 2014). They also reflect a broader trend from a variety of regulatory organisations to develop guidelines and principles on uncertainty communication (e.g. EFSA 2016).

On the other hand, given the dearth of empirical evidence on the communication of uncertainty specifically, the principles they embody are rarely specific to uncertainty communication research. For instance, the Progressive Disclosure of Information approach, referenced in several guides to uncertainty communication, is anchored in a general principle of information communication that has been applied in various fields, including journalism. Similarly, kite charts, box plots, or maps / cartography are not tools specific to uncertainty communication, but rather ways of communicating various types of information.

The specific challenges of how to communicate uncertainty remain largely unaddressed in the literature, and this is reflected in some of the sources reviewed: their authors acknowledge that various formats for communicating uncertainty information exist. Since the strengths and weaknesses of these alternative formats are not well established, even these guidelines and the feedback they have collected include opinions rather than firm evidence that one tool is proving more effective than another.

The only notable exception to this overall picture is the corpus of empirical research conducted on the intended and perceived meanings of verbal expressions of uncertainty, particularly probability ranges (Budescu *et al* 2014; Ho *et al* 2015; Jenkins *et al* 2018). The key learning from that literature – the notion that verbal representations of uncertainty should be defined and tied to a numerical scale – has been taken up in various guidelines to uncertainty communication, including the Dutch Environmental Assessment Agency's guidance on Uncertainty Assessment and Communication, reviewed for this study.

4.1.2 Discussion of the approaches reviewed against the needs and context of SNCBs

Across the three sources reviewed, approaches and tools have the potential to:
- accommodate different types of uncertainty commonly dealt with by SNCBs in their regulatory advisory role;
- cover multiple sources of uncertainty;
- express uncertainty both qualitatively and quantitatively;
- cater for different levels of user capabilities;
- allow updated and revisions to the advice; and
- present information on different elements of uncertainty including the sources and impacts of uncertainty.

However, the decision on the most appropriate approach will depend on the nature of uncertainty, context of development, data availability, existence of appropriate methods, organisational capabilities and more. There is therefore no one-size-fits-all approach and it is unlikely that a single approach or tool will be sufficient to communicate all aspects of uncertainty likely to emerge. Instead a combination of these may be required. Regulators also indicated this in their feedback, suggesting that certain tools could be used in conjunction with others. For example, something similar to the Uncertainty Table Tool could be included within the inner layers of advice prescribed by the PDI approach, while something like the Uncertainty Proxy Score would do well in outer layers.

With reference to the specific approaches and tools reviewed:

- FERA's Uncertainty Table Tool would be appropriate for communicating uncertainty in a wide range of cases, where outcome quantification is possible. For those cases, it can provide a tool that usefully combines qualitative and quantitative expressions of uncertainty. It can also account for the interdependencies between uncertainties, and provides information on the direction and scale of the uncertainties' impact on the risk assessment.
- The PBL's approach would be appropriate for communicating uncertainty in a wide range of cases and particularly where competing priorities and goals exist. PDI's layered approach to communicating uncertainty is highly relevant to SNCB work and presents numerous advantages. It can also be combined with other tools, in particular for representing uncertainty graphically.
- Defra's Plant Health Risk Register guidance presents a selection of approaches and tools. The tools cover a wide spectrum of graphical representations of information that can be adapted to uncertainty communication. Box plots and radar or kite charts appear to be the most suitable to represent the types of uncertainty SNCBs frequently come across. Uncertainty proxy scores and uncertainty ranges may also be applied to the uncertainties dealt by SNCBs, however there is limited information on the user capabilities and relevant resources that may be required.

4.2 Limitations

This study set out to explore potential approaches that could support SNCBs in the communication of uncertainty in their advice to regulators of the marine industries in the UK.

The scale of this study means that only a limited number of approaches could be explored in some level of detail. Other sources were identified at an early stage but were not selected for further investigation. The study team alongside the project Steering Group made an informed choice to focus the project's resources on those sources that appeared most relevant and most likely to deliver findings against the goals of the project. This project is therefore by no means an exhaustive review of approaches and tools available to regulators for communicating uncertainty.

Resource and time limitations dictated the length and level of detail which could be incorporated into this report, particularly with regard to illustrative examples of the tools reviewed. With regards to the example used to illustrate the approaches, the fictional offshore wind farm development was chosen in collaboration with the project Steering Group, as an example that was inclusive (to the extent possible) of a number of issues commonly faced by SNCBs and regulators in the context of marine conservation. A single example cannot encompass the range of uncertainties, types of advice and areas of casework across SNCBs and regulators, however. Nevertheless, a number of cross-cutting lessons have been identified and included in this report.

The versatility of cases and types of uncertainty also has implications for the assessment of these approaches and tools against set criteria, such as, issue relevance and sufficiency. There is therefore an inherent element of subjectivity to scores presented in the assessment table, which should be seen as indicative. Appropriate caution should be applied before deciding on the use of a particular approach on a real-world scenario.

Lack of evidence on practical application of the approaches discussed, either in the form of controlled evaluations – of which none was found – or user feedback also made it difficult to reach firm conclusions against the relevant criterion. The inherent shortcomings of the current state of the art on uncertainty communication, as summarised in this report under section 1.2, also means that very few firm conclusions could be drawn from the literature.

4.3 Recommendations

4.3.1 Recommendations on SNCBs' approach to communicating uncertainty

- **Structure further the communication of uncertainty using PDI's layered approach –** The PDI approach presents similarities with current practices and it provides a framework that could be relied on to systematise the presentation of uncertainty across SNCBs.

- **Prevent misunderstanding by linking verbal expressions of uncertainty to numerical scales:** While verbal expressions of uncertainty tend to be preferred out of reluctance to use symbols or quantitative expressions, there is ample evidence that verbal expressions can be misunderstood by their intended audience. There is robust research demonstrating the benefits of linking verbal expressions of uncertainty to numerical scales, which greatly reduce the potential for misunderstanding (Budescu *et al* 2012; Ho *et al* 2015; Jenkins *et al* 2018) and minimise variations in the interpretation of information by different readers (Budescu *et al* 2014).[10]

- **Invest in training to engage staff and develop better uncertainty communication practices:** Training may help ensure the consistent application of the chosen approaches to communicating uncertainty. Wardekker *et al* (2008) highlight that consistency increases the credibility of the message. Additional benefits of training include staff ownership of uncertainty communication and awareness of its role and importance as part of the advice provided to regulators.

4.3.2 Recommendations on future SNCB research in this area

- **Test alternative formats of uncertainty communication in controlled settings –** Empirical research will provide firm evidence on which to base future uncertainty communication practices, including the potential use of some of the tools presented in this study. Such research can involve quasi-experimental designs whereby alternative ways of communicating the same uncertainty information are tested in a controlled setting with decision-makers. In such a setting, the understanding and risk perceptions of participants can be measured, enabling one to assess how alternative formats (quantitative, qualitative, symbolic, textual, graphical *etc*) contribute respectively to shaping the manner in which the advice is received. User perspectives on formats for communicating uncertainty can be explored further through semi-structured

[10] The latest research shows that the order in which the different formats are presented matters, with the best results (in terms of interpretation by the recipient) obtained by presenting numbers *before* verbal expressions (Jenkins *et al* 2018).

conversations or focus groups. ICF has conducted research of this nature for EFSA, combining a quasi-experimental design and focus groups (Etienne *et al* 2018).

- **Ground uncertainty terms in empirical evidence –** The challenge of formulating uncertainty in a language that is readily understandable by decision-makers can be addressed to some extent by developing 'evidence-based lexicons' (Ho *et al* 2015): sets of uncertainty concepts (such as notions of likelihood) defined on the basis of how the intended audience understands them in the context in which they will be used. Ho *et al* (2015) provide tools and a method to develop such lexicons, which they have implemented in various fields. A similar approach could be applied to the context of marine protection regulation in the UK.

- **Consistently and regularly collect and review feedback from regulators for continuous improvement –** Collecting specific feedback on the manner in which uncertainty was communicated can help improve practices of uncertainty communication by SNCBs. A consistent approach to collecting feedback and to reviewing it across SNCBs could help build evidence to inform improvements to uncertainty communication practices throughout.

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