HIGH-QUALITY KNOWLEDGE FOR CLIMATE ADAPTATION: REVISITING CRITERIA OF CREDIBILITY, LEGITIMACY, SALIENCE, AND USABILITY

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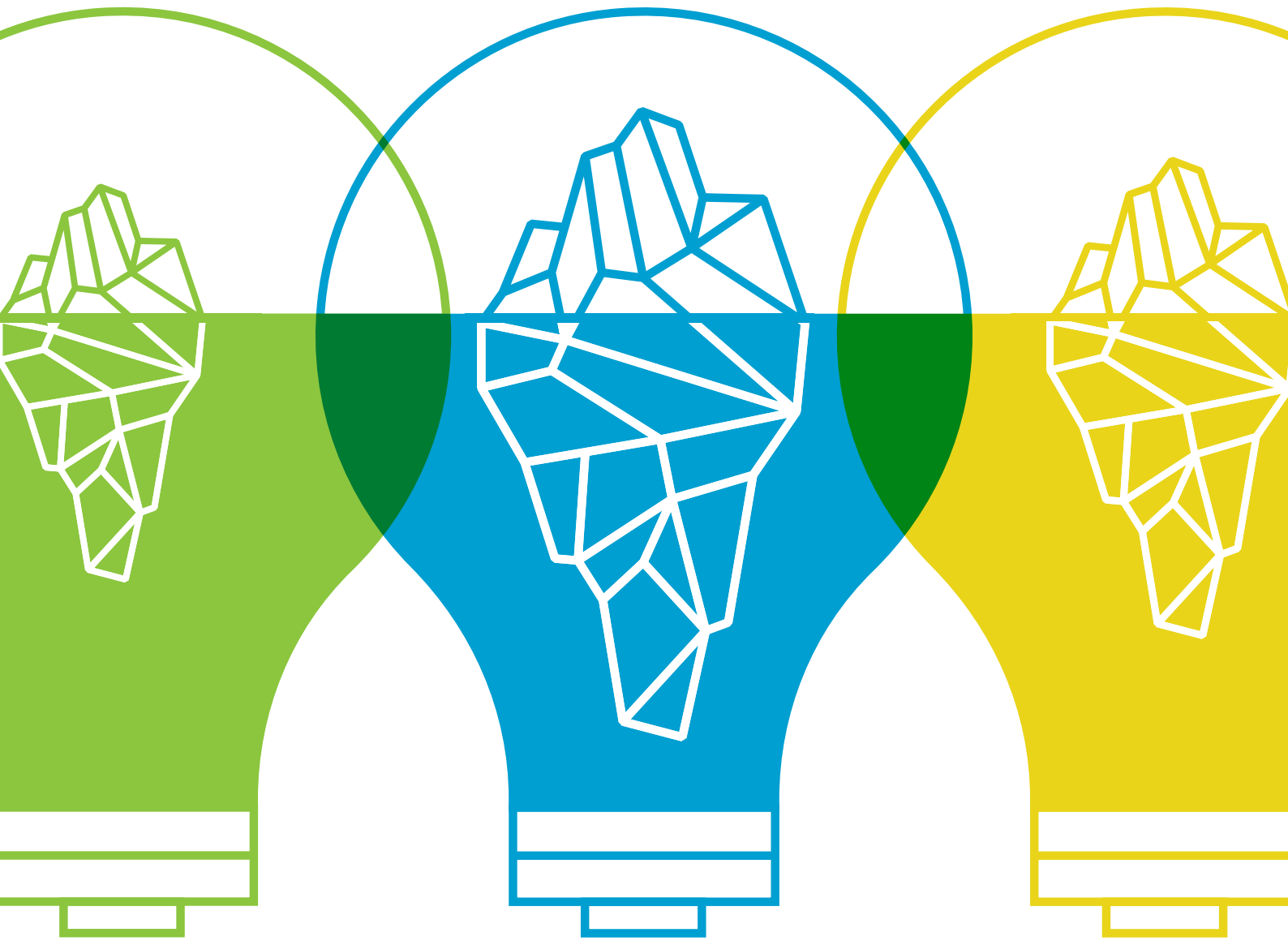

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HIGH-QUALITY KNOWLEDGE FOR CLIMATE ADAPTATION: REVISITING CRITERIA OF CREDIBILITY, LEGITIMACY, SALIENCE, AND USABILITY

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EDITORIAL
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Editorial: High-Quality Knowledge for Climate Adaptation: Revisiting Criteria of Credibility, Legitimacy, Salience, and Usability

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Editorial on the Research Topic

High-Quality Knowledge for Climate Adaptation: Revisiting Criteria of Credibility, Legitimacy, Salience, and Usability

Climate adaptation in human systems is a process of learning and adjustment (IPCC, 2022). It involves continuously re-building a stock of knowledge, skills and foresight for anticipating, interpreting and acting relative to actual or expected climate. But what distinguishes knowledge of "high quality" for climate adaptation? This raises important ontological, epistemological and methodological questions, and at their core are the quality criteria people apply in appraising knowledge.

Climate-adaptive knowledges have long been inherent to societies relationship to their environment, for example in cultural patterns of seasonal activities (Kwiecien et al., 2021). Over the past 20 years climate adaptation has become a topic of scientific enquiry across diverse disciplines, with efforts to fit that science to societal contexts and norms of quality for decision-making (see e.g., "climate services"; Hewitt et al., 2012). As such, societies have come to make sense of climatic change by juggling a repertoire of traditional, local, practical, scientific and technical knowledges—from proverbs to tailored forecasts—all assessed against different criteria of quality.

Notwithstanding this plurality, certain principles have emerged in the scientific literature as fundamental to appraising knowledges' fitness for adaptive action. Specifically, the principles of credibility, legitimacy, and salience (Cash et al., 2003), as well as usability and usefulness (Lemos and Morehouse, 2005). These remain influential, but there is nuance to knowledge quality that broad principles miss. We argue for more critical studies of knowledge quality to uncover what principles mean in particular contexts, and what other criteria are appropriate.

This special issue assembles nine articles from 37 authors, which take up the quality of adaptive knowledge as a topic. Three important themes emerge across these articles.

CRITICAL TAKES ON QUALITY: CONTEXT MATTERS

Five articles in this issue argue that knowledge quality is variously interpreted by different actors. Broad principles may not make sense in all contexts of knowledge development and use.

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The articles discuss the contingency of knowledge quality relative to urban adaptation approaches (Boon et al., 2021), traditions within science (Skelton, 2021), co-producing climate services with policymakers (Bremer et al., 2021), institutionalizing of knowledge in the CGIAR programme (Dinesh et al., 2021), and the legitimacy of knowledge for flood risk management (Vanderlinden et al., 2021).

These discussions share a regard for divergent ideas on the role of knowledge. Firstly, these differences are visible among knowledge producers. Traditions of adaptation science disagree on what is important, varying from curiosity to applicability, or the ability to challenge the status quo. There are also multiple knowledge producers, ranging from academics to professional consultants, government scientists, and citizen scientists, with diverging roles and visions. Secondly, the contexts of application are diverse. Knowledge needs for adaptative action vary according to local conditions, stakeholders, space, and time (Cradock-Henry and Frame). There can be differences between users' voiced knowledge "wants" and their "needs" for transformative adaptation. Since the roles of knowledge vary strongly across contexts, and are not self-evident, joint reflection on, and institutionalization of, knowledge quality and knowledge building is needed.

APPLYING CORE PRINCIPLES: OPERATIONALIZATION OF QUALITY

Notwithstanding the contingency of quality to context, five articles in this issue report on efforts to operationalise *a priori* principles of quality in mobilizing knowledge; mostly variations on the principles of Cash et al. (2003) and Lemos and Morehouse (2005). These principles were given effect to in developing climate services for municipal adaptation (André et al., 2021) and managing algal blooms (West et al., 2021); transdisciplinary urban innovation (Basta et al., 2021); institutionalization of knowledges in the CGIAR programme (Dinesh et al., 2021); and developing heuristics of climate scenario development (Cradock-Henry and Frame, 2021).

These contributions highlight the practical limitations of producing knowledge that meets quality principles when faced with contested, uncertain and urgent adaptation challenges. Authors emphasize the technical limitations to quality due to scarce data, gathered over short time series, and often commissioned *ad hoc* according to narrow framings. They also note the challenging work of reflecting diverse ways of knowing in the design, conduct and decision-making around research.

Another key insight is that adaptive action is affected not only by explicit "knowledge *products*"—e.g., a seasonal forecast—but also by the *processes* of knowledge production, which can give rise to wider impacts on actor networks, learning, practices, values, leadership, or shared understandings. Authors in this issue joined their voice to others (e.g., Hulme and Dessai, 2008) in calling for a shift in focus toward principles of procedural quality, including equitable participation in extended modes of knowledge production.

BROADENING QUALITY: NEW CRITERIA

Authors question whether the principles discussed above are sufficient for guiding the production of high quality information, and put forward additional criteria. Basta et al. translates "principles" (legitimacy, relevance, credibility and effectiveness) into quality criteria (inclusiveness, equity, flexibility and consistency) relevant to the transdisciplinary co-production of knowledge. Cradock-Henry and Frame similarly suggest that there are important procedural aspects of climate scenario development that need to be taken into consideration to improve the legitimacy of this information.

Effectiveness stands out as an important criterion: can the knowledge production process generate the desired action (Basta et al.; André et al.)? *Equity* is another criterion that was raised to ensure that affected participants contribute to knowledge production (Basta et al.). Equity is an important contextual component that, when taken into consideration in co-production processes, promotes high quality knowledge (Cradock-Henry and Frame).

CO-CREATING QUALITY

Overall, contributions to this issue suggest that quality criteria need to be broadened with specific consideration for underpinning processes and contexts of knowledge production. Attention to the processes of generating information can provide insights that address issues about the context and operationalization of quality criteria.

The critical perspectives provided in this special issue provide a foundation for an urgently needed reflective turn in the practice of co-creating and co-appraising the quality of context-specific adaptive knowledges, aware of the very different roles that knowledge can play in informing local, cross-sector and transformative climate adaptation.

AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

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REVIEW
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Orders of Social Science: Understanding Social-Scientific Controversies and Confluence on What "High-Quality" Knowledge and "Good" Adaptation Is

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Various scholars have noted—and experienced—tribal tendencies between social-scientific "schools of thought" or "paradigms." The intensity and fervor of such controversies has led some scientists to compare them with frictions between religious *orders*. In the research domain focused on the use of climate science for climate adaptation, such disputes revolve around the what "high-quality" climate knowledge and "good" adaptation is or should be. Emphasizing this diversity of *orders of social science and the humanities*, this article describes five distinct ways social scientists and humanities scholars have thought and written about climate adaptation: *descriptivists* aim to empirically portray climate adaptation as objectively as possible from an assumed subject-independent perspective; *pragmatists'* research wants to increase climate resilience through usable climate information; *argumentivists* strive for assessing the justification of climate scientific findings, as well as adaptation decision-making that is based on these findings; *interpretivists* seek to empirically redescribe how the use of climate science for adaptation is shaped by, and shapes, various other social processes and political actors; and *critical* scholars work toward revealing how pervasive powerful interests and marginalizing discourses shape adaptation projects negatively. By comparing these five orders' respective scientific, environmental and social aims and concerns, this article pinpoints to how epistemological, ontological and methodological priorities not only drive scientific controversies on issues such as what "high-quality knowledge" is, but also how interdependent orders' methodological choices are with their epistemological and ontological positions. However, this analysis also reveals that while some scholars implicitly stick to their order, others are comfortable to collaborate across such borders. Overall, the diverging aims, priorities, and methods are unlikely to be ever fully reconciled. A better understanding of why academics from different orders differ in the approaches they take and the issues they care about will likely lead to a larger appreciation of the differences of other orders' research and broaden our understanding of key dynamics in studying "good" climate adaptation and "high-quality" climate knowledge.

Keywords: research paradigms, diversity of social science and the humanities, social-scientific perspectives on climate science and adaptation, scientific controversies, use of climate science for climate adaptation, climate knowledge

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INTRODUCTION: A DIVERSITY OF RESEARCH STYLES AMONG SOCIAL SCIENTISTS AND HUMANITIES SCHOLARS

While most social scientists and scholars from the humanities are keen to emphasize that their research benefits people and the environment, some can also be harsh toward and intolerant of research undertaken by researchers with other styles. As such, descriptions of "tribalist tendencies amongst academics, such that researchers must cluster into schools of thought and create possibly fake factional conflicts amongst themselves" recur (Dunleavy, 2003, p. 15). This article explores five distinct research styles with which social scientists and humanities scholars frequently describe, analyse and critique social phenomena around the use of climate science in climate adaptation. By comparing the distinct aims, interests, concerns, and methodology of each *order of social science and the humanities*, I show how these five *orders* differ in what they judge "high-quality" knowledge and "good" adaptation to be. Such an understanding is important in several ways, including an appreciation of the diversity of perspectives research by social scientists and humanities scholars are able to offer for climate science and adaptation; noticing what blind spots and preoccupations different orders have; being able to more critically reflect by what academic calls-to-action are triggered; what insights and conclusions different orders are likely to offer; being a workable framework through which to group academic literature in one's reference management; as well as giving an oversight as to what issues are currently debated across a range of social-scientific strands.

Appreciating social-scientific frictions and understanding confluence in what "high-quality" knowledge and "good" adaptation is carries also important practical, social and political implications: while climatic changes dramatically alter livelihoods and lived experiences around the world, the prominence of science in shaping and underpinning policies makes both agreements and antagonisms among social scientists relevant to a range of issues, practices, and actors beyond academia. If indeed "today 'science' is the theology of the 'developed world' and technology serves as its religion," as Roy (1993, p. 247) writes, then the intensity and fervor with which some social scientists and humanities scholars exhibit their trade in (dis)respect to each other is similar to the frictions between religious *orders*. While some scholars see the frictions between these *orders of social science and the humanities* as worsening environmental controversies (e.g., Sarewitz, 2004), others worry more generally that a unified approach to science may produce too many societal controversies [Jasanoff, in Horgan (2019)] or is harmful to science itself (Feyerabend, 1993[1975]). Thus, with adapting to climate change and using climate science becoming increasingly relevant, understanding how contested key dimensions around living with climate change are from a social research perspective can assist decision-makers and citizens alike to act in a circumspect and aware manner.

This article is influenced by similar comparative research coining terms such as "thought styles" (Fleck, 1979[1935]), "paradigms" (Kuhn, 1996[1962]) or Foucault's "episteme" (cf. Gutting and Oksala, 2019). More recent research has focused on the ways social scientists and humanities scholars not only fertilize each other's research, but also on "paradigmatic controversies." Guba and Lincoln (2005), for instance, conclude that frictions and differences between scholars emerge from different ontological, epistemological, and methodological preferences. While some such assumptions are irreconcilable—or "incommensurable" (Kuhn, 1996[1962])—with each other, paradigms can also fertilize each other's research. In similar fashion, the scholar of qualitative research methodologies Freeman (2016) introduces five distinct "modes of thinking" social scientists and humanities scholars employ in order to produce their findings. She further emphasizes the importance of the researchers' own personal commitments in mediating which mode of thinking a researcher is drawn to. Freeman (2016), however, also makes explicit that many social scientists employ more than one mode in a research project. For instance, "categorical thinking"—the creation of criteria to identify and describe phenomena—is present in almost every piece of research. But while some stick to that mode, others venture into other modes including "dialectical" or "diagrammatical" thinking (cf. **Table 1**). All these works thus pinpoint to the observation that a rich yet frictional diversity of scholarship exists, each one offering different perspectives on climate science and climate adaptation.

In the domain of climate science and climate adaptation, frictions among social scientists recur around the role of climate science for decision-making, the aims and processes of "good" climate adaptation projects, and what criteria climate knowledge ought to have in order to be "high-quality." For instance, the knowledge dimensions of "credibility, saliency, and legitimacy" put forward by Cash et al. (2003) as well as the distinction by Lemos and Morehouse (2005) between the "usefulness" and "usability" of climate knowledge have had a lasting effect on the way climate knowledge for adaptation is envisaged. However, this contrasts with other calls for taking more socially situated perspectives of climate change, emphasizing the role of institutions, and actors rather than that of knowledge (Hulme, 2011; Castree et al., 2014). Disturbed about inequalities and power reproduced through science-informed policies, critical scholars call for more inclusive knowledge production reflecting local people's experience more (Forsyth, 2003; Agrawal, 2010) as well as a different understanding and depiction of people inhabiting this earth (Chakrabarty, 2009; Latour, 2017).

This study thus takes this Special Issue as an opportunity to illustrate and produce appreciation on the diversity of perspectives five *orders of social science and the humanities* have adopted and offered in their research on what I elsewhere dubbed "adapting climate science": the production, customization, use and appropriation of climate science for climate adaptation (Skelton, 2020a). Section Methodology describes the multi-stage process of collecting, selecting, and comparing peer-reviewed research articles, taking their shared and different motivations and problem definitions as a basis for clustering the articles

TABLE 1 | Characteristics of and positions taken by different *orders of social science and humanities*.

Issue	Descriptivist order	Pragmatist order	Argumentivist order	Interpretivist order	Critical order
Inquiry aim*	Undistorted descriptions and explanation through the use and creation of criteria and categories. Propositional knowledge intrinsically valuable	Production of issue-driven, actionable knowledge fostering environmental resilience	Establish validity of scientific knowledge and decision support tools adequately incorporating uncertainties	Challenging orthodox descriptions through reconceptualizing phenomena as products of interacting forces	Social emancipation and transformation through revealing how societal injustices are stabilized
Inquirer posture*	Scientist as distanced honest broker informing decision makers	Transformative researcher as strategic facilitator of environmental action	Meticulous analyser of scientific knowledge and decision-making	Wary yet intrigued commentator of social behavior and aspirations	Transformative intellectual as an advocate for social emancipation
Notion of "high-quality" climate knowledge	Empirical, explanatory knowledge (statistically) characterizing study subject with other categories; assuming stable categories	Instrumental knowledge able to foster adaptation action; often actively co-produced between scientists and practitioners	Produced by appropriate scientific methods and/or logical arguments. Explicit treatment of knowledge's uncertainties	Co-constitutive knowledge critically aware of how particular practices and imaginations are products of a particular constellation of human, non-human, institutional, material and conceptual entities	Revelational, emancipatory knowledge revealing pervasiveness of powerful and marginalizing cultural practices through discourses
Notion of "good" adaptation	Harmoniously understood by actors. Enacted and legislated similarly across countries. Anticipatory policies and action consulting latest scientific and experts, yet decided by politicians. Includes environmental, social and legislative changes	Anticipatory, effective and widely implemented action upon environment. Risk management with anthropocentric and technocratic tendencies; primacy of co-produced (geophysical) climate science	Decision-making appropriately dealing with climate science's uncertainties; with proper demarcation of roles of scientists and decision-makers	Adaptation action mindful of entities shaping—and thus limiting—human abilities in consciously managing its environment. Wary of human fallacies of control and unintended consequences; critical of technocratic adaptation options	Transformative and emancipatory; challenging orthodox ways of policy-making; local and inclusive process; primacy on people's livelihoods and experiences
Ontology*	Post-positivist: reality imperfectly apprehensible; relatively stable categories and classifications also within the social domain to describe phenomena of interest		Notions of "reality" debated, with post-positivists and anti-realists of various hues	Constructivist: realities and meaning co-constructed through a variety of human and non-human factors	Historical-realist: shaped by political, economic, ethnic, and gender values
Values in research*	Values deemed insignificant for research findings	Explicit in pro-environmental values, yet rarely critically debated	Debated; with efforts to differentiate them	Formative to study aim and focus	Formative to study aim and focus
Epistemology*	Objectivist: findings probably true and empirically accessible		Degrees of "objectivity" debated	Subjectivist: findings are collectively yet implicitly mediated, in particular through science, politics, and technology	Subjectivist: findings are collectively mediated. Emancipatory values guide validity of results
Methodology*	Empirical, predominantly quantitative research favoring statistical analysis. Deductive reasoning; with falsification of hypotheses	Conceptual work focusing on aspirational and/or problematizing issues—yet not necessarily empirical. Can draw on both quantitative and qualitative data; with participatory workshops	Logical argumentative analysis; with deductive reasoning. Mostly conceptual, some empirical studies	Empirical, comparative and mostly qualitative research including ethnographic accounts and interviews. Inductive reasoning	Empirical, mostly qualitative research. Strong *a priori* theoretical foundations and deductive reasoning

(Continued)

TABLE 1 | Continued

Issue	Descriptivist order	Pragmatist order	Argumentivist order	Interpretivist order	Critical order
Dominant "mode of thinking" (cf. Freeman, 2016)	Categorical thinking: "to create criteria from which to identify and organize data units" in order "to determine what something is in relation to the conceptual scheme that gives it meaning"		(no equivalent)	Diagrammatical thinking: "to engineer new articulations of the effects of turbulent encounters between diverse human and non-human practices" by "unhing[ing] established forms of thinking"	Dialectical thinking: "to put into action a theory of change and rectify oppressive structures and practices" by "uncover[ing] inherent tensions that are assumed to exist in humans and societies"
Controversies and critiques (from)	• Not issue-driven enough (pragmatist) • Overconfident with findings' validity (argumentivist) • Technocratic tendencies; assumes stable categories (interpretivist, critical) • Maintains social injustices (critical)	• Too normative (descriptivist) • Overconfident with findings' validity (argumentivist) • Technocratic tendencies (interpretivist) • Increases social injustices (critical)	• Not enough focus on environmental action (pragmatist) • Maintains science's hegemony; constrains research (interpretivist, critical)	• Activist tendencies (descriptivist, argumentivist) • Too conceptual (pragmatist) • Speculative on cause and effect (argumentivist)	• Activist tendencies (descriptivist, argumentivist) • Not enough emphasis on environment (pragmatist) • Speculative on cause and effect (argumentivist)
Confluence & learnings (from)	• Stronger epistemological argument (argumentivist)	• Attention to social injustices (critical) • Problem descriptions (descriptivist)	• External empirical validity (descriptivist) • Attention to role of values in science (interpretivist, critical)	• Discourses stabilizing social behavior (critical) • Descriptions (descriptivist)	• Values stabilizing social behavior and science (interpretivist) • Descriptions (descriptivist) • Uncertainty of science (argumentivist)
Preferred journals	Global Environ Change; Climatic Change; Clim Policy; P Natl Acad Sci USA (PNAS); Reg Environ Change; Phil Trans R Soc A	Climate Services; Climate Risk Management; Nat Clim Change; Weather Clim Soc; WIREs Clim Change; Mitig Adapt Strat Gl; PNAS; Environ Res Lett	WIREs Clim Change; Philos Sci; Philosophy Compass; Synthese; B Am Geogr Soc (BAMS); Perspect Sci; P Natl Acad Sci USA (PNAS)	Nat Clim Change; Environ Sci Policy; Climatic Change; WIREs Clim Change; Climate Services; Futures; Reg Environ Change; Sci Technol Hum Val	Geography Compass; Dev Change; Minerva; Prog Hum Geog; R Institute Brit Geogr; Gend Dev; Clim Dev; Geoforum; WIREs Clim Change

**denotes issues along which also Guba and Lincoln (2005, p.194–196) analyzed their paradigmatic controversies. Guba and Lincoln (2005) do not have an equivalent to the pragmatist and argumentivist orders in their paradigms. These two orders thus extend their typology.*

into *orders of social science and the humanities*. Importantly, academics' motivations and concerns influence not only the choice of data, methods and topics, but at a deeper level the different ontological, epistemological, and methodological commitments made by the researchers. The sections on the *descriptivist, pragmatist, argumentivist, interpretivist, and critical order* then describe the respective research topics, foci, problem framings, and proposed solutions so similar within each order, but so different between them. In section Discussion I then discuss how these distinct positions and aspirations influence different notions of "high-quality" climate knowledge and "good" adaptation. I conclude that a more thorough understanding of the differences allows not only a more conscious way of doing research, it could also allow to appreciate how other perspectives offer complimentary insights into the social dynamics climate change produces.

METHODOLOGY

In order to obtain an in-depth understanding of and appreciation for the diversity of thought being produced by social scientists and humanities scholars on *adapting climate science*, this review employs a number of strategies to navigate the overwhelming amount of peer-reviewed articles available while aiming to meaningfully characterize the literature along similarities in philosophical positions. Peer-reviewed articles and book chapters have been one of the most important products scientists produce, and so their comparison allows meaningful insights into how and why a diversity of styles of thinking exist. While other scientific practices—such as attending conferences and talks, participating in seminars and reading clubs, and having conversations in all these venues—also substantiated or provided impetus for refinement of the typology, the final step of the review only considers peer-reviewed articles and book chapters. Overall, I undertook three distinct phases to meaningfully compare similarities and differences between particular ways of describing and researching social phenomena around adapting climate science.

First, during the exploratory phase in early 2017, I sketched 1 year's worth of reading literature on the production, customization, use, and appropriation of climate science for climate adaptation into an initial typology of the diversity of perspectives, priorities and concerns present in academic debates. Motivation for this exercise was to onboard my interdisciplinary Ph.D., committee, which included a climate physicist. Presenting this initial typology at my institute, I also received valuable feedback and supplementary reading—including Guba and Lincoln's (2005) *Paradigmatic Controversies, Contradictions, and Emerging Confluences*. They contrast four "inquiry paradigms"—Positivism, Post-positivism, Critical Theory et al., and Constructivism—by their differing metaphysics or basic beliefs. While Positivism was dropped out of this article's orders due to a lack of such inquiries on *adapting climate science*, the other three are mirrored in the *descriptivist*, *critical*, and *interpretivist* order respectively. Two other clusters of literature—*pragmatist* and *argumentivist*—did not have an equivalent, yet clearly extended the inquiry paradigms of Guba and Lincoln (2005). Based on this supplementary reading, I double-checked to which order I assigned already read articles in my reference manager.

The second phase, taking place from mid-2017 to mid-2019, was divided into three distinct actions. First, I continued reading and summarizing literature on the production and use of climate information for climate adaptation, as well as assigning each article an order in my reference manager. Second, to better understand how, and more importantly why, such a diversity of thinking exists among social scientists and humanities scholars more generally, through self-study of such scholarship as well as taking part in a number of seminars and reading groups dedicated to illuminating multiple orders of social science and the humanities. One key text in these endeavors was Freeman's (2016) *Modes of Thinking for Qualitative Data Analysis*, contrasting "categorical," "narrative," "dialectical," "poetical," and "diagrammatical" modes of thinking. Two such ways of thinking—narrative and poetical—were not encountered in my literature review. However, her descriptions of "categorical" mirror in many ways the scholarship produced by *descriptivists*, "dialectical" that by the *critical* order, and "diagrammatical" that by *interpretivists*. And third, attending talks, conferences, and workshops of social scientists and humanities scholars from different orders, as well as presenting myself and receiving their feedback, also provided valuable input either substantiating my understanding of how and why social scientific thought is so diverse, or by inviting me to revisit and refine the typology. For example, the modes of thinking described by Freeman (2016) emphasized that on the topic of *adapting climate science* two additional modes—with the pragmatists being very dominant and the *argumentivists* less so—can be differentiated. At the end of the second phase, I thus had a refined understanding of how and why different orders exist, as well as a reference manager indexing several hundred articles and book chapters on adapting climate science.

The third phase of this review, from mid-2019 to mid-2020, was dedicated to analytically comparing the scholarship collected in the reference manager, carrying out a multi-step approach. First, as the collected literature was scarcer for the *argumentivist* and *critical* order, I undertook a dedicated and targeted review effort to close this gap, so that similar amount of research informed the subsequent analysis[1]. That is, the refined typology of phase 2 highlighted where I had ample of scholarship to draw upon for this analytical comparison, and where additional efforts were required to balance the amount of material used. Second, as my background research into why contrasting schools of thought are so prevalent among social science and the humanities pinpoint toward the importance of the ontological, epistemological and methodological positions, I drew in particular on Guba and Lincoln (2005) for comparing the key diverging issues between these five orders. These include, inter alia, inquiry aim, inquirer posture, or ontology (see issues denoted with * in **Table 1** for full set). These dimensions also

[1]Despite the dedicated effort to source articles by the *critical* order, this order had fewer articles on offer. This seems thus to be a characteristic of this order.

helped to characterize the similarities within and between the two orders missing in both Guba and Lincoln (2005) and Freeman (2016), namely *pragmatists* and *argumentivists*. Additionally, I compared different notions of what "high-quality" knowledge and "good" adaptation is, what critiques are brought forward by other orders, and what confluences orders have. Third, based on my typology of phase 2 and the compared characteristics, I double-checked whether my previous assignment of an article to an order is still warranted. Fourth, within each order, I grouped the articles by similar topics, before noting and then summarizing the shared and key characteristics found in **Table 1**.

Overall, this review aimed to condense the sheer amount of scholarship on adapting climate science not by selecting articles based on keywords, but by a multi-phase process. An initial identification of the five orders took place relatively early, but was then challenged not only through consecutive reviewing of additional articles, but also through scholarship dedicated to similar questions of diversity and frictions in social research more generally. In the final analytical phase, a number of processes were taken to ensure the review's methodological integrity, including the search for additional literature to substantiate the description of two orders, double-checking prior grouping of articles to an order, and drawing on key distinctions with literature dedicated to the subject of "modes of thinking" (Freeman, 2016) and "paradigmatic controversies" (Guba and Lincoln, 2005), in order to best guarantee within-order homogeneity and between-order distinctiveness.

THE DESCRIPTIVIST ORDER: MIRRORING CLIMATE SCIENCE AND CLIMATE ADAPTATION

Descriptivist scholars show a particular desire to mirror how climate science is produced and used, and which adaptation processes have been adopted. This order is composed of political scientists, psychologists, economists as well as environmental social scientists who share a similar understanding of social science and its aims: providing undistorted descriptions and explanations. Three features recur frequently (see **Table 1**): *Methodologically*, an empiricism predominantly carried out by using (and assuming) stable categories with shared meanings to describe study subjects, relying mostly on the use of quantitative data such as surveys, or the creation of quantitative metrics from qualitative source material such as government reports for statistical purposes. *Ontologically*, a belief that the phenomena of interest are imperfectly apprehensible and measurable through pre-existing categories and stable classifications, such as age, wealth, geography or gender. And *epistemologically*, that unless falsified, descriptivist research produces findings probably true and empirically accessible. The following paragraphs give a flavor what phenomena social scientists in the descriptivist camp have explored.

The production and origin of climate science is one prominent descriptivist account. Such largely quantitative studies use bibliometric methods to assess the growth of climate science, its expansion into other disciplines, or the producers' geography (e.g., Pasgaard and Strange, 2013). All find that a minority of countries—richer and with higher carbon emissions—produce the bulk of climate research. More qualitative accounts of how climate projections informing about future climatic changes were jointly produced with a number of actors (e.g., Jacobs and Buizer, 2016), how such projections are made available across the globe (Hewitson et al., 2017), or how the boundary organization UK Climate Impacts Programme UKCIP aimed to mainstream climate adaptation (Hedger et al., 2006).

Descriptivist research also illustrates climate adaptation policies, climate service practice and their use of climate science is. This includes mapping of stakeholders working on climate adaptation and services (e.g., Lorenz et al., 2019), the positive effect designated climate adaptation officers have on governmental policy (Stiller and Meijerink, 2016) or case studies on what role institutions and "boundary organizations" play (e.g., Ekstrom and Moser, 2013). Lorenz et al. (2017) analyzed how differently German and British local authorities used climate information in decision making, relating differences back to contrasting regulatory and fiscal governance systems. Similarly, Porter et al. (2014) describe what adaptation action UK households have taken, adding descriptions of less institutionalized and expert-driven adaptation processes.

Descriptivist attention is also focused on the differences of governmental adaptation policies. Comparing different national adaptation strategies in Europe, Albrecht and Arts (2005) found a convergence to a similar understanding of adaptation policy across countries. Similarly, Biesbroek et al. (2010) compare European countries' national adaptation plans across six dimensions, including how adaptation is both implemented and linked up with other policy domains. Still, climate adaptation is understood differently across sectors (Widmer, 2018). Also the uncertainty so prominent in climate scientific discussions is often simplified in such governmental documents (Füssel and Hildén, 2014).

Evaluating adaptation efforts across countries has also gained scholarly attention. Methodological discussions concern how to meaningfully compare the diversity of adaptation practices across countries (Dupuis and Biesbroek, 2013), including what indicators are useful to assess the effectiveness of particular adaptation options (Arnott et al., 2016). Others have developed indicators to track countries' adaptation progress, using the availability of climate science or the existence of national adaptation plans as proxies (Ford et al., 2013). This methodology has then been applied to describe climate adaptation progress globally (Berrang-Ford et al., 2014), and, controversially, labeling countries explicitly into adaptation "leaders" and "laggards" (Lesnikowski et al., 2015).

Psychologists, among others, have assessed both the public's ability to comprehend climate information, their attitudes toward climate adaptation and their knowledge on climate change. The comprehension of texts, tables or figures depicting the uncertainty attached to climate information has been a common

study theme, in order to empirically find which are the most influential (e.g., Taylor et al., 2015; McMahon et al., 2016). This also includes analyzing how readable scientific reports are, such as the IPCC's summary for policymakers (Barkemeyer et al., 2015). More recently a strong proponent of the *pragmatist* co-production paradigm ran two *descriptivist* decision-lab studies to assess different modes of user interaction (in-person, live webinar, and a self-guided recorded webinar), finding little effect on users' understanding, as well as perceptions of credibility and fit, of climate information (Lemos et al., 2019). This suggests that scaling up of user interactions by less resource demanding means is possible in many situations.

Other psychologists have undertaken empirical studies on how UK residents understand climate change impacts and climate adaptation (Harcourt et al., 2019), as well as conducting a meta-analysis to understand what motivates people to adapt (van Valkengoed and Steg, 2019). In particular, norms, negative emotions, and the perceived efficacy of climate adaptation outcomes were found to be key indicators. However, numerous such studies suggest that many people do not distinguish between climate adaptation and mitigation (e.g., Harcourt et al., 2019).

Descriptivists thus understand "high-quality" climate knowledge to be empirical and explanatory, often using statistical analysis to characterize their study subject through other categories (**Table 1**). An implicit assumption is that knowledge derived in one origin is also valid in others. This is also mirrored in notions of "good" adaptation as being harmoniously understood by different sets of actors, as well as similarly enacted and legislated in different countries. While adaptation policy-making is squarely seen as politicians' task, consulting the latest research findings and experts is a key feature in "good" adaptation.

THE PRAGMATIST ORDER: MAKING CLIMATE SCIENCE *FOR* AND *WITH* SOCIETY

Characteristically, *pragmatist* academics produce research aimed at increasing the social, ecological and technological resilience toward climatic impacts by improving adaptation decision-making through the production of more usable climate science. Initiated in the 1990s by calls for more issue-driven rather than curiosity-driven science (e.g., Funtowicz and Ravetz, 1993), *pragmatists* advocate science–stakeholder collaborations to produce relevant and usable knowledge as a required first step in triggering climate action. **Table 1** shows that *pragmatist* research shares many methodological, ontological and epistemological positions with *descriptivists*. For instance, although *pragmatists* are focused on participatory research, their articles still predominantly write from a more subject-independent perspective. But, importantly, pragmatists see their research output as contributions to a larger transformation, and see themselves as strategic facilitators of environmental action, often taking vocalizing their positions in calls-to-action.

Echoing throughout the pragmatist literature is the proclamation that climate science has to play a dominant role in how societies address climate change. Such scholarship is often quite upfront about this, even stating these ambitions in the title, such as to "Using climate predictions to better serve society's needs" (Hewitt et al., 2013, p. 105) or "Science for successful climate adaptation" (Preston et al., 2013). In line with such assertions, a whole research field has formed based on *pragmatist* motivations. For instance, "climate services" have been prominently pushed by the World Meteorological Organization WMO, national meteorological agencies as well as the European Commission (cf. Vaughan and Dessai, 2014). Dominated by goals of increasing resilience, pragmatist research puts climate science in the service of climate adaptation.

A range of barriers to using climate science for adaptation decision-making have been identified. Moser and Ekstrom (2010), for instance, developed a diagnosis framework to find, and possibly solve, barriers to adaptation planning. Assuming an "idealized, rational" decision-making process—labels that they themselves use—the authors propose a process asking two questions: What could act as a barrier? And how do the actors contribute to this barrier? This diagnosis then allows them to find "points of intervention" fostering climate action (Moser and Ekstrom, 2010, p. 22,026). Similarly, Ernst et al. (2019) identify three clusters of constraints—production, dissemination, and stakeholder engagement—in producing climate services. Ironically, two of these clusters were already strategically employed to promote and facilitate adaptation decision-making in Sweden, yet failed to adequately produce the intended results. Similar challenges with producing usable and thus "high-quality" knowledge are reported from a US-based regional climate service center (Briley et al., 2015). Cvitanovic et al. (2015), meanwhile, turn the perspective around, looking at the barriers scientists perceive in stakeholder engagement. Overall, the aim of identifying—and thus overcoming—barriers in the use of climate science for adaptation is a recurring *pragmatist* research theme.

Climate services also profited from research emphasizing that the existing climate and social science is hardly used. Calls for the reconciliation of the "demand and supply" of climate information (e.g., McNie, 2007), the closure of the "science–action gap" (Moser and Dilling, 2011) or the "usability gap" (Lemos et al., 2012) all tried to foster broad awareness and public action on climate change. Or, as Swart et al. (2014, p. 1) put it: "while an abundance of adaptation strategies, plans, and programmes have been developed, progress in turning these into action has been slow. The development of a sound knowledge basis to support adaptation globally is suggested to accelerate progress, but has lagged behind." The normative assumptions and policy preferences of many pragmatist research papers crystallize in aims such as: fostering climate action on the basis and primacy of science.

To produce the required "sound knowledge base" (Swart et al., 2014), "usable science" (Lemos et al., 2012) and "actionable knowledge" (Kirchhoff et al., 2013) to accelerate climate adaptation efforts around the globe, various academics have argued for engaging stakeholders in research projects.

This process was labeled "co-production of knowledge"[2] (e.g., Lemos et al., 2012), "co-creation" (e.g., Mauser et al., 2013), "co-design" (e.g., Moser, 2016a), or "co-development" (e.g., Leitch et al., 2019), while in Continental Europe it continued to be recognized under the independently established research paradigm of "transdisciplinarity" (e.g., Pohl, 2008). By doing so, the pragmatists' perceived need to advance global action on climate change with their research has joined earlier calls for a new type of science (Funtowicz and Ravetz, 1993). Interestingly, also stakeholders have become more vocal in calling for science–practice partnerships (e.g., Beier et al., 2017).

Another way of ensuring climate knowledge's relevance for a range of stakeholders has been taken by research on "user needs," offering a way to produce usable knowledge without costly face-to-face interaction. Some such use(r) requirement studies are noteworthy for their specificity, for instance for Australian vineyards (Dunn et al., 2015). Others have mapped sectoral information requirements, such as water (e.g., Mehta et al., 2013), policy-makers' climate information preferences (Hanger et al., 2013) or information needs for community-level adaptation (Srinivasan et al., 2011). The findings of such studies can illuminate what specific information—for instance, drought indicators—is desired by users, or through which channels it can be accessed. Such studies are thus another pragmatist example of producing "high-quality," "usable" climate knowledge for "good" adaptation.

Drawing on much descriptivist scholarship analyzing climate science communication and comprehension, various pragmatist studies have highlighted how to improve the consideration of climate science in climate adaptation. For instance, conveying climate science through stories is one such recommendation, such as the "tales of future weather" (Hazeleger et al., 2015) and "narratives" (Dessai et al., 2018). In reviewing climate change communication from 2010 onwards, Moser (2016b) emphasizes that opportunities for communicating the impacts of climate change, also within politicized contexts, arise increasingly not only from IPCC's Assessment Reports and UNFCCC COPs, but also from extreme weather events, statements by business associations or religious leaders, and political events such as elections and even pandemics.

Pragmatist scholarship emphasizes issue-driven, instrumental, and scientific knowledge as particularly able to effectively foster climate action (**Table 1**). And such knowledge is more likely to be used by society when scientists engage in more direct interaction with stakeholders and practitioners. As such, "high-quality" knowledge is often equalized to being "actionable" or "usable." Further, pragmatists widely understand "good" adaptation as a process underpinned by geophysical climate science, allowing the anticipatory management of climate risks.

[2]The term "co-production" enjoys two different meanings (Bremer and Meisch, 2017). On the one hand, pragmatists understand it as *doing* co-production with stakeholders, whereas the interpretivists take to the *studying* co-production in its initial sense as coined by Elinor Ostrom in the 1970s, i.e., examining the ways science and society influence each other's practices and phenomena.

THE ARGUMENTIVIST ORDER: ANALYZING KNOWLEDGE, DEMARCATING SCIENCE

Academics following the *argumentivist* order usually use a purely conceptual approach to both meticulously analyse what climate knowledge claims can be validly derived from certain research activities, as well as to propose ways in which decision-makers can successfully navigate and incorporate not only climate science's uncertainties, but also their own values and risk preferences in climate adaptation projects. Composed mainly of analytic philosophers of science (to use a pleonasm), argumentivists' work can trace back its origins also to the writings of Popper, Hempel or Lakatos. *Methodologically* they are unified by their commitment to work predominantly conceptually in order to logically and argumentatively dissect, reconstruct and critique arguments. In line with such an emphasis, argumentivists take—and critique—a variety of ontological and epistemological positions. Such internal debates should be understood as an exemplary case of the unifying theme of this order, namely meticulous focus on arguments. Overall, *argumentivist* philosophers of climate science engage with philosophical and conceptual issues that arise in the practices of climate science.

Various analytic philosophers discuss the adequacy of climate simulations for making reliable predictions and for understanding aspects of the climate system (e.g., Smith, 2002; Parker, 2014). A climate scientist by training, Held (2005) worries that the attempts to create realistic models makes them so complex that it is impossible to trace why they behave the way they do. Thus, the complexity of climate models—made possible by ever increasing computer power—might make it difficult to actually assess whether model results are reliable. Further, with data and observations becoming more abundantly available, machine learning and big data applications provide new opportunities for climate scientists to research and understand climate change. However, Knüsel et al. (2019) argue that in big data-only approaches, the data alone is insufficient to warrant an assumption of constancy (ceteris paribus). Theory-based knowledge is thus still relevant to climate predictions produced by machine learning algorithms. Overall, analytic philosophers carefully analyse to what extent such modeling approaches are able to provide high-quality knowledge.

With climate scientists increasingly using multiple climate models to assess some of the inherent uncertainties attached to climate change, and the prominence climate models have in informing adaptation decisions, *argumentivists* have been actively engaged in discussions on combining models in ensembles. For instance, Parker (2010) has characterized the different types of "model ensembles" which exist. As such, perturbed-physics ensembles, multi-model ensembles, and initial condition ensembles help analyzing different sources of uncertainty. Baumberger et al. (2017) argumentatively follows up the implications of how to appropriately select and weight climate models. More recently, with datasets playing an important role in calibrating and validating climate

models, Zumwald et al. (2020) propose to extend the use of ensembles to multiple datasets in order to better assess climate science's uncertainties.

However, how to obtain and interpret quantified uncertainty estimates from climate model ensembles has been a source of friction between climate scientists and argumentivists. For instance, some analytic philosophers strongly objected to how the climate scientists producing the British climate projections UKCP09 (Murphy et al., 2010) communicated their findings as probabilities. The criticism of British climate scientists' "myopia" (Frigg et al., 2013) was caused by disagreements on how to interpret the "probabilities" derived from climate simulations. The British climate scientists assumed that these probabilities are a good way of expressing their actual uncertainty. But Frigg et al. (2013) caution against interpreting the British climate projections UKCP09 as being able to be reliable expressions of uncertainty of future climates up to the end of the twenty-first century. Therefore, this argumentivist analysis has implications for how adaptation projects ought to take up and integrate climate science, in particular for high-risk events.

With "unknown unknowns" (Parker and Risbey, 2015) making it impossible to know the full event space and the corresponding probabilities with certainty, decision principles and tools have been proposed which consider these constraints. Betz (2010, 2016) argues decision-makers need to focus more on their risk preferences when judging "worst-case" and "best-case" scenarios of climate change, rather than its probabilities Similarly, thoughtfully integrating uncertainty explicitly in policy deliberations, both Bradley and Steele (2015) and Hirsch Hadorn et al. (2015) discuss decision strategies to analytically decide whether to accept, revise, or postpone adaptation and mitigation decisions. Roussos et al. (2020) consider three dimensions for more confident decisions using model ensembles: the models' output as probabilities; an expert judgement of confidence in these probabilities; as well as an actor's stakes and cautiousness. These three dimensions allow to characterize and deal with different sources of uncertainty. As such, argumentivists have offered ways in which climate science could be more appropriately taken up in current adaptation decision-making, to ensure "good" adaptation by "high-quality" knowledge.

Argumentivists also contributed to the pragmatist discussions of how to co-produce actionable knowledge. Thompson et al. (2016) argue that climate services too often treat climate models' unmodified output as real-world probability distributions. To avoid the pitfalls associated with such unwarranted confidence in climate models while taking climate science seriously in climate adaptation, they propose that structured expert elicitation processes would allow a range of experts to systematically discuss climate science with other available knowledge in order to produce more scientifically justified as well as decision-relevant climate services. In a similar vein, Parker and Lusk (2019) enrich the pragmatist studies of including user values in the co-production of climate knowledge by highlighting that the types of errors which users want to avoid—risk of overestimating or underestimating particular climatic changes—is of importance when producing actionable knowledge. Parker and Lusk (2019) enrich co-production discussions by emphasizing that users can also guide scientists' methodological choices: knowing whether under- or overestimation is of greater consequence to users can favor one approach over another.

Argumentivists are thus bound together by their commitment to "high-quality" knowledge being produced by appropriate methods or flawlessly argued, always explicitly dealing with science's uncertainties (**Table 1**). This is mirrored in their understanding of "good" adaptation as adequately acknowledging yet still incorporating these uncertainties meaningfully. Often, argumentivists take care in demarcating where the expertise of scientists end and the role of politicians start.

THE INTERPRETIVIST ORDER: RE-CONCEPTUALIZING CO-CONSTITUTIVE INFLUENCES

Interpretivist scholarship aims to unhinge established forms of thinking and descriptions, by redescribing collective behaviors and discourses as products of complex encounters between cultural norms, collective aspirations, socio-political pressures and technological innovations. Composed of scholars of Science and Technology Studies, empirical human geographers, and qualitative interdisciplinary researchers, *interpretivist* scholarship shares the following three features (see **Table 1**). *Methodologically*, interpretivists favor an empirical and mostly qualitative perspective, drawing for instance on ethnographic accounts and semi-structured interviews. Often comparative in nature, much scholarship uses inductive reasoning to bring often unnoticed yet stable patterns into focus. *Ontologically*, interpretivists see social practices, meaning, and realities as being the product of multiple influences—beliefs, imaginations, technologies, knowledge, politics. And *epistemologically*, a subjectivist view of findings being collectively mediated by reciprocal interactions of society, science, politics and technology dominates. With such a background, interpretivist research has emphasized how various practices around "high-quality" climate science and "good" climate adaptation are socially negotiated and stabilized, and so subject to human fascinations, manipulations and fallacies.

Interpretivist scholars have had continuing interest in the way socio-cultural factors shape climate scientists' work. Shackley (2001) and contributions edited by Heymann et al. (2017) empirically compare the "epistemic lifestyles" or "cultures of prediction" of climate modeling centers as a sociological phenomenon. This includes, for instance, the mutually beneficial interplay between modelers and experimentalists through parametrisations (a method for replacing sub-scale atmospheric processes in climate models with empirical observations), thus also socially—and not only epistemically—legitimizing climate models as an accepted research mode (Shackley et al., 1998; Sundberg, 2007). Further, Mahony and Hulme (2012) describe how the UK regional climate model PRECIS was motivated by the wish to make the climate center's science globally available while simultaneously collecting the knowledge of the regional expert stakeholders to reduce obvious model errors. Further,

climate scientists often imagine users of climate information to be either similarly numerate as themselves (Porter and Dessai, 2017) or through other simplified categorisations, such as being an academic, practitioner or by sector (Skelton et al., 2019a). Both studies show how powerful imaginations—yet empirically inadequate descriptions—legitimize and guide much development of climate services.

How science and politics mutually influence each other is another intriguing research topic for interpretivist researchers—confusingly also known as the *study* of "co-production" rather than pragmatists' *doing* co-production with stakeholders (cf. Bremer and Meisch, 2017). With the concept of "civic epistemologies," Jasanoff (2005) emphasizes that democracies have distinct preferences as to which kind of science and expertise is seen as legitimate for policy-making. For instance, Skelton et al. (2017) found patterns of judging "good" climate science and "good" stakeholder participation in climate projections matching the political cultures of the UK, Switzerland and the Netherlands, respectively. Another such comparative study is the evidence-based research on the politics of climate adaptation in the UK and Australia (Tangney, 2017). Other interpretivist studies focus on single countries, such as how Germany established political consensus on climate change (Beck, 2012), or the goals of the UK Met Office as a world-leading climate science center also being fuelled by political ambitions to support the UK's climate negotiation position (Mahony and Hulme, 2016).

Another interpretivist research strand investigates how the relationship between climate science and climate action is framed and politically embedded. For instance, Gillard (2016) highlights the significant rhetorical shift between two consecutive British governments, from one dedicated to being a "climate leader" in both adaptation and mitigation to one skeptical of the state's role in orchestrating policy targets. Similarly, Tangney (2017) critically examines how ideas and fascinations with evidence-based approaches in decision-making politicizes climate science, in particular by asking science to be the *only* source of answers on the normative policy dimensions. On a global level, the lack of democratic legitimacy of supranational knowledge bodies such as the IPCC have led Bäckstrand (2003) to call for a wider stakeholder interaction in the synthesis of climate science for decisions. Overall, there is thus widespread interpretivist interest in how changes in how environmental governance is perceived shift policy responses.

Interpretivists have also noted how the use of climate science is part of a wider societal concern with anticipating the future. Enserink et al. (2013) show that decision-makers and scientists understand "scenarios" differently, so much so that what was meant to clarify led to confusion. Social and emotional factors also play a role in interpreting climate simulations, including a certain "seductive power" in acknowledging the model's uncertainty (Lahsen, 2005). Further, Groves (2017) examines how "anticipation" and the fascination of desired futures shapes climate politics today. Similarly, Skelton (2020b) analyses why building technicians and greenspace managers appropriated knowledge on urban heatwaves so more successfully than spatial planners and health specialists. He argues that the more "cognitive links" sectors share with climate science concepts (e.g., indoor climate, bioclimates) and the more authority and control experts have over climate adaptation options, the more climate knowledge fits "comfortable" with a sector's priorities. This interpretivist strand of research thus highlights how prospective knowledge on future climate change has already significantly altered our perceptions and thoughts today.

Further, cautioning against dominant *pragmatist* fascinations is a common interpretivist practice—even a *raison d'être* for some (cf. Horgan, 2019). Many scholars critique the dominance of the "interaction imperative" embedded in climate services, either because it is too consensual (Klenk and Meehan, 2015); because joint co-design of knowledge does not necessarily lead to trust (Lahsen, 2007); because too often stakeholder engagements are just "lip service" (Klenk et al., 2015); or because participation often perpetuates rather than challenges existing power dynamics (Chilvers and Kearnes, 2016; Turnhout et al., 2020). Others critique the "managerial" intentions prominent in adaptation discourses prominent in both socio-technical as well as socio-ecological paradigms (Gillard et al., 2016). Further, interpretivist scholars see the shift of climate services from the public to the private domain critically (Keele, 2019), and have scrutinized the way the World Bank has produced and circulates "best practices" for adaptation (Webber, 2015). In general, being wary of other social science orders' efforts, the study of discourses and the collective fabrication of desired futures by science–society interactions (so-called "sociotechnical imaginaries," cf. Jasanoff and Kim, 2015) is a distinguishing feature of interpretivist scholarship.

Thus, *interpretivists*' understand "high-quality" climate knowledge to consider the interrelated factors stabilizing human practices and sense-making in a particular way (**Table 1**). Such an understanding of "high-quality" knowledge then translates into "good" adaptation action as being mindful of the profound influences individuals, institutions, ideas, practices, materials, and non-humans have on human action. Interpretivists are thus wary of technocratic fallacies of control possibly producing severe unintended consequences.

THE CRITICAL ORDER: REVEALING INJUSTICES REPRODUCED BY SCIENCE

Working toward increased social emancipation, the *critical* order aims to reveal how actors and institutional practices stabilize a particular understanding and framing of climate change—the so-called discourse—and so maintain and reproduce social injustices and privileges enjoyed only by few. Critical scholars aim to unveil how culturally ingrained depictions privileging benevolent scientific, political or economic leaders in their ability to effectively manage environmental pollution, or inversely, shifting the understanding of what the problem is and who needs to act onto less responsible and affluent actors. Although comparatively few *critical* studies on climate have been published, key similarities between

postcolonial, feminist and political ecological scholarship are, *methodologically* often apply prior theories and concepts to climate science and climate adaptation. *Ontologically*, critical scholarship is shaped by political, economic, ethnic and gender values, while *epistemologically*, critical thought is subjectivist, where findings are collectively mediated and thus changeable.

Post-colonial studies take a close and critical look at how ideas and discourses on climate adaptation have neo-colonial underpinnings of Western superiority and a disregard of nations' policy-making sovereignty. Bankoff (2001), for example, points out that discourses of vulnerability updates, and so maintains, older conceptions of Africa, Asia, and South America being dangerous and/or requiring "Western" support. Between the Seventeenth and early Twentieth century, such places were framed as disease-stricken lands in need of Western medicine, before being portrayed as impoverished and in need of Western investment and aid after World War II. The current discourse, as Bankoff (2001) argues, is one in which these countries are vulnerable to natural hazards, with science seen as its remedy. As such, his study demonstrates how persistent such marginalizing framings are. Further critique has been directed at *pragmatist* discourses romanticizing so-called indigenous knowledge, not only by seeing it as being of distinctly different quality than scientific knowledge, but by subjugating such knowledge to the pragmatists' aims rather than respecting those of its original holders (Agrawal, 2010; Klenk et al., 2017). Such studies thus emphasize how other *orders*' judgements of "high-quality" knowledge and "good" adaptation can be problematic.

Climate models have received critique for their embedded neocolonial assumptions underpinning their development and deployment. For instance, the UK established the Met Office Hadley Center also because of a political concern that without its own, national climate model, the UK would be unable to independently act in international climate negotiations, relying instead on knowledge produced in the US and continental Europe (Mahony and Hulme, 2016). Inversely, Anglosaxon climate scientists were at the forefront for producing one-size-fits-all tools for generating climate projections *for* poorer countries, further circulated through workshops held by UNFCCC while continuing to fund own climate scientists rather than adaptation elsewhere (Skelton et al., 2019b). Climate projections and their models thus carry colonial connotations of power and influence over sovereign, national adaptation policy-making (Mahony and Hulme, 2018). Similarly, Lahsen (2007) reminds that Brazilian policy-makers do not automatically trust climate science just because Brazilian scientists were involved. Rather, joint climate research projects are often eyed suspiciously for their goals favoring US over Brazilian interests. While not a *subaltern* view developing a narrative independent of more powerful actors common in postcolonial scholarship (e.g., Chakrabarty, 2012), Miguel (2017) shows that emerging economies such as Brazil have started to develop their own national climate models in an explicit effort to be more scientifically independent in their national climate policies. Overall, both explicit and implicit postcolonial studies illuminate how neocolonial conceptions of "good" adaptation are manifested in climate models as favoring a distinct perspective on what "high-quality" scientific knowledge is.

How a discourse mirrors the interests and perspectives of more powerful actors is also revealed by feminist scholars. Seager (2009) traces how the 2°C target was first coined and subsequently internationally endorsed through a politics with "gendered political and ideological underpinnings," as climate risks below 2°C are acceptable and manageable only for temperate, mid-latitude and richer countries. "Many ecosystems and peoples will hit limits to adaptation long before 2°C, and some already have" (Seager, 2009, p. 15). Such a "mechanistic" and "masculinized" understanding of humans' ability to effectively manage their environment is, in many *critical* eyes, an unwarranted fallacy of control. By endorsing the 1.5°C target in 2015, however, in particular poorer nations successfully changed the climatic discourse in their favor, and the orthodox science–politics relationship topsy-turvy. Taken by surprise, climate science had to catch up—rather than inform—climate policy (cf. Livingston and Rummukainen, 2020).

Drawing on feminist geography and feminist political ecology, Sultana (2014) uses her own research in South Asia to show how divisions of labor, cultural norms of "proper" behavior for women, and unequal rights and decision-making power exacerbate women's vulnerabilities and workload when climate impacts hit. Specifically, even in crises certain "lines of work," such as fetching drinking water, remain almost exclusively the burden of women. "Notions of shame, honor, and dignity are strongly enforced by both men and women in maintaining social practices even during disasters," and with it the "[p]roper decorum and constructions of feminized subjectivities result in women being unwilling to associate with unknown men, be alone in public places, and be outside of familiar kinship structures" (Sultana, 2014, p. 376). The combination of women being less likely to seek refuge and male elders not always supporting women in sheltering tragically produces higher mortality rates for women during catastrophes. Consequently, Jost et al. (2016) find that due to such patriarchal factors the adaptive capacity of women is lower than that of men.

Taking an intersectional perspective—a notion that emphasizes that multiple sociocultural strands of influence (e.g., religion, ethnicity, ability) intersect and so produce a person's identities and cultural roles—Carr and Thompson (2014) argue that a binary lens of gender is a too simplistic category to base policies aiming to foster "good" adaptation. Similarly, Ravera et al. (2016) show that identities based on caste, wealth, age and gender produce different adaptation strategies in two Indian states. They show that "a priori assumptions on the basis of male/female dichotomy are unable to lead to a comprehensive understanding of farmers' choices, vulnerability, adaptation process, and barriers to adoption" (Ravera et al., 2016, p. S346). In other words, the intra-gender variability of experiences and adaptation practices is too large to be explained solely by a single binary,

revealing how intersectional thinking can better capture such multi-factorial differences.

Paying close attention to how powerful economic interests influence discourses so as to retain their privileges, Forsyth (2003) elaborates how a "critical political ecology" can help to understand and address the adverse effects "environmental orthodoxies"—widely held inaccurate and simplistic explanations of environmental problems—have when they underpin environmental policies. Motivated by how many policies worsen rather than improve local livelihoods in particular in poorer regions, Forsyth (2003) draws on recent *argumentivist* and *interpretivist* scholarship to trace back how actors and institutions stabilize "environmental orthodoxies" which inadequately underpin many policies and so reproduce local inequalities. Taylor (2014, p. 11) uses such a perspective to critique how simplified and biased the dominant conception—or "discursive apparatus"—of climate adaptation is, with "its grounding notion of climate as an external system that provides exogenous stimulus and shocks to which society must then adapt". Rather, "lived environments" such as rice paddies are "actively yet unequally" produced by interlinked and coupled human and meteorological forces. Such a binary nature–society perspective often successfully veils issues of power and ethics in policies. For instance, talking to Indian farmers about climate adaptation in the orthodox way blanks out that these farmers effectively have to respond to greenhouse gas emissions produced largely by wealthy actors elsewhere, often blaming instead local farming practices as inadequate.

Many critical scholars thus pay attention to how uncomfortable knowledge gets omitted and lost when people stabilize ideas. Chakrabarty (2009, p. 216, emphases in original) asks blatantly "[wh]y should one include the poor of the world—whose carbon foot print is small anyway—by use of such all-inclusive terms as *species* or *mankind* when the blame for the current crisis should be squarely laid at the door of the rich nations in the first place and of the richer classes in the poorer ones?" With such normative efforts of "denaturalising" discourses, critical political ecologists aim to bring into focus—and therefore attention—"the uneven distribution of gains and risks arising from deeply fused social and ecological processes" (Taylor, 2014, p. 16). Similarly, Turnhout et al. (2020) argue that "depoliticising" co-production projects on the actionability of climate knowledge can, when used in unreflective manner, reinforce elite perspectives. Critically reminding that dominant solutions might just be an easy way to shift responsibilities of blame and action elsewhere is thus a key characteristic of political ecologists and like-minded scholars.

Critical scholars understand "high-quality" knowledge as having high revelatory and emancipatory potential for social change (**Table 1**). Such knowledge is often geared around how powerful interests shift the discourse, responsibilities and action in their interests. "Good" adaptation action thus pays tribute to more local experiences and is more inclusive of marginalized sections of populations. Often, too, "high-quality" knowledge aims to promote a more situated understanding of people in their environments (e.g., Latour, 2017).

DISCUSSION: UNDERSTANDING WHY DIFFERENT NOTIONS OF "HIGH-QUALITY" KNOWLEDGE AND "GOOD" ADAPTATION EXIST AMONG THE FIVE *ORDERS OF SOCIAL SCIENCE AND THE HUMANITIES*

This article has compared five distinct ways social scientists and humanities scholars study climate adaptation and climate science, illustrating both different academic perspectives as well as the diversity of social, cultural, and political facets in "adapting climate science" (cf. Skelton, 2020a). However, novice scholars are unlikely to be the only ones potentially baffled how to adequately make sense of and order this diversity. This study shows that grouping by topic, even method, is not always meaningful to understand how, and more importantly why, social science research is driven by different motivations, critiques different elements, and takes different ontological and epistemological positions. The five *orders* portrayed here—*descriptivist*, *pragmatist*, *argumentivist*, *interpretivist*, and *critical*—aim to produce an understanding of the wealth of social scientific thinking, as well as their respective areas of frictions and confluence. In particular, it extends earlier classifications of "paradigmatic controversies" (Guba and Lincoln, 2005) and "modes of thinking" (Freeman, 2016) by showcasing two additional orders common to the study of adapting climate science specifically, and arguably social environmental science more generally: *pragmatists* and *argumentivists*. **Table 1** summarizes the above sections, enabling straightforward comparison of the orders' different aims, concerns, positions as well as different notions of what "high-quality" climate knowledge and "good" adaptation is.

My analysis revealed that what is understood as "high-quality" climate knowledge is different between, yet similar within, *orders* (**Table 1**). Influenced largely by orders' inquiry aim and posture, *pragmatists* favor instrumental, issue-driven, usable knowledge which is able to foster climate action, while *descriptivists*' notion is less activist and more curiosity-driven, aiming to mirror social phenomena. *Argumentivist*, *interpretivist* and *critical* scholarship, however, is united by a more wary stance toward knowledge in general. There the similarities end though, with *argumentivists* in strong favor of explicit treatment of knowledge's uncertainties. For *interpretivists* meanwhile "high-quality" knowledge re-describes—re-orders, so to speak—our stable social practices, often revealing a mismatch between how people express something and how an anthropologist would describe this behavior. To end, for *critical* scholars "high-quality" climate knowledge is emancipatory by being concerned about how dominant discourses mask political, economic and cultural ways injustices, veiling responsibilities and shifting the action imperative to other peoples.

Consequently, the five orders also contrast as to what "good" adaptation is. While for instance *critical* scholars are concerned with emancipatory adaptation which fosters equality and is more

inclusive of people's lived experiences, for many *interpretivists* "good" adaptation is more democratic and less technocratic, with a more succinct acknowledgment of how science helps stabilizing a particular way of "good" adaptation over others, but itself being embedded with value assumptions. Similarly, *argumentivists* emphasize that climate science's uncertainties ought to be appropriately integrated in order to ensure "good" adaptation—often also by emphasizing where and how decision-makers' own value and risk preferences should be center stage. *Pragmatists* have a broader take on "good" adaptation, as one which actually takes place and is grounded in mostly geophysical climate science. *Descriptivists* are less upfront about what criteria are required for "good" adaptation, apart from that measures and policies need to be in place, and effectively reduce geophysical climate risks.

Thus, this research emphasizes that numerous distinct notions of "high-quality" climate knowledge and "good" adaptation exist among social scientists and humanities scholars. Uniting and differentiating features of these five *orders* are diverging aims and concerns—categorical description, knowledge for climate action, knowledge quality check, redescriptions of established patterns, and exposing of power. Interestingly, these aims are mirrored—likely even required to be precipitated—in deeper ontological and epistemological positions. **Table 1** emphasizes that orders favoring social change prefer perspectives which describe their phenomena as something inter-subjectively constructed and delicately maintained collective process—and thus changeable through the subjects' values and norms. Correspondingly, orders more interested to meaningfully describe and/or analyse phenomena require categories to be more stable and less constructed. Similarly, in studying phenomena around "adapting climate science," the five orders also employ methods particularly able to actively produce the insights supporting the order's aim or sharing its concern. In previous scholarship on "research paradigms" (Guba and Lincoln, 2005) or "modes of thinking" (Freeman, 2016), the intricate links as how methodological, ontological, and epistemological positions and research aims largely require and complement each other gets less attention. As this article argues, however, internally consistent links within an order are dominant. This is likely not random. My own experience using data collected in a *descriptivist* and *pragmatist* fashion yet wanting to write in an *interpretivist* or *critical* style was frequently challenging: Too often the qualitative source material was missing which would allow the production of such insights.

Further, these differences have been the source for some misunderstandings and friction between orders (cf. Guba and Lincoln, 2005; Freeman, 2016). **Table 1** gives examples for what a particular order is critiqued and criticized, and by whom. Fault lines appear most often when two orders' key aims not consider each other adequately at best, or remain largely incommensurable at worst. For instance, *argumentivists* frequently take issue with other order's epistemic overconfidence; while *critical* scholars often object to other orders' flippancy as to how scientific knowledge can exacerbate livelihoods and reproduce injustice by legitimizing technocratic rather than democratic governance. However, from my reading, such critiques often reverberate mostly within one's own order, strengthening one's own argument and clarifying one's position—rather than engaging in a constructive way. Still, critique is likely unavoidable, as some differences are not easily resolved. Even if unaware, readers will take cues from the way the text is written, how results are collected and described, and how authors positions themselves within the literature (Dunleavy, 2003). Thus, working toward an order's aims is still mostly taking place within orders, with specializing journals and conferences assisting such specialization.

While some differences in aims and opinions are unlikely to be fully resolved, careful readers will have noted that some social scientists and humanities scholars are associated with more than one *order*, in particular when co-authoring articles. However, more common than such inter-*order* collaborations are cross-fertilizations and learnings between distinct orders. For instance, through a Special Issue, Arnott et al. (2020) collect a variety of perspectives to illuminate a nascent "science of actionable knowledge." Such confluence is particularly visible for the pairs descriptivist–pragmatist and interpretivist–critical, bound by a ontology of how stable or constructed categories are. For the latter pair, this includes for instance attention to ideas' and discourses' "performativity": the effect that language not only describes, but also orders, structures and encodes a particular way of thinking and therefore acting. In practice, such (diagrammatical) thinking "brings to the analytic task a way of reading, or a form of intervening, into this moving matter [of reality]" (Freeman, 2016, p. 105). But characterizing the five *orders* also reveals that learning takes place across this dichotomy. For example, taking input from *critical* scholarship, *pragmatists* increasingly recognize issues of social justice as important in fostering adaptation action (see **Table 1**). Similarly, *argumentivists*' focus on uncertainties in science has helped *critical* scholars to reveal that powerful actors promote, consciously or not, their interests through describing science as being more certain than epistemically warranted.

This classification of social-scientific orders may help to understand where such frustration arise, and while scholars do not need to share another order's opinion, understanding one's own, and other academics' behavior could produce more tolerant reviews and possibly fruitful collaborations. Castree et al. (2014) have argued for the importance of a more socially situated view of climate change. Such a focus would allow to extend the knowledge of human impacts on the environment with a more profound awareness of how these environmental changes produce new—as well as reinforce old—assumptions and conceptions for people's lives and well-being. While both Castree et al. (2014) and Hulme (2011) lament the marginalization, even absence, of the social sciences and the humanities in many scientific climate change discussions, this review also highlights that not all *orders* are similarly interested in collaborating with biophysical climate scientists or assisting climate policies and governance in achieving climate resilience. While some dear-held aims might be at odds with such a collaborative

approach, a more profound understanding of the diversity and wealth of social-scientific perspectives can crystallize the manifold social, political, and cultural dimensions climatic change has.

AUTHOR CONTRIBUTIONS

MS was responsible for all parts of the research, including developing the research question, reviewing the literature, as well as writing and revising the manuscript throughout the peer-review process.

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Does Transformational Adaptation Require a Transformation of Climate Services?

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Cities, regions and countries are increasingly adapting to climate change. Adaptation approaches often build on disaster management activities to deal with climate extremes and make improvements to already existing systems to prepare for climate change, e.g., through water engineering or cooling existing buildings. But ideally, adaptation strategies aim also at tackling the root causes of climate risks through broader sustainable development pathways. Such transformational approaches, however, are still in their infancy. In this perspective paper we argue that there is a lack of guidance to support policy-makers to develop transformational adaptation strategies. There is a need and opportunity to develop climate services that support transformational adaptation. We explore how climate services can support transformational adaptation, drawing from literature, practical experience and illustrative examples. We identify four knowledge requirements: (1) system knowledge to identify the root causes and solutions; (2) inspirational and cross-disciplinary knowledge to develop a long-term vision; (3) a clear climate message and guiding principles to mainstream the vision; and (4) design principles that are connected to the priorities and interests of the stakeholders. We conclude that developing climate services for transformational adaptation involves a delicate process of simplifying and aggregating climate knowledge, as well as integrating it with knowledge about the physical, economic and social systems of cities and regions. This means that climate service providers need to widen their scope and skills, and collaborate with experts in the fields urban planning, landscape architecture, ecology, health, and sociology.

Keywords: climate services, transformational adaptation, long-term planning, system analysis, sustainable development

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INTRODUCTION

Policy-makers need access to climate information to effectively plan for climate change adaptation (e.g., Fussel et al., 2006). Yet developing and delivering science-based climate knowledge that actually supports policy-makers is not straightforward. The divide between research and the valorization of knowledge products has been characterized as a "valley of death" (Markham, 2002). Climate service providers aim to bridge this gap by transforming scientific climate knowledge into "something" societal actors can use (Brooks, 2013; Buontempo et al., 2014; Brasseur and Gallardo, 2016).

Policy-makers increasingly understand the climate change vulnerabilities of their areas and start to plan for adaptation (Biesbroek et al., 2010; Georgi et al., 2016; Aguiar et al., 2018). Adaptation practices often involve incremental changes: addressing single climate risks in targeted sectors (Araos et al., 2016; Aguiar et al., 2018). Such actions consider the short to medium term and mainly aim to conserve the achievements of the past in terms of physical infrastructures and practices. There are less examples of adaptation practices that make fundamental changes to reduce climate risks in the long term and in the context of overall development (Fedele et al., 2020).

Transformational adaptation holds the promise to avoid lock-ins into unsustainable development, by taking a long-term and integral perspective and addressing the root causes of climate vulnerability (Lonsdale et al., 2015; Georgi et al., 2016; Fedele et al., 2019). Yet there is little practical support for policy-makers to adopt transformational approaches, and various authors stress the need for guidance and support (e.g., see Rickards and Howden, 2012; Vermeulen et al., 2018; Chu et al., 2019). Climate services have the potential to support transformational pathways. Climate services entail "The transformation of climate-related data—together with other relevant information—into customized products, such as […] in relation to climate that may be of use for the society at large" (Street, 2016, p. 3). We specifically focus on services for adaptation, which "support the assessment of vulnerability in a wider perspective, and includes the design and appraisal of adaptation strategies" (Goosen et al., 2014, p. 1036).

In this perspective paper, we explore how climate services can support transformational adaptation in practice. First, we introduce our perspective to high-quality climate services (section What Kind of Climate Services Do Policy-Makers need?) and types of adaptation planning (section Adaptation Planning in Practice). Next, we introduce three Dutch examples of transformational adaptation and supportive climate services (section Three Dutch Examples of Transformational Adaptation). Finally, in section Knowledge Requirements for Climate Services That Support Transformational Adaptation we propose four knowledge requirements for climate services and provide suggestions for future climate service practice and research.

WHAT KIND OF CLIMATE SERVICES DO POLICY-MAKERS NEED?

What a policy-maker regards as "supportive knowledge" is different for specific policy-makers and their contexts (Lemos et al., 2012). Policy-makers cover specific policy domains, each having their own traditions of decision-making and knowledge use. Hence they appreciate knowledge differently. Consequently, knowledge quality is often evaluated through analysis of *user perception*, investigating to what extent users perceive the knowledge as salient, credible, legitimate, useful and/or usable (Cash et al., 2003; Lemos and Morehouse, 2005).

These criteria indicate the relevance of co-production for increasing knowledge quality, by generating mutual understanding of needs and possibilities; and by establishing trust (McNie, 2008; Meadow et al., 2015). The reliance on short-term user satisfaction, however, should be regarded as of limited use for the deliberate design of high-quality climate services. We argue that there are knowledge requirements typically relevant for transformational adaptation. Evidently, these general requirements should be translated to specific local actors and elaborated to suit local circumstances. Below, we explore which knowledge requirements can best support the communities producing and using climate knowledge, in order to co-produce high-quality climate services.

ADAPTATION PLANNING IN PRACTICE

There is no archetypical way of adaptation planning (Heidrich et al., 2016). It is driven by various motivations, such as recent climate disasters and political commitments (Aguiar et al., 2018). Some cities however, have started to see adaptation also as an opportunity to increase their attractiveness as livable and resilient cities (Georgi et al., 2016).

When trying to understand the practice of adaptation, an interesting perspective is to regard the rationale from which the adaptation actions come about. We distinguish three broad categories of adaptation: reactive, incremental and transformational adaptation (Georgi et al., 2016). *Reactive adaptation,* or coping, focuses on reducing the negative consequences during and after an extreme climate event. This type of action is common practice in natural hazard management or heatwave protocols. *Incremental adaptation* aims to prevent the negative consequences of climate change by protecting existing infrastructural and social systems. This is a proactive type of action. Examples are increasing the sewerage capacity or placing flood gates at buildings. Reactive and incremental adaptation actions are well-known and commonly applied. In contrast, transformational adaptation remains more elusive in practice, even if the concept is being discussed in the scientific literature. Different ideas exist on what transformational adaptation actually is (O'Brien, 2012; Feola, 2015; Lonsdale et al., 2015). *Transformational adaptation*, in our perspective, is about addressing the root causes of vulnerability to climate risks and about avoiding lock-ins for unsustainable development (e.g., see Fedele et al., 2019). This proactive approach goes beyond minimizing negative impacts of climate change, by the creation of added value, usually demanding more fundamental changes to the existing systems.

Examples of transformational adaptation have been much less reported than reactive and incremental adaptation (Heikkinen et al., 2019; Fedele et al., 2020). An important reason is that barriers for transformational adaptation are larger in comparison to reactive and incremental adaptation. Examples are high investments of time and resources, dealing with a plurality of stakeholders, sectors, and government levels with diverse interests and responsibilities, and divergence from the business-as-usual. Moreover, there is a lack of familiarity with transformational adaptation practices (Fedele et al., 2019). Another explanation for the limited application of

transformational approaches may be found in the way frames and practices can be institutionalized in disciplines or organizations. For example, in policy domains where risk management is the dominant approach (e.g., in environmental, natural hazard, or water management), the range of adaptation solutions that are considered, may be largely informed by a frame that is oriented toward *preventing* the negative consequences of climate change, rather *promoting* positive outcomes (de Boer et al., 2010). Transformational adaptation may require a more positive frame to decision-making, with an integrated approach that identifies opportunities for co-benefits.

Several nuances must be added. Firstly, the distinction between the approaches is not hard. Adaptation actions and strategies can both have reactive, incremental and transformational aspects. For example, greening a neighborhood can be an incremental solution to absorb excess rainwater in a flooding hotspot. But it can also be part of a more fundamental change to improve the cities' sponge capacity and biodiversity. Secondly, we suggest there is no hierarchy between the approaches; a mix of these approaches may be needed to plan and prepare well for climate change risks. The three approaches have different advantages and disadvantages (Georgi et al., 2016). However, the underrepresentation of transformational adaptation may turn out to be costly in the long term, nullifying investments in reactive and incremental adaptation as those solutions may not be sufficient to deal with climate change.

THREE DUTCH EXAMPLES OF TRANSFORMATIONAL ADAPTATION

To illustrate how climate services can support transformational adaptation, we present examples from three local Dutch authorities. We interviewed key policy-makers in the field of adaptation from the municipality of Amersfoort and Rotterdam and the Water company of Amsterdam[1]. We asked them to characterize their adaptation efforts along the three adaptation approaches, and then focused on the transformational elements and the services that have supported them. **Table 1** summarizes the main outcomes of the interviews. In the next paragraphs we describe some key elements that came forward.

In all authorities, the policy-makers recognized the three approaches in their practice and described a mix of reactive, incremental and transformational adaptation efforts in their areas. They recognized transformational approaches in various activities and policies, including a vision addressing the root causes of climate risks, defining long-term system goals, and starting dialogues with citizens. To support these activities, they use climate change information in a variety of forms. We observe two processes that were central to the transformational approaches and that influenced the perception of the climate services that support transformational adaptation: stakeholder engagement and mainstreaming.

Stakeholder Engagement: The examples show that transformational adaptation requires the involvement of a wider group of stakeholders as compared to reactive and incremental adaptation. This includes both involving the wider public and engaging professionals from a diverse set of disciplines. The collaborative processes inform the formulation, concretization and implementation of transformational actions. Stakeholders with diverse knowledge are brought together to increase the understanding of the city's systems and formulate long-term goals. To concretize and implement transformational actions on the shorter term, the policy-makers involve citizens and businesses. The policy-makers use easy-to-understand maps and tools to make climate risks and actions understandable.

Mainstreaming: In all examples, adaptation measures and policies are not carried out in isolation. They are mainstreamed into sectoral policies on green and the environment or they are included in integral programmes on sustainability or resilience. The policy-makers explained that climate information plays a limited role in integrating adaptation in these plans, adaptation is only one of the arguments for action. A clear and simple climate message was used to put adaptation on the agenda.

KNOWLEDGE REQUIREMENTS FOR CLIMATE SERVICES THAT SUPPORT TRANSFORMATIONAL ADAPTATION

Reflecting on scientific literature, the examples and our own experience (Goosen et al., 2014; Swart et al., 2017; Laudien et al., 2019) with supporting local and regional stakeholders in their adaptation efforts, we present four generic knowledge requirements for climate services that may support transformational adaptation processes. The requirements address four broad processes: understanding risks and solutions; vision development; mainstreaming the vision; and implementation of actions by city stakeholders. Thereafter, we discuss implications for evaluating the quality of climate services. We conclude with suggestions for future climate service practice and research.

System Knowledge to Identify Root Causes and Solutions

Addressing the root causes of climate risks is central to transformational adaptation. This requires that the mechanisms underlying the risks are well-understood. Generating knowledge on systems, their history, and dynamics has been identified as an important capacity for transformational adaptation and climate governance (Lonsdale et al., 2015; Hölscher et al., 2019). In the presented examples, especially knowledge on the natural system was used to understand the climate risks and to identify solutions. To offer relevant support for transformational adaptation, climate services should increasingly focus on how climate risks and possible solutions relate to all systems of the city. Policy-makers need a more thorough understanding of how risk mechanisms work over different scales and for

[1]We interviewed five policy-makers that play a key role in adaptation planning. The functions of the policy-makers are: strategic advisor spatial planning (Amersfoort), advisor environmental management (Amersfoort), advisor water, subsurface, and climate (Rotterdam), advisor climate change adaptation (Rotterdam), and strategic advisor water (Amsterdam).

TABLE 1 | Results of the interviews with policy-makers from three local Dutch authorities.

	The municipality of Amersfoort	The municipality of Rotterdam	The Water company of Amsterdam
Adaptation programme	The Amersfoort adaptation strategy is part of the city's Sustainable City Programme. The strategy builds on a long-term regional vision that regards water systems, green areas and the subsurface as one interrelated natural system.	The Rotterdam adaptation strategy is concretized in the programme "Rotterdam Weather Wise" and integrated within the Rotterdam Resilience Strategy. The adaptation strategy aims to establish and maintain a robust water system, recognizing that the city is reaching the limits of resilience of the current systems.	The water company Waternet has been working for years on adaptation together with the municipality of Amsterdam. Recently, the municipality launched its long-term adaptation strategy. The strategy marks the start of an ongoing process where stakeholders of all relevant disciplines and organizations elaborate and flesh out the strategy.
Transformational elements as described by the policy-makers	In addition to reactive and incremental elements, the policy-makers recognize two transformational aspects of the strategy. Firstly, they use the natural system as the guiding principle for planning. This allows them to address the causes of climate risks in an integrated manner. The natural system acts as a backbone; it does not dictate what the future city will look like. A second transformational element is the aim to create added value. They identified "Greening the city" as a major opportunity for multiple goals, including recreation and biodiversity.	The policy-makers explain that initially incremental actions were dominant, for example improving the embankments. Now, the policy-makers indicate that transformational approaches are more common. Firstly, to understand climate risks, the policy-makers began to analyze subsurface and groundwater conditions in relation to the climate risks. Secondly, the policy-makers started a dialogue with citizens on how to redevelop the city. Illustrative for the adoption of the more transformational approach, is how pluvial flooding is addressed. While first "invisible" technical measures were taken, the solutions are now designed together with citizens, sometimes even on their own initiative. This results in more broadly supported solutions that add value for the neighborhood.	The policy-maker recognizes the three adaptation approaches and emphasizes that all are needed. An example of transformational adaptation in Amsterdam is the ambition to green the city and plant more trees. Adaptation became a central theme in their vison for urban green space. However, since Amsterdam's subsurface is filled with cables and other infrastructure, this ambition cannot be realized in the short-term. Another transformational characteristic of the strategy is that it has no specified endpoint, it is rather the start of a collaborative process with stakeholders.
Supportive climate services	The city used various climate services. Examples are climate risk maps and estimated costs of inaction. The city regards climate information in combination with knowledge on the natural system, to better understand the mechanisms of climate impacts and potential solutions. To incorporate adaptation in the Sustainability programme, the policy-makers used a simple vulnerability map highlighting the climate hotspots. They indicated that for reactive and incremental adaptation, factual information is important; investments need to be well-underpinned by technical and economic data. For supporting transformational action however, stakeholders need information that is tailored to their interests and perspectives in a way that it invites action.	To engage professionals and citizens, the policy-makers indicate that information on climate risks and solutions needs to be simplified and translated for the target groups. To reach a diversity of stakeholders, the city develops interactive maps, showing an overview of risks, priorities and opportunities. For the broader public, the narrative must be even more simple and attractive. Providing factsheets is helpful but sharing an appealing vision of the future city may be even more important.	Waternet and the municipality used various climate services, such as localized climate variables and risk maps. The policy-maker indicated that especially for large adaptation investments, they need detailed information to substantiate expenses. Yet in cases where adaptation is only one of the arguments for action, such as greening the city, they need less detailed information. No detailed climate information was fed into the vision on urban green space. The policy-maker stresses that the most important requirement is that the information is tailored to the target audience. While risk diagrams are good instruments to start the conversation with water managers, attractive measures may help to convince citizens to green their neighborhood.

different stakeholders. This includes regarding upstream and downstream areas from catchment scale to local scale and understanding groundwater, ecology, and subsurface processes. However, it also demands an understanding of the social and economic systems, for example by accounting for people's needs, behaviors, values, power relations, and economic opportunities. Next to understanding how the current systems produce risks mechanisms, policy-makers need to generate an understanding of the solutions that can reduce the vulnerability to climate risks. These solutions should have environmental, socio-economic, and cultural features. To support this process, climate services could provide practical knowledge on nature-based solutions and their local suitability. Naturally, to understand the root causes of climate risks does not only require system knowledge, one also needs a knowledge base with knowledge and information about local climate risk and vulnerability characteristics.

Inspirational and Cross-Disciplinary Knowledge to Develop a Long-Term Vision

Transformational adaptation is not something that can be done overnight and by working from a single discipline. It is about redesigning entire areas to address the root causes of climate risks, while at the same time creating added value for the area.

This requires a long-term vision: a collective understanding of the systems that need to be changed and the development pathways that are possible and desirable. Such a vision can be developed in a collective process, engaging stakeholders from a wide range of disciplines including spatial planners, water managers, architects, health care professionals, asset managers, and citizens. To be usable for developing a collective vision, climate and system knowledge must be easily understandable and translatable to the various engaged disciplines. Moreover, a context is needed where stakeholders can pool and integrate knowledge and resources across scales and sectors (Hölscher et al., 2019). This means that knowledge should be offered in a form that facilitates interaction, inclusion, dialogue, and consensus building. This is more easily accomplished with inspirational decision-support tools that stimulate creativity (de Boer et al., 2010). In co-production with the stakeholders, the complex climate risk and system information can be translated into an appealing narrative that connects with the values and objectives of diverse stakeholders. This narrative can be further elaborated and specified in the course of the vision development process. In New York such a narrative was developed in a design competition for green infrastructure to enhance the flood resilience of the area. The outcomes pushed a long-term vision with a new visual identity and the idea to embrace water as an integral part of livability in the city (Trogrlić et al., 2018).

Clear Climate Risk Message and Guiding Principles to Mainstream the Vision

As illustrated with the examples, transformational adaptation is not a stand-alone activity, it needs to be mainstreamed into strategies, policies, and planned development that address other challenges. For adaptation planners to be able to incorporate the transformational vision in policies, strategies, and implementation plans, they must convince colleagues from other sectors to take adaptation into consideration. They need to communicate through clear messages on the climate risks and possible solutions. The examples show that climate information doesn't have a significant role to play here; there is no room for details. Rather, information that is perceived usable for mainstreaming, involves general summaries of climate trends or hotpots and guiding principles. An example of a guiding principle implemented by the city of Shanghai, is increasing the city's sponge capacity with green and permeable pavements as an ecological alternative to deal with flooding and sea level rise (C40 Cities Climate Leadership Group, 2020). Such principles are solution directions that fit the long-term vision, without exactly pinpointing what needs to be done and where. For climate services this means that underlying sophisticated and quantitative climate information needs to be summarized, narrated, and placed in a wider perspective to provide the main message on climate risks and potential solutions. This also means that the technical details, such as uncertainty information, are secondary to the general message. Incremental adaptation often requires quantification of impacts and effectiveness of solutions to underpin large engineering investments. But for transformational adaptation it is more relevant that the information can be connected to the broader environmental, social and economic challenges of the area.

Design Principles That Are Connected to the Priorities and Interests of the Stakeholders

Governments cannot implement the vision alone; they are dependent on the private sector and civil society to concretize and implement actions that redirect developments toward the long-term vision. In order to engage stakeholders to implement actions, both content and presentation method of climate knowledge need to be tailored to the various stakeholder groups. From the examples it appeared that this tailoring mostly means that stakeholders can identify with the knowledge and that it connects to their values and objectives. One way to do this is to explore potential frames that are dominant in the stakeholder groups and that drive their motivation for taking action (de Boer et al., 2010). For example, companies may be activated if they are presented with numbers of estimated losses in case of climate extremes. Citizens however, may be more likely to green their private space when they are pointed to the beauty of green and its value for health. But of course, also within these groups large differences exist.

High Quality Knowledge for Adaptation

We presented four general knowledge requirements for climate services that aim to support transformational adaptation. The requirements were identified by accounting for relevant policy-making processes and for the main principles of transformational adaptation. Evidently, the services that incorporate these knowledge requirements, have an explicit focus and intention to support the identification and implementation of transformational strategies, rather than reactive or incremental actions. This has implications for how we evaluate the quality of these and other services.

Returning to *the section: what kind of climate services do policy-makers need?* we argue that the quality of knowledge in services should not only be evaluated in terms of user or producer perception, but also in terms of the decisions and long-term impacts that follow from using the service. Evaluating the quality of outcomes and impacts, however, is not straightforward; it is difficult to identify how and to what extent long-term information impacts decision-making on the ground (Singh et al., 2018; Tall et al., 2018), and there are fundamental different views on approaches and metrics to evaluate adaptation efforts across actors, space and time (Doria et al., 2009; Dilling et al., 2019; Weichselgartner and Arheimer, 2019).

We therefore suggest, as a first step in evaluating the quality of outcomes and impacts, to make the climate services' underlying assumptions and intentions explicit. There is a multitude of contrasting frames on adaptation (e.g., see Dewulf, 2013), and such frames are also built-in into decision-support tools (de Boer et al., 2010). In turn these frames influence the type of approaches and actions that are promoted. Quality evaluations should make this explicit: what kind of actions

will you identify by using this service? And what actions are consequently not considered? What are the advantages and disadvantages of using this knowledge for drafting an adaptation strategy over different scales of time? Answering these questions would enable to identify risks for maladaptation and overinvestment, when developing and using a service for a specific purpose.

Way Forward

Explicitly developing transformational adaptation plans can help to identify more holistic solutions that are sustainable in the long run. However, this demands larger investments and good sustained collaboration between policy departments and with other stakeholders. This makes transformational adaptation challenging for policy-makers and their advisors: how to reach and engage all relevant groups of stakeholders in an equal manner? How to identify and address the root causes of risks and capture opportunities? And how to establish and flesh out a vision for the future supported by citizens and businesses? This requires a delicate process of simplifying and aggregating climate knowledge and integrating it with other knowledge types to make it comprehensible and supportive to addressing multiple challenges. Climate service providers who aim to support transformational adaptation should therefore widen their scope and connect climate information to other types of expertise, such as urban planning, landscape architecture, ecology, health and sociology. We call for more research on how climate science can be successfully connected to such other disciplines in different real-world situations, to support transformational adaptation.

DATA AVAILABILITY STATEMENT

All relevant data is contained within the article. The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author/s.

AUTHOR CONTRIBUTIONS

EB led the drafting of the paper, with contributions from all co-authors. The interviews with policy-makers were conducted by EB, HG, and FvV.

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Assessing the Quality of Knowledge for Adaptation–Experiences From Co-designing Climate Services in Sweden

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Adaptation to climate change is becoming more urgent, but the wealth of knowledge that informs adaptation planning and decision-making is not used to its full potential. Top-down approaches to knowledge production are identified as one important reason for the gap between science and practice and are criticized for not meeting the needs of intended users. In response to this challenge, there is a growing interest in the creation of user-oriented and actionable climate services to support adaptation. At the same time, recent research suggests that greater efforts are needed to evaluate the effectiveness of knowledge co-production processes and the best criteria by which to gauge the quality of knowledge outcomes, while also considering different stakeholder perspectives. This paper explores these issues through a critical assessment of the quality of knowledge for adaptation generated from a climate services co-design process in two case studies in Sweden. The study draws on experiences from a 5-year research collaboration in which natural and social science researchers, together with local stakeholders, co-designed climate services to support climate adaptation planning and decision-making. The well-established knowledge quality criteria of credibility, legitimacy, saliency, usability, and usefulness remain relevant, but are not sufficient to capture factors relating to whether and how the knowledge actually is applied by climate change adaptation planners and decision-makers. We observe that case-specific circumstances beyond the scope of the co-design process, including the decision-making context as well as non-tangible outcomes, also play crucial roles that should be accounted for in the knowledge assessment processes.

Keywords: natural hazards, co-design, knowledge co-production, Sweden, decision making, adaptation, usability, climate services

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INTRODUCTION

Despite a strong increase in climate change impact and adaptation research and practice over the past decade, the wealth of knowledge and experience is seldom used to its full potential in climate change adaptation planning and decision-making. This gap between research and action (Klein and Juhola, 2014; Palutikof et al., 2019) signals that there is a lack of actionable knowledge to support

adaptation decision-making (Ernst et al., 2019; Mach et al., 2020). Climate services have emerged as a response to the urgent need for more context-specific, user-driven and decision-oriented climate information that can better support decision-making and action on climate change (Vaughan and Dessai, 2014; Daniels et al., 2020). In an ambition to close the science-policy-action gap that appears to hinder climate-resilient development, a growing number of social and behavioral science studies have identified barriers to an effective uptake of climate information in stakeholder assessments and in policy- and decision-making (e.g., Vulturius et al., 2020a,b).

One key barrier identified is the conventional top-down approach to adaptation (e.g., Dessai and Hulme, 2004), or what is commonly framed in terms of supply-oriented or supply-driven climate services (Lourenço et al., 2016; Daniels et al., 2020). Climate information providers have been shown to have incomplete understanding of decision contexts (McNie, 2007) and narrow perceptions of user types (Porter and Dessai, 2017). There is also inadequate attention to the wider decision-making context (Vincent et al., 2018), which involves many pressing concerns beyond future climate impacts, and is shaped by competing interests, decision-making cultures and legitimacy claims (Dilling and Lemos, 2011). Moreover, there is empirical evidence that a scientific approach to, and differential understanding of, uncertainty and technical information may confuse rather than help decision-makers (Patt and Dessai, 2005; Porter and Dessai, 2017; Christel et al., 2018).

Other scholars highlight that relationships between providers and users are often weak or *ad hoc* (Lemos and Morehouse, 2005; Lowrey et al., 2009; Brasseur and Gallardo, 2016). A related concern is that scientific information and its providers lack credibility, legitimacy and trust in the eyes of users (Cash D. W. et al., 2003; Moser and Ekstrom, 2010); decision-makers also underestimate the importance and value of climate information (Cortekar et al., 2017). Other barriers to user-oriented, decision-driven climate services are inflexible institutional rules (Dilling and Lemos, 2011); a mismatch in spatial, institutional and temporal scales of research vis-à-vis decision-making and policy timescales (Bruno Soares and Dessai, 2016; Vincent et al., 2018); as well as underestimation of the value of integrating different knowledge types, from scientific to indigenous (Lemos et al., 2012).

To overcome the challenges of climate information for policy-making and action, recent studies increasingly advocate a transdisciplinary knowledge integration approach (Daniels et al., 2020) where "...researchers and knowledge users meaningfully interact to co-create knowledge that is actionable in decision-making" (Mach et al., 2020, 30). Such an approach has been shown to be useful not only for adaptation decision-making (Vaughan and Dessai, 2014), but for fostering mutual understanding and learning, enhancing the perceived saliency, credibility, and legitimacy of research outcomes; empowering users, motivating them, and increasing their sense of ownership; building trust, creating networks, and boosting institutional capacity (Bremer et al., 2019; Cvitanovic et al., 2019; Gerger Swartling et al., 2019; Schneider et al., 2019; Daniels et al., 2020)

However, it has been challenging to scale up knowledge co-production, learn from practice, and improve approaches because of a lack of reflection and clarity on how the concept is interpreted and applied (Norström et al., 2020); even the terminology is inconsistent. As a first step, there is a need for increased reflexivity and transparency among scholars adopting co-production approaches about how and when they should be used (Bremer and Meisch, 2017; Jagannathan et al., 2020); as well as how to move beyond learning within projects to capture lessons learned across contexts (Lang et al., 2012).

There is a growing literature on achieving high-quality knowledge for adaptation, and this has highlighted the need to better understand how to evaluate the effectiveness of knowledge co-production processes, and what criteria are best used to gauge the quality of outcomes. In this paper we start from the notion of adaptation as a process of continuous learning to build our understanding of a changing climate and adapt accordingly. That, in turn, requires high-quality knowledge to guide effective adaptation action. The aim of this study is to critically assess the perceived quality of knowledge generated from a climate services co-design process to inform adaptation planning and decision-making (i.e., adaptation knowledge), based on how well it meets currently accepted principles of adaptation knowledge quality. The research questions are:

1. To what extent does the adaptation knowledge meet different quality criteria?
2. What factors in the co-design process contributed to the resulting adaptation knowledge meeting those criteria?

We adopt three quality criteria—credibility, legitimacy, and saliency—developed by Cash D. et al. (2003) in studies to identify enabling conditions for high-quality knowledge generation. *Credibility* refers to the trustworthiness of the knowledge as well as its "scientific plausibility and technical adequacy" (Cash D. W. et al., 2003, 4). As noted by Lemos and Morehouse (2005), the process by which the knowledge is produced is important, as practitioners rarely are able to assess the quality of the information *per se*. *Legitimacy* denotes the fairness of the process from a "political and procedural" perspective—that is, that all relevant stakeholders were consulted and that the knowledge is perceived as unbiased (Cash D. et al., 2003; Norström et al., 2020). *Saliency* generally denotes the relevance to user needs (Clifford et al., 2020; Norström et al., 2020). Two other terms describe closely related criteria: *usefulness*–whether the knowledge and information are provided at temporal and spatial scales that match users' practices and needs–and *usability*–whether users can actually access and use the information as it was provided (e.g., online or on paper, in English or in the local language, in complex scientific terms or simple wording) (Lemos and Morehouse, 2005).

To structure our analysis, we also apply an evaluative framework for the co-production of usable climate science, developed by Wall et al. (2017). It is useful for our study because it captures the contributions of a set of indicators associated with the quality of knowledge co-production, covering different components of the process. The indicators include

context-related factors (i.e., input and external factors) that capture "preexisting conditions that may influence researchers' and stakeholders' ability to engage in the co-production of science and ultimately use the information" (Wall et al., 2017, 100). In summary, inputs refer to project setup and the various skills, resources and capacities that both researchers and stakeholders bring into the process, whereas *external factors* refer to circumstances outside the process, including aspects such as staff turnover, political will, and financial resources. Other factors in the framework relate to the *process,* including timing and level of stakeholder engagement, frequency of meetings, etc. Finally, there are three factors—outputs, outcomes and impacts—that gauge different aspects of the results of the process. *Outputs* denote the concrete products of the process (e.g., peer-reviewed articles or technical reports) and their delivery and dissemination. *Outcomes*, the main focus of this paper, involve the actual knowledge produced, evaluated by its perceived credibility, legitimacy, saliency and usability. *Impacts* refers to the actual use of the results, which includes inter alia contributing to problem understanding, instrumental use, confirmational use, motivational use, and factual use, and how it eventually informs adaptation planning and action.

In this paper we start from perceived outcomes of the co-design process and draw on the framework by Wall et al. (2017) to identify components that have been critical to the achievement of the adaptation knowledge quality criteria.

MATERIALS AND METHODS

Description of Case Studies

This paper builds on work carried out in the project HazardSupport, which ran from 2015 to 2020. The project aimed to develop a new, collaborative method for tailoring information about how climate change affects natural hazards, in order to inform adaptation decisions while also generating new scientific knowledge for adaptation for broader dissemination. The study involved providers, intermediaries and users of climate services from the Swedish Meteorological and Hydrological Institute (SMHI) and Stockholm Environment Institute (SEI), as well as municipal officers from Karlstad and the City of Stockholm. HazardSupport employed a co-design process that included focus groups meetings, workshops, interviews, and meetings (**Figure 1**).

The number of case study participants varied over the course of the co-design process (**Table 1**). In total nine municipal officers were engaged in Karlstad Municipality and seven officers were engaged in City of Stockholm. Initially a larger group of participants representing different areas of work were involved, including: technical services and property management, urban planning and building, and fire and rescue services (Karlstad) and; city development, urban development and management, property management, and environmental administration (Stockholm). The rationale was to include a range of perspectives and experiences in the discussions and thereby increase the potential for learning within the group, as well as to ensure the robustness of the final results (e.g., Bremer and Meisch, 2017). However, as the project evolved, a smaller group of key individuals were actively engaged in the project.

In Sweden, municipalities play an important role in planning and implementing adaptation measures. Since 2018 they have been obliged to consider climate risks, and how to minimize or eliminate these risks in the built environment (Government bill, 2017/18:163). Consequently, Swedish municipalities have advanced their adaptation work in recent years (Matschke Ekholm and Nilsson, 2019), yet, municipalities also report that they lack planning and/or decision-support (Sjöberg et al., 2019). The City of Stockholm and Karlstad Municipality are among the forerunners in Sweden, and due to their exposure and vulnerability to water-related hazards, they have comparatively long experience with adaptation.

City of Stockholm Case Study

The adaptation challenge in the Stockholm case study related to the city's rapid growth and urgent development needs. The official target of building 140,000 homes by 2030 (City of Stockholm 2018) is forcing the city to densify and expand. As identified by municipal officers during the initial phase of HazardSupport, this development goal might have implications for the vulnerability of the city to climate change. The city was particularly interested in the use of green infrastructure as a climate adaptation measure. While green infrastructure can be used to address several climate hazards, its role in heat stress mitigation was the focus in this project.

A key question for Stockholm has been to further understand how the city can develop while ensuring that it adapts to current and future climate risks. The main objective of the case study was to investigate (i) how the urban climate will be affected by the expansion and densification of the city, and (ii) the potential of green infrastructure to reduce heat stress during warm summer days.

For this purpose, a dynamic downscaling weather forecast process (Amorim et al., 2020; Gidhagen et al., 2020) was applied to estimate future summer temperatures over Stockholm, based on the development plans for 2030 and 2050. These two scenarios were defined by SMHI in cooperation with representatives from the Municipality.

Model results revealed a warming effect occurring mostly over the urbanized area, closely connected to the expansion/densification pattern, and not widespread over the entire city. In fact, the already dense city center did not show significant changes in air temperature. In terms of magnitude, our results showed a local maximum warming of 1.35°C as an average for the entire summer due to urbanization alone (before accounting for climate change), and the number of hot days per year could increase by 10 up to in 2050. For further details, see Amorim et al. (2020).

Parks showed a cooling effect of a magnitude equivalent to the city's urban heat island. This means that vegetation can help counteract, locally, the human-induced warming of the urban atmosphere, with benefits to the thermal comfort of city dwellers. The case study concluded that in conjunction with urbanization, city planning should prioritize measures that increase access to nature areas, including the connection of public urban green

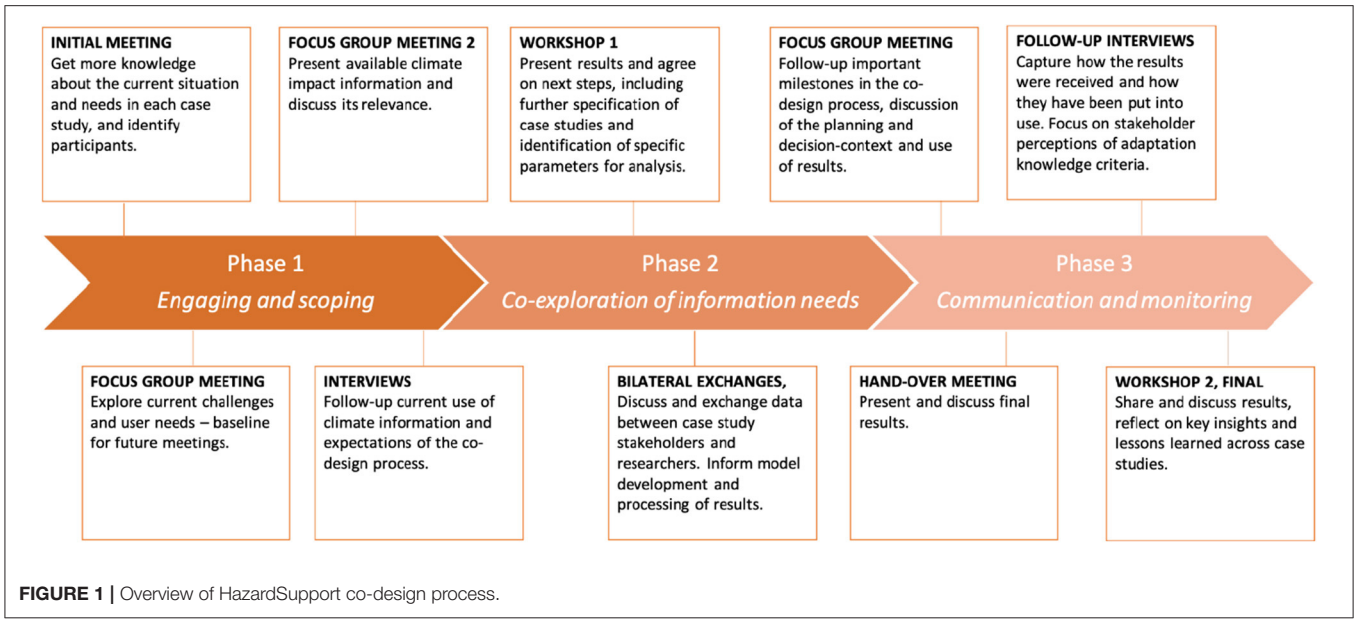

FIGURE 1 | Overview of HazardSupport co-design process.

TABLE 1 | Overview timing of meetings and number of participants.

Meetings and interactions	Timing (number of participants)	
	Karlstad Municipality	**City of Stockholm**
Phase 1: Engaging and scoping		
Initial meeting	Jan-16 (6)	April-16 (2)
Focus group meeting 1	March-16 (6)	Sept-16 (4)
Focus group meeting 2	May-16 (6)	Nov-16 (3)
Interviews	Spring-17 (8)	Spring-17 (4)
Phase 2: Co-exploration of information needs		
Workshop 1	April-18 (4)	April-18 (2)
Bilateral exchanges	2018–2019	2018–2019
Phase 3: Communication and monitoring		
Focus group meeting 3	May-19 (4)	May-19 (2, plus 1 interview)
Hand-over meeting	Jan-20 (3)	April-20 (1)
Follow-up interviews	April-20 (2) June-20 (1) Sept-20 (1)	Sep-20 (3)
Workshop 2	Sep-20 (2)	Sep-20 (2)

spaces through green corridors. This is particularly relevant for vulnerable groups, such as elderly or people who are ill. Lastly, in Nordic cities, such climate-sensitive planning should account not only for the warmest days of the year, but also for the cold and dark season, when sunlight is most desired.

Karlstad Municipality Case Study

In the Karlstad case study, the adaptation challenge in focus was flood protection for the Skåre area, in northern Karlstad. Skåre is an attractive residential area with plans for densification. Situated in the river delta of the large snow-fed Klarälven river, which connects to the nearby lake Vänern, and with the tributary Skårenoret running through the area, Skåre is today subject to multiple flood hazards, including the spring flood of Klarälven and cloudbursts. The issue of flood protection in Skåre reached a critical point in 2016, when flood risks led the County Administrative Board to reject a densification plan for Skåre proposed by the Municipality. In order to continue development in the area, Karlstad initiated a flood defense program for Skåre to investigate and implement a comprehensive flood protection solution, primarily a flood barrier.

To mitigate the threat of flood hazards in the Skåre area, Karlstad Municipality has been investigating the potential for building a flood barrier along the western shore of the Klarälven. The measure calls for studies of potential adverse effects of the flood barrier, such as changes in flood hazards from the Skårenoret inside the planned flood barrier, including cloudbursts evacuating through the Skårenoret.

To meet this need, SMHI used information about current local cloudburst intensity and frequency to gauge the magnitude of the cloudburst hazard for identified durations of one and six (based on Olsson et al., 2017, 2019) and created model simulations of peak flood levels. The analysis concluded that the flood barrier would not increase flood risk from cloudbursts, as any additional water in the Skårenoret could be evacuated with pumping stations near the flood barrier.

For single hazards, the flood barrier would thus be mainly beneficial. However, the multi-hazard nature of Skåre prompted further investigations. The focus was on co-occurrence of extreme floods in river Skårenoret together with a cloud burst. The topic was addressed by looking at the seasonality of the extremes, as well as the meteorological conditions where the extremes occur. The records were limited to about 20 years, but the available data did not show any significant co-occuring events, since the main cloud burst season peaks in July–August, while peak floods in Skårenoret occur in late

autumn. The preliminary conclusion was thus that the co-occurrence of extremes is unlikely. However, the analysis calls for longer time series to set appropriate return levels for such events.

Method (Co-design Process)

The co-design process was facilitated by three members of the research team with experience of knowledge co-production processes, who had the dedicated role to act as intermediaries between case study stakeholders and climate researchers.

The first phase of the project aimed at *engaging* relevant stakeholders within the case studies (see section Description of Case Studies) and *scoping* their current use of and need for tailored climate change impacts information to guide future adaptation planning and decision-making. This included exploring adaptation challenges and the institutional and decision-context as a basis for co-defining questions to address over the course of the project. This was achieved through initial meetings with key contact persons and two sequent focus group meetings with a larger group of stakeholders in each case study. Both focus group meetings were open in character and applied different participatory techniques such as brainstorming exercise and maps to structure the discussions. A survey with free text answers was also conducted with the participants and researchers to gain deeper insight into their expectations of the project and as well as its final outputs and results. Further, semi-structured interviews were completed via phone with a majority of the participants and researchers.

The second project phase focused on refining problem definitions by *co-exploring* case studies' specific information needs, for example, regarding spatial and temporal scales and other parameters such as assumptions of future scenarios. During an interactive workshop preliminary findings were shared with the case studies and used to stimulate the discussions on the direction for developing final results in the form of new scientific knowledge and tailored climate change impact information. In addition, there were a number of email exchanges and phone meetings to follow up and fine-tune the climate information, and to exchange data between stakeholders and researchers.

In the third phase of each case study (*communication* of results and *monitoring* of the process and outcomes), the final results were shared and discussed. Participants' perceptions of the co-design process were also explored at a focus group meeting. This meeting centered around a few key questions covering the following aspects: the interaction and dialogue between case studies and researchers; challenges to the process, as well as how the results related to ongoing activities and adaptation plans. A timeline was also drawn where important milestones to the co-design process were highlighted.

The results were presented at a meeting and summarized in a written report. Stakeholders were given the opportunity to review a draft version, ask questions, and provide feedback. A few months after the final results were shared, stakeholders were interviewed to capture their perceptions of the information in relation to the adaptation knowledge quality criteria. The interviews were semi-structured and, questions included different dimensions of the criteria such as whether and how the results had been used, their relevance, presentation and communication, and perceived (scientific) quality. The co-design process ended with a final stakeholder workshop in which participants from both case studies met virtually with a wider group of stakeholders to share the case study results and reflect on key insights and lessons learned from the project. During a break-out session, stakeholder discussed across case studies, their experiences of the project and the collaboration process that contributed to or hindered the uselessness of the results.

Our analysis builds in particular on detailed notes from the meetings, interviews and final stakeholder workshop carried out in phase 3. First, we deductively applied (Shaw and Holland, 2014) the knowledge quality criteria (credibility, legitimacy, saliency, usability, and usefulness) to the material to assess the extent to which they were perceived to be met by the case study representatives. Secondly, we analyzed the entire co-design process and identified inductively factors that had contributed positively or negatively to addressing the criteria. In this part of the analysis, we also included research teams' observations and reflections. The results were synthesized and related to the evaluation framework by Wall et al. (2017) to highlight the most critical factors in this particular co-design process.

RESULTS

Results are presented in two parts. First, we describe how each of the adaptation knowledge quality criteria were achieved in the case study of City of Stockholm (section Perceptions of adaptation knowledge quality: City of Stockholm) followed by Karlstad Municipality (section Perceptions of adaptation knowledge quality: Karlstad Municipality) and summarized in **Table 2**. Second, most critical factors–representing different elements of the co-design process–that contributed positively or negatively to addressing the criteria are outlined (section Elements of the Co-design process that contributed to addressing the adaptation knowledge quality criteria). See **Table 3** for an overview.

Perceptions of Adaptation Knowledge Quality: City of Stockholm

Results from the modeling of how ongoing urbanization will affect the urban climate of Stockholm were expected to feed into municipal planning processes by providing improved information about the role of climate-sensitive planning, and particularly urban green infrastructure, for heat stress mitigation. Stakeholders stressed that the results from the two scenarios would be particularly useful to enhance awareness and create discussions about the future development of the city.

Credibility

Participants expressed very high trust in both the model results and in SMHI as a state agency and research institution; therefore, the scientific accuracy was taken for granted. For example, one municipal officer noted that "in the context of climate change, there is a high level of confidence in the scientific quality of SMHI and that it is substantiated." This also meant that, given that the municipal staff now have numbers and statistics confirming their

TABLE 2 | Results overview: achievement of adaptation knowledge quality criteria in case studies.

Criteria	City of Stockholm	Karlstad Municipality
Credibility	- High trust in SMHI as a research institution - Appropriate balance between scientific credibility and actionability	- High trust in SMHI as a research institution - Has been a major motivation for stakeholders to participate - Scientific limitations related to multiple extremes, but not perceived as a major problem
Legitimacy	- Not a major concern - Wider stakeholder engagement could have strengthened uptake and use	- Not a concern
Saliency	- Problem understanding, motivational and confirmational use - Used in environmental program to motivate focus on heat stress and green infrastructure - Limited policy attention to heat stress in the Municipality	- Factual, confirmational and instrumental use - Feeds directly into planning process for a flood defense wall
Usefulness	- Results mainly useful to inform planning, but not to evaluate specific interventions	- Useful in relation to a particular location and to a limited number of people in the organization - Timeliness of results important
Usability	- GIS maps accessible format - Clearly articulated conclusions	- Results presented in maps perceived as accessible - High technical capacity required to interpret results

previous assumptions, the results added value to their internal planning processes and increased the credibility of the municipal staff in their communication with other actors (see also Saliency).

Moreover, participants said the results were clearly communicated, and they appreciated that the researchers were not overly cautious in their communication of the results, but instead proposed clear recommendations. They liked that the researchers did not adhere so strictly to standards for scientific credibility during the co-design process that they could not provide information credible enough to use in a planning context.

Legitimacy

Legitimacy was not perceived as a major concern in the City of Stockholm case study. One participant noted though that the group of involved stakeholders had been limited in number, and that it would have been useful to engage stakeholders from different departments within the City, to increase the chances of wider uptake and use of the information. This relates (indirectly) to legitimacy of the process since representation of stakeholders' is one factor that is known to characterize this criterion.

Saliency

Research results were overall perceived as relevant to provide further guidance and to inform practitioners' work on mitigating heat stress through green infrastructure. So far, the results have both inspired and strengthened the content of the local Environment Programme adopted by the City in May 2020 (City of Stockholm, 2020). Participants said the results provided valuable planning support and gave them better arguments for further highlighting the importance of green infrastructure to mitigate heat stress by providing them with a better understanding of the issue. The relevance of the results was also mirrored in their demand for SMHI to disseminate and discuss the results with a wider audience, including other departments within the City administration. At the same time, the results were mainly perceived as planning support, not decision support, which would inform more concrete measures.

The saliency of the results was ensured through the co-design process, in which representatives of the City of Stockholm and SMHI worked together to both define the problem and choose the scenarios. Data were also shared to make sure that SMHI scenarios corresponded to the City of Stockholm's planning scenarios as expressed in strategic documents such as the current master plan.

Usefulness and Usability

Considering the spatial scale of the two scenarios for Stockholm's future urbanization, the results were perceived primarily to be useful for planning and communication. To develop action plans, participants thought more detailed information at the district level would be needed, for example, to be able to estimate the effects of specific measures. However, participants recognized the limitations of the current status of scientific knowledge, and that they received the best available information.

The usability of the results was perceived as positive—for example, the use of GIS maps that showed areas at risk of heating. Participants also said that the results had been communicated clearly and concisely in the report, which made it easier for lay persons to understand them and interpret their implications. In addition to the report, participants also mentioned that the ongoing oral communication via seminars and meetings throughout the project had been helpful in their understanding of the results.

Perceptions of Adaptation Knowledge Quality: Karlstad Municipality

The information developed within HazardSupport was intended to feed into the Municipality's appraisal of a potential flood defense wall in advance of budget and implementation decisions.

Credibility

A main rationale for Karlstad Municipality in participating in the project was to "have some weight going into the discussions with the County Administrative Board. Working with a Swedish administrative authority like SMHI gives that weight." The

collaboration with SMHI, which was perceived as a credible science provider, was thus expected to allow municipal officials to strengthen their arguments on flood protection for the Skåre area in relation particularly to the County Administrative Board.

The knowledge generated through the project was perceived as highly credible by all practitioners from the Municipality, and like the Stockholm case study participants, they saw SMHI research as credible: "We have full confidence in what they have delivered—it is a reliable and trustworthy Swedish administrative authority."

For the data on multiple extremes, the results were based on a short time series, which the SMHI researcher said gave it low scientific credibility (Berg et al., 2019). While the Karlstad Municipality stakeholders had originally hoped to be able to get more solid information on multiple extremes, they appreciated the limitations in terms of what is scientifically possible, and felt they could still use the information provided, even if it was relatively uncertain. Municipal officers noted that "no one else than SMHI can provide this information [on multiple extremes]," and they appreciated getting any information that was "good enough" for their decision-making.

SMHI and Karlstad Municipality agreed at the handover meeting that if the Municipality wanted access to the project data, for instance, to hand it over to consultants for additional analyses, SMHI would provide a contract for the data specifying a best-before-date for its validity. This is because the output data are based on modeling and may lose credibility as modeling techniques improve over time. This solution was suggested by SMHI researchers to maintain their credibility and ensure that no outdated information would be used and further circulated.

Legitimacy

There are no indications that legitimacy has been a concern in the Karlstad Municipality case study.

Saliency

The knowledge provided by SMHI relates directly to an ongoing planning process in Skåre, where the Municipality needs to demonstrate that building the flood barrier would not increase the flood risk within the area it is supposed to protect. SMHI provided Karlstad Municipality with information on return times and probabilities of cloudbursts, and municipal officials said they now have more certainty about the risks associated with cloudbursts. However, the information was not new *per se*, but rather confirmed previous assumptions. The knowledge on multiple extremes was new to Karlstad Municipality, and can be interpreted as a factual (vs. conformational) use of information.

Usefulness and Usability

From a usefulness perspective, the timing of the delivery of results was important for Karlstad Municipality, as the information feeds into an ongoing planning process. There were continuous discussions between SMHI and municipal officers about the time plan for delivering the final results, and the timing of the delivery corresponded to the needs expressed by the Municipality.

With regard to usability, the SMHI researcher gave a presentation and was available for questions in conjunction with the delivery of the final report, at the request of the municipal officers. As the information concerned a relatively narrow and technical topic, some of the stakeholders afterwards said they found it challenging to interpret the information. Results presented in the form of maps of flooding consequences of cloudbursts were perceived as easier to interpret, as municipal officers are used to working with this format. The maps were also useful to address uncertainty, as the Municipality could easily observe that the water levels were far from reaching critical infrastructure. Stakeholders also noted that the conclusions were summarized in bullet points, which was perceived as making the results more accessible.

A Hindsight Perspective on Knowledge Quality Criteria in Karlstad Municipality

At the conclusion of the project, and after the final information had been delivered and followed up, some potential challenges surfaced with regard to the knowledge quality criteria. While it remains uncertain, at the time of writing this article, exactly how the process unfolded, we address some potential, though speculative, explanations below.

After receiving the final results [see Method (Co-design Process)], Karlstad Municipality handed over the data to a consultant for further computations to define the need for installed pump capacity to evacuate excessive water across the flood barrier. At this stage, questions arose relating to the appropriateness of the delimitations in the definition of the catchment area (a *usefulness* concern). In hindsight, there also appear to have been at least partially divergent understandings of what would be delivered within the project, in particular with regard to how detailed the data related to the needed pump capacity would be (a *saliency* concern). This divergence may be related to insufficient articulation of needs at an early stage in the process. High staff turnover may also have been a factor, as new staff members may have entered the project with different interpretations of what had been previously decided, or started at a point in a municipal planning process when new, more specific information needs had emerged. It also appears that the technical nature of the final results, and the fact that not all relevant stakeholders were able to interpret the information at the time of the handover (a *usability* concern), may have contributed to the situation, as some of the issues that later arose might have been possible to solve or mitigate.

Elements of the Co-design Process That Contributed to Addressing the Adaptation Knowledge Quality Criteria

Case Study Information Needs and Path to Use

An important prerequisite in any climate service co-design process is a jointly defined question that is interesting both from a scientific and practical perspective. In HazardSupport, one critical factor as regards the perceived saliency of the results is that both municipalities had an interest and an evident need for improved planning and decision support to advance their adaptation work (IN2).

TABLE 3 | Important factors in HazardSupport co-design process, based on components in the Wall et al. (2017) evaluation framework of knowledge co-production processes.

Inputs (IN)
- Overlap between scientific and practical relevance (IN1)
- Ability to articulate need (IN2)
- Pre-existing relationships (IN3)
- Path to use (IN4)
- Trust (IN5)
Outputs (O)
- Timeliness of report (O1)
Impacts (IM)
- Problem understanding, motivational, confirmational, instrumental or factual use (IM1)
External factors (EF)
- Staff turnover (EF1)
- Policy priority of issue at hand (EF2)
- State of science (EF3)
- Stakeholders' technical capacity to interpret results (EF4)
Process (P)
- Communication and documentation (P1)

Note that trust is not explicitly mentioned under section Elements of the Co-design process that contributed to addressing the adaptation knowledge quality criteria but part of results in sections Perceptions of adaptation knowledge quality: City of Stockholm and Perceptions of adaptation knowledge quality: Karlstad Municipality.

During the first phase of the project, several meetings were facilitated to identify and define case study needs (including decision contexts and current uses of climate information), and how climate researchers could meet those needs given the current status of scientific knowledge and expertise. However, despite stakeholders' good level of understanding of flood-related risks in Karlstad Municipality, it took several iterations and multiple meetings before a decision could be made on which parameters and climatic factors to analyze, which were then refined throughout the entire process.

The presentation of emerging results at a stakeholder workshop in phase two (**Figure 1**) seemed to be instrumental to further define and jointly agree on the next steps. However, as concluded in section A hindsight perspective on knowledge quality criteria in Karlstad Municipality, some questions regarding the scope of the study surfaced after the final results had been shared with the stakeholders. These experiences show that it may be difficult for users to develop an understanding of their needs and priorities as regards climate information. This is a particular concern if users have limited experience with the issue, but can also happen with more experienced users. The co-design process therefore plays an important role to support stakeholders to articulate their needs and to ensure that there is mutual understanding between stakeholders and researchers. Also, circumstances outside the scope of the project (e.g., as internal planning processes progress and needs change, or when the information is used by external actors, in this case a consultant) may change stakeholder perceptions of the saliency of the results.

The path to using the information has been different in the two case studies (IN4). Both internal processes and external events contributed to an increased sense of urgency and relevance of the adaptation challenges (EF2). In Karlstad Municipality, the issue of building a flood defense wall has become more and more concrete as the internal planning process evolved, with increasingly specific information needs as a result. In Stockholm, a severe heat wave that hit Sweden in 2018 functioned as a wake-up call and facilitated internal discussions of the need to consider heat stress in municipal planning. While it is yet an emerging topic in the City's adaptation planning, in comparison with water-related hazards such as heavy rainfalls or flooding, heat stress has gained traction over the course of the HazardSupport project. It was addressed in the new local Environmental Programme, for instance, which has increased the salience of knowledge on heat stress.

In both case studies it was clear that the information developed within the project constituted one piece of a much larger information puzzle for the municipalities. The results gained from the project were combined with other types of information, and connected to a much wider decision-making context in which the climate adaptation aspect was weighted against other concerns, such as budgetary consequences related to the flood defense wall in Karlstad, and the need for housing in Stockholm.

Path to Use Affects Knowledge Quality Requirements

The two case studies represent different uses of climate information (IM1), with implications for how the knowledge quality criteria were perceived. In the Stockholm case study, the results were mainly used to get a better understanding of the adaptation challenge [i.e., "problem understanding use" (sensu Wall et al., 2017)] as well as to motivate the search for more information (i.e., "motivational use"). The new, quantified results from SMHI largely confirmed the users' expectations about the correlation between green infrastructure and heat stress in the city, which reinforced their argument in relation to other parts of the Municipality (i.e., "confirmational use"). The information can be used in a variety of contexts to make the case for addressing heat stress in planning. In Karlstad, on the other hand, the climate information concerned a much more specific, technical question related to the localized flooding implications of building a flood defense wall. This piece of information is needed in a specific planning process and is of limited general interest beyond the specific location. Instead, it is used in an "instrumental" and "factual" way in the sense that stakeholders were provided with more precise data and numbers. Further, though to a minor extent, knowledge about multiple extremes was used to improve their understanding of the problem.

While the direct connection to a specific planning process arguably creates good conditions for generating tailor-made information, it also makes the co-production process and achievement of the criteria more sensitive. For example, in relation to saliency, there is on the one hand a clearly defined need for climate information. On the other hand, this puts higher requirements on the user to clearly articulate the need and for the provider to understand the need and the decision-making context. It is also sensitive to changes in need over time, for instance, as a planning process progresses and the need becomes clearer, or as new colleagues get involved who may perceive the

need differently. This puts high requirements on communication over time, to ensure that saliency is maintained.

Similarly, from a usefulness point of view, the timing of the delivery of results (O1) is much more critical in a case such as Karlstad Municipality, where results need to be delivered in the right phase of the planning process, as opposed to the City of Stockholm case, where results can likely be used over years to come in a range of contexts, such as seminars, presentations, and dialogues. From a usability point of view, the Karlstad Municipality case required quite detailed and specific technical competence (EF4) from the user to be able to interpret and use the information in the planning process, ask for clarifications and adjustments in the data, etc. This is a capacity that only a small number of staff in the Karlstad Municipality had. In the City of Stockholm case, on the other hand, as the results are more generic, they are accessible to a wider group of civil servants or even the wider public.

Continuity, Documentation, and Communication Key in Long-Term Projects With High Staff Turnover

The HazardSupport project spanned a relatively long time period (5 years), which was a prerequisite for doing both research and developing the specific climate information. It also allowed substantial time for running an iterative co-production process. From a scientific point of view, it also allowed for the exploration of new methods and synchronization with other activities that provided necessary information. However, as mentioned in section A hindsight perspective on knowledge quality criteria in Karlstad Municipality the long time span also meant a high staff turnover in the project (EF1), in both case studies and on both the researcher and practitioner side which proved to be a challenge. Especially in Karlstad case study where this seems to have affected the perceived saliency of the information, as well as the usability, as new project members were not aware of how they could access additional information from SMHI. The associated risks related to knowledge quality need to be mitigated with consistent documentation and communication throughout the project (P1).

At the same time, building strong relationships between users and providers of climate information takes time, and from this perspective, 5 years can be seen as solid foundation to further build on. This was for example brought up by stakeholders in the City of Stockholm, who referred to an ongoing exchange and dialogue between officers within the City and SMHI over many years. This meant they had both a preexisting relationship (IN3) and a good level of mutual understanding about needs and capacities, which facilitated phase one of the project and possibly contributed to the high level of credibility and perceived saliency of the results.

Cutting-Edge Research vs. Repackaging Existing Knowledge

An important factor for the co-design process and usability of results, and to ensure buy-in from both researchers and users, was the focus on identifying issues that were interesting and relevant from both a scientific and practical point of view (IN1). This meant that developing the knowledge base to inform adaptation planning and decision-making was the purpose, rather repackaging existing scientific knowledge into a practical tool or service. However, as the co-design process evolved, stakeholders expressed a need for specific and tailored data, which were difficult to deliver as the issues in focus were at the cutting-edge of science (EF3) e.g., as regards multiple extremes in Karlstad Municipality. Balancing the demands for achieving scientific and practical outcomes was challenging from the researchers' point of view as it was difficult to predict the exact outcomes of the research process. The capacity to develop information at relevant scales and with very high resolution—required by stakeholders for decision-making—was therefore limited.

DISCUSSION

In this section, we discuss the results with a focus on the relevance and interrelatedness of the criteria, as well as the need to consider context-dependent factors in the assessment. Then we discuss the need to capture additional dimensions of the co-design process that could further our understanding of how to achieve actionable adaptation knowledge as well as associated non-tangible outcomes.

Knowledge Quality Criteria Are Interrelated and Context-Dependent

First, the analysis showed that all criteria were relevant, and were all, except legitimacy, actively addressed in interviews with stakeholders. Saliency seemed to be the most critical criterion to the co-design process and to how stakeholders perceived the quality of the adaptation knowledge. This is likely explained by the characteristics of the project, with its emphasis on developing new knowledge to inform adaptation planning and decision-making, as opposed to new tools or repackaging of existing information. As discussed under section Cutting-Edge Research vs. Repackaging Existing Knowledge, this focus was driven by stakeholder needs, which required new scientific knowledge.

It is also worth noting that the two case studies differed in terms of the specific adaptation challenges and natural hazards at hand, which meant that they needed information at different levels of detail. For the City of Stockholm, the primary use was for awareness-raising, whereas Karlstad Municipality needed specific information to feed into a planning process. This difference related to saliency spills over into the other knowledge criteria, which become more critical as saliency requirements become more specific. Going forward (especially in the City of Stockholm), tools to assess and implement measures at the district level will be needed, and the usability and usefulness of the adaptation knowledge will likely be more critical. However, if the saliency criterion is not fulfilled, it is unlikely that the other criteria will be met.

We also note that the saliency criterion benefited from the structure of the co-design process (c.f. de Vente et al., 2016) particularly the first phase, which helped to ensure a mutual understanding of needs, capacities, and limitations. The literature also highlights the importance of jointly defining the problem,

which is a critical part of setting the right conditions for a successful co-design process (c.f. Hegger et al., 2012; Jagannathan et al., 2020; Norström et al., 2020).

It is also clear from our results that the criteria may be interpreted differently among researchers than among practitioners (c.f. Hegger et al., 2012). Specifically, stakeholders in the City of Stockholm said the results were credible enough for use in planning, even if they did not, at the time, meet standards for scientific credibility. They appreciated that researchers shared results during the co-design process that were salient to the Municipality—a sign that a good balance was in this case struck between credibility and other criteria.

Moreover, the results in this study indicated that context-specific factors can affect the relevance of the quality criteria. As noted in the cases studies, the trust in both the knowledge provided and SMHI as knowledge provider was very high, and in 2020, SMHI was ranked as the national agency in Sweden with the highest reputation (Orbe and Sjörén, 2020). This does not mean that the credibility criterion was irrelevant, but its greatest importance was at the outset, laying a foundation for the collaborative process and making it more attractive for stakeholders to join.

The legitimacy criterion does not appear to have been an issue in either case. It is worth noting that both case studies took place within local government administrations under democratic control, which may explain why legitimacy did not surface as a concern. The subjects of the studies were also relatively uncontroversial, and climate change concerns are now commonly addressed in Swedish municipal planning (Matschke Ekholm and Nilsson, 2019). This may also reduce the importance of both credibility and legitimacy concerns in this context. If the legitimacy and credibility criteria were not met, it would probably negatively affect the perceived saliency. For example, participants clearly saw the high credibility of the adaptation knowledge as particularly useful and something that added value to their own work to further motivate and communicate the need for adaptation measures, especially in dialogue with other actors, such as decision-makers.

Decision-Making Contexts and Non-tangible Outcomes Matter

Our findings showed that all five criteria—credibility, legitimacy, saliency, usefulness, and usability—are relevant to assessing the quality of knowledge for adaptation. Together, they capture a range of interconnected features that are all necessary to the development of scientific knowledge that can support adaptation planning and decision-making. However, the criteria are not sufficient to understand whether the knowledge is indeed perceived as *actionable* by actors responsible for its implementation. The step of actually putting information into use hinges on other factors beyond the scope of the co-design process. Our results illustrate that the adaptation knowledge needs to be aligned with existing planning tools and processes and combined with other types of non-climate-related information.

The climate information itself is only one of many considerations for practitioners (as also noted by Klein and Juhola, 2014), and understanding whether knowledge is actionable requires an assessment of the broader planning and decision-making contexts, typically looking beyond climate change adaptation issues *per se*. The fact that the two municipalities' evolving internal processes and external events affected the perceived saliency of the knowledge over time suggests a need to iteratively assess the planning and decision contexts as the co-design process evolves. Furthermore, as suggested by Hansson and Polk (2018) in the context of transdisciplinary research, additional stakeholders may be involved in the actual use of adaptation knowledge, and they may have different perceptions of its quality than those directly involved in the co-design process. Thinking upfront about a potentially broader user base could help project leaders to identify additional participants whom they might want to include in the co-design process. To consider context-based factors in the assessment of knowledge co-production processes is also necessary, as proposed by Norström et al. (2020).

Though it is too early to assess the long-term impacts of the co-design processes in these two case studies, we note the potential for important intangible outcomes as well, such as shared learning, capacity-building, and long-term relationships that then help increase stakeholders' adaptive capacity. Our analysis showed that the knowledge quality criteria did not fully capture these long-term and more intangible effects [what Jagannathan et al. (2020) refer to as community outcomes]. As crucial as it is to meet the knowledge quality criteria in order to bridge the gap between science and practice, other process-oriented values, such as "mutual interest in longer-term collaboration" (Wall et al., 2017), can contribute to that objective in the longer term, and can play a key role in supporting adaptation planning and action beyond an individual project. Further, Reed et al. (2021) note the complexity of measuring and attributing policy impacts of research and point to the need to consider both positive and negative effects as well as tailoring the impact evaluating design with "aims and context of the evaluation."

Along with meeting the quality criteria, we therefore suggest, similar to Daniels et al. (2020) and Beier et al. (2017), that, to be most effective the co-production of knowledge for adaptation should focus not primarily on standalone projects and knowledge products, but rather on processes in which decision contexts, needs, goals, and capacities are fully appreciated. To consider context-based factors in the design of participatory processes is further acknowledged by de Vente et al. (2016). Such a process-centric, transdisciplinary knowledge integration approach to climate services has shown to support a shared understanding of a problem, build trust, capacity, and confidence to engage in unfamiliar knowledge spaces, and, in turn, strengthened relationships and networks over a longer timeframe (Daniels et al., 2020). The co-design process in this study shows great potential for that approach. The project benefited from building on long-term relationships that underpinned the development of the knowledge base. Going forward, those relationships can provide a strong foundation on which to build strategies and policies and co-produce additional knowledge as needed.

CONCLUSIONS

This study shows that the proposed knowledge quality criteria, and in particular the saliency criterion, are relevant yet insufficient to fully capture whether and how adaptation knowledge is perceived as actionable. Our findings suggest that the criteria do not capture the wider decision-making context that in turn affects stakeholders' perceptions of the quality of the knowledge and their ability to apply it to adaptation planning and decision-making. Further, the criteria overlook important long-term and intangible effects of the co-design process, such as strengthened relationships, networks learning and capacity.

These conclusions point to two key ways to improve both the knowledge co-production process, and the criteria used to assess the quality of its outcomes. First, we observe a need to design knowledge co-production processes that consider the wider decision-making context to the greatest extent possible, and this ought to be captured in the adaptation knowledge quality assessment. Second, in the design and consequently the quality assessment, non-tangible outcomes should also be considered and acknowledged. For example, it matters whether the work created conditions for long-term engagement and building relationships, trust, and mutual learning. Such outcomes may be critical to the success of the adaptation process—and in the process, they may improve the quality of the adaptation knowledge itself.

DATA AVAILABILITY STATEMENT

The datasets presented in this article are not readily available because it contains confidential data. Requests to access the datasets should be directed to corresponding author.

ETHICS STATEMENT

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. Written informed consent for participation was not required for this study in accordance with the national legislation and the institutional requirements.

AUTHOR CONTRIBUTIONS

KA: conceptualization, methodology, validation, formal analysis, investigation, writing—original draft, writing—review & editing, and funding acquisition. LJ: conceptualization, methodology, validation, formal analysis, investigation, writing—original draft, and writing—review & editing. ÅGS: conceptualization, methodology, validation, investigation, writing—original draft, writing—review & editing, and funding acquisition. PB: validation, writing—original draft, and writing—review & editing. DS and JHA: validation, writing—original draft, writing—review & editing, and funding acquisition. LS: validation, writing—review & editing, and project administration. All authors contributed to the article and approved the submitted version.

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Quality Assessment in Co-developing Climate Services in Norway and the Netherlands

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Climate services, and research on climate services, have mutually developed over the past 20 years, with quality assessment a central issue for orienting both practitioners and researchers. However, quality assessment is becoming more complex as the field evolves, the range and types of climate services expands, and there is an increasing appeal to co-production of climate services. Scholars describe climate services as emerging from complex knowledge systems, where information moves through institutions and actors attribute various qualities to these services. Seeing climate services' qualities as derived from and activated in knowledge systems, we argue for comprehensive assessment conducted with an extended peer community of actors from the system; co-evaluation. Drawing inspiration from Knowledge Quality Assessment and post-normal science traditions, we develop the Co-QA assessment framework; a checklist-based framework for the co-creation of criteria to assess the quality of climate services. The Co-QA framework is a deliberation support tool for critical dialogue on the quality of climate services within a co-construction collective. It provides a novel, structured, and comprehensive way to engage an extended peer community in the process of quality assessment of climate services. We demonstrate how we tested the Co-QA—through interviews, focus groups and desktop research—in two co-production processes of innovative climate services; an *ex post* evaluation of the "Klimathon" in Bergen, Norway, and an *ex ante* evaluation for designing place-based climate services in Dordrecht, the Netherlands. These cases reveal the challenges of assessing climate services in complex knowledge systems, where many concerns cannot be captured in straight-forward metrics. And they show the utility of the Co-QA in facilitating co-evaluation.

Keywords: climate information, knowledge system, co-evaluation, post-normal science, extended peer review

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INTRODUCTION

The field of climate services is establishing itself as important for, "*the provision of climate information in ways that supports decision-making through engagement with the users of that information*" (Bruno Soares and Buontempo, 2019, p. 4). The past 15 years has seen a rush of climate service-labeled initiatives—both public and private—to translate and transfer scientific climate

information for use in various institutions worldwide (Vaughan et al., 2018); from French utility giant EDF (Bruno Soares and Dessai, 2015), to small groups of African farmers (Tall et al., 2018). One important challenge remains how to *assess the quality* of this information, where "quality" is related to, "both the different types of uncertainty in knowledge and the intended *functions* of the information" (Funtowicz and Ravetz, 1993, p. 740). When scientific knowledge is used for informing societal decision-making, its quality should thus not only be assessed according to the *internal* epistemic norms of the scientific community, but it should also be assessed according to its *external* "fitness for function" (Craye et al., 2005). Indeed, efforts to better link science production and use have seen a multitude of initiatives to "co-produce" climate services [e.g., Bremer et al. (2019c) and Vincent et al. (2018)], leading to a more fluid situation around who or what the producers, users, forms, and purposes of climate services might be.

The challenge is how to recognize and appraise quality in uncertain and malleable information, which travels through various institutions and is interpreted toward different ends (implying changing functions of knowledge use) along the way. In a research institution, the quality of "normal" disciplinary science is established by a bounded, somewhat stable, and largely agreed set of epistemic norms and criteria, through standards of good scientific practice and peer review procedures. But deploying scientific climate information "outside the lab," to support climate-related decisions characterized by uncertainty, plurality, high stakes, and urgency, opens up for fundamentally new norms of quality (Funtowicz and Ravetz, 1993). Knowledge quality criteria become unbounded, highly unstable, and contentious.

Notwithstanding these challenges, scholars argue it is important to assess climate services quality in order to: (i) develop information that is fitted to institutions' functions and problems; (ii) demonstrate the particular outcomes, impacts, and added value for an institution; (iii) justify public and private investment; and (iv) distill lessons for climate services scholarship and practice, including lessons on evaluation itself (Tall et al., 2018; Bruno Soares and Buontempo, 2019; Vaughan et al., 2019b; Lemos et al., 2020). Reviews show that evaluation is becoming more commonplace in climate services initiatives but that there are varying levels of commitment and no commonly accepted approaches or frameworks, with a consequence that many evaluations adopt a narrow perspective on quality that assesses a subset of qualities (Vaughan et al., 2019a, b; Tall et al., 2018). Very often this sees a division between *either* assessing information's scientific rigor ("getting the science right") *or* some measure of its use ("getting the science used"); something which arguably reinforces a disconnect between science and policy/practice and reifies dichotomous and simplified categories of science "providers" and "users." It also creates a blind spot around other relevant qualities of climate services; cultural, social and ethical.

Here we offer a fresh perspective and approach to the challenge of assessing climate services' *quality*, as distinct from the work on *value* (Ford et al., 2013; Vaughan and Dessai, 2014; Meadow et al., 2015; Vogel et al., 2017; Wall et al., 2017; Vaughan et al., 2019a). We adopt a perspective that climate services emerge from and travel through context-specific "knowledge systems" of institutions and actors (Buizer et al., 2016), accumulating diverse characteristics or qualities in the process; from scientific rigor to practical usefulness, political legitimacy or cultural appropriateness for instance. And that these characteristics are bundled in unique configurations—and politically contested—by actors in institutions appraising the quality (or fitness) of climate services for particular functions. From this point of departure, our research was steered by the question: *how can we comprehensively identify the characteristics associated with a climate service which determine its quality for particular functions in a particular context?* This question in turn translates into the two aims of our research and this paper: to (i) develop a framework for identifying climate services' characteristics in order to collaboratively assess their quality; and (ii) test the framework through cases to study how it supports climate service assessment.

Section Assessing the Quality of Climate Services starts from our argument that climate service assessment tends to focus either on products' inherent scientific quality conferred in the lab, or relative to the various standards of use that differ across institutional spheres. We join others (Meadow et al., 2015; Vincent et al., 2018) in recommending more comprehensive and rounded assessment of the constitutive qualities of products, in collaboration with an "extended peer community" of actors in a knowledge system. Section Knowledge Quality Assessment and the Co-QA Assessment Framework suggests that the field of Knowledge Quality Assessment offers insights into comprehensive and collaborative assessment, and goes on to present the novel Co-QA (Collaborative Quality Assessment) framework. Section Case Studies and Methods demonstrates how we implemented the Co-QA framework in two case studies of different climate services; an *ex post* evaluation of the "Klimathon" in Bergen, Norway, and an *ex ante* evaluation for designing place-based climate services in Dordrecht, the Netherlands. Both cases were conducted in the context of the European Research Area for Climate Services project "Co-development of place-based climate services for action" (CoCliServ). Section Results: Assessing Climate Services and the Co-QA Framework presents the findings of these evaluations, including an appraisal of how the framework performed in each case study, before Section Discussion finishes with some commentary on the framework, and on the wider importance of comprehensive and bottom-up "co-evaluation."

ASSESSING THE QUALITY OF CLIMATE SERVICES

In conceptually framing our research we adopted a perspective held by some climate service scholars who see climate information as emerging from and traveling through complex and heterogeneous "knowledge systems" (Kirchhoff et al., 2013; Bruno Soares and Dessai, 2015). Buizer et al. (2016, p. 4598) discuss knowledge systems as, "networks of linked actors, organizations and objects that perform a number of

knowledge-related functions [. . .] involved in linking knowledge and know-how with action." This echoes the classic work of Star and Griesemer (1989) who described such systems as ecologies of intersecting institutions, or social worlds, wherein actors attribute different meanings and uses to scientific information and variously appraise its qualities. An example of one such climate knowledge system is the Norwegian flooding simulation described by Bremer et al. (2019c), which was commissioned by a utilities company, derived from data of the Water and Energy Directorate, produced by a consultancy, and deployed in public fora, as part of a municipality policy process.

Within knowledge systems, Star and Griesemer (1989, p. 388) noted, "scientific actors face many problems in trying to ensure integrity of information in the presence of such diversity." Information is re-interpreted and re-packaged as it travels and is translated to the particular institutional rules, norms and cultures that it passes through [see Scott (2014)]. These problems of knowledge quality are amplified when knowledge systems face "wicked" (Rittel and Webber, 1973) or "post-normal" (Funtowicz and Ravetz, 1993) problems like climate adaptation. Under conditions of high uncertainty and high stakes, quality is not universally agreed or inherent to information products. At best, quality is contingent on knowledges fitness for particular functions, opening up for nearly infinite possible quality criteria, always in flux as our understanding of the problem evolves (Funtowicz and Ravetz, 1990). The status of climate services can change as they travel in a knowledge system; they may remain "information" or become interpreted and enacted as knowledge, or as more diffuse understandings.

Under these conditions, what does it mean to talk about the quality of climate information? There is an enduring tradition of appraising knowledge as "justified true belief," but as post-normal science scholars (Funtowicz and Ravetz, 1990, 1993) point out, where knowledge faces high stakes problems characterized by significant uncertainties, like the future of climatic change, its approximation to the "truth" ceases to be a universal standard of quality. This opens up for a plurality of more context-specific standards—political, cultural, practical and so on—by which knowledge's quality can be appraised and trusted, relative to the problem at hand. As such, the post-normal science perspective sees knowledge quality as determined via plural standards, but with a common concern for its *fitness for the purpose* of addressing a problem. Deciding which standards of quality should be deployed in assessing a climate service is then a highly political choice of which characteristics of knowledge or information are most important for supporting climate adaptation; is it their conforming to rigorous scientific methods? Their political expediency? Their practical implications? We see scholars and practitioners have adopted three broad approaches to determining climate services quality.

In one set of articles, a climate service's quality mainly corresponds to its *scientific robustness* as determined by normal disciplinary peer review and widely accepted standards of good scientific practice (epistemic norms), and typically discussed as data pedigree and predictive skill. Here quality is determined by the logics of scientific disciplines and their standards of what constitutes rigorous methods and data collection, upheld by recognized scientists in those fields. When a product like a seasonal forecast is deemed scientifically robust, the main concern then is that this information is not "distorted" as it moves through a knowledge system (Vaughan et al., 2019a). Like "immutable mobiles" (Latour, 2005), large, centralized climate information providers such as the European Center for Medium Range Weather Forecasts (Bruno Soares and Dessai, 2015), or Copernicus Climate Change Service (Perrels, 2020) issue "standardized packages" (see Fujimura, 1992; also Kirchhoff et al., 2013) of data, information and tools. Quality is thus attached to scientific standards, and travels with the information (Vaughan et al., 2019b).

A second set of articles sees a climate services quality corresponding to its *plasticity* for being adopted and used across different institutional settings, like a "boundary object" (Kirchhoff et al., 2013; Meadow et al., 2015; Buizer et al., 2016). For Star and Griesemer (1989, p. 393) boundary objects satisfy disparate information requirements in different institutional settings, "plastic enough to adapt to local needs [. . .] yet robust enough to maintain a common identity." Seen this way, quality is assessed relative to whether people recognize it as useful and useable according to the particular standards of use in each institution (Dilling and Lemos, 2011). For instance, a seasonal forecast's use will be differently appraised by meteorologists than by an insurance company calculating its losses, or a farmer timing her harvest [see e.g., Tall et al. (2018), Vaughan et al. (2019a,b), and Bouroncle et al. (2019)]. From this standpoint, users are in the best position to determine quality; either through their voiced preferences, or through other metrics of "impact," like the uptake of a climate service. But by focusing on what each group makes of climate information, such assessment arguably misses a more holistic appreciation of a product's provenance and the diverse qualities it has inherited from the knowledge system, which need to be considered and weighed together. For instance, many studies evaluate a product's scientific qualities separately from its use and impact (Vaughan et al., 2019a), though the importance of having widely used products based on robust data is obvious. Assessment in this tradition is not totally siloed though. Inspired by Lemos and Morehouse's (2005) ideas of co-production as "iterative interaction," there is work to improve climate services' use through collaboration between actors in a knowledge system, ranging from loose feedback loops and consultation on "what works," to tight-knit efforts for co-creating services tailored to particular groups (Vaughan and Dessai, 2014).

A third set of articles seeks a more *comprehensive and rounded account* of the diverse qualities accumulatively attributed to climate services in a knowledge system, integrating a broad suite of criteria (Cash et al., 2006; Vaughan and Dessai, 2014; Meadow et al., 2015; Vincent et al., 2018). This perspective distinguishes between the different *types* of qualities bound up in a product—see e.g., distinctions between credibility, legitimacy, and salience of Cash et al. (2003)—and recommends considering these qualities together. Resembling approaches to post-normal science, quality assessment becomes a process of weighing imperfect information's various characteristics, including its scientific rigor and practical use, in determining its fitness for certain functions. Because high quality climate services

are more than just scientifically robust, or flexible in use. They fit institutional logics (Harjanne, 2017), connect with institutions' risk perception (Bremer et al., 2019b), nurture relationships (Haines, 2019), empower vulnerable groups (Daly and Dilling, 2019; Turnhout et al., 2020), facilitate social learning (Vanderlinden et al., 2020), link up with histories and identities (Bremer et al., 2020; Krauß, 2020; Marschütz et al., 2020), and appreciate climate as part of other pressing concerns of communities (Baztan et al., 2020), to name a few characteristics. From this standpoint, a number of authors have assembled frameworks comprising criteria of the inputs, process, outputs, outcomes, and impacts of climate services (Meadow et al., 2015; Vogel et al., 2017; Wall et al., 2017), with others linking categories of context, process, products and value (Vaughan and Dessai, 2014). Most of these frameworks (e.g., Ford et al., 2013) are filled with quality criteria drawn "top-down" from the scholarship, but other scholars have argued that comprehensive quality assessment is best conducted in collaboration with actors in a knowledge system, voicing their own "bottom-up" quality criteria specific to their context (Cash et al., 2006; Meadow et al., 2015; Vincent et al., 2018) as an "extended peer community" (Funtowicz and Ravetz, 1993). This can be intertwined with co-designing research with peer communities, with quality questions often a recurring theme in putting together citizen science initiatives for instance (Bremer et al., 2019a; Wildschut and Zijp, 2020).

Adopting the perspective that climate services qualities are derived from and activated in complex knowledge systems, we see that climate services can have different types of qualities, and argue with others that these ought to be comprehensively "co-evaluated" by actors of the knowledge system. But Vincent et al. (2018) and others have noted that there are few examples of such co-evaluation to date. We aimed to develop a framework for unpacking climate services' characteristics for co-evaluation and turned to the field of Knowledge Quality Assessment as a guide.

KNOWLEDGE QUALITY ASSESSMENT AND THE CO-QA ASSESSMENT FRAMEWORK

Knowledge Quality Assessment (KQA) offers frameworks and approaches for more comprehensive co-evaluation of climate services. KQA is an emerging field of practice at the interface between knowledge and action that seeks to systematically reflect on the strengths and limitations of knowledge in relation to its fitness for function (Clark and Majone, 1985; van der Sluijs et al., 2008). Function can be, for instance, informing a local climate adaptation decision-making process. KQA comprises systematic analysis of, and critical reflection on uncertainty, assumptions and dissent in scientific assessments in their societal and institutional contexts; in knowledge systems (van der Sluijs et al., 2008; Haque et al., 2017). It includes critical analysis of underlying methods and implicit and explicit narratives in scientific assessments (Saltelli et al., 2020b). The goal of KQA is to enhance societies' capacity to deal with uncertainties surrounding knowledge production and knowledge use in the management of complex sustainability issues (van der Sluijs et al., 2008).

In their seminal paper "The Critical Appraisal of Scientific Inquiries with Policy Implications," Clark and Majone (1985) presented one of the first comprehensive frameworks for quality assessment at the science-policy interface. The framework acknowledges that each actor that has a stake in quality control in a knowledge system, has a different *role* in the process of critical evaluation. For instance, scientists will emphasize other criteria in quality control than policy-makers. Their taxonomy distinguishes three general *modes* of critical appraisal: the input, the output and the process by which inquiry is conducted. Input refers to data; methods, people, competence, and (im)matureness of field for instance. Output relates to questions such as whether the problem is solved and the hypothesis tested. Process concerns issues such as good scientific practice, procedures for review, documenting.

Other well-developed KQA tools and frameworks in the literature include the Numeral Unit Spread Assessment Pedigree (NUSAP) notational system for qualifying quantities (Funtowicz and Ravetz, 1990; van der Sluijs, 2017); the six reflective lenses framework for auditing narratives of sustainability (Saltelli et al., 2020b); the five principles for responsible use of models in policy support (mind the assumptions, hubris, framing, consequences and unknowns; Saltelli et al., 2020a); and the checklist for systematic critical reflection on uncertainty and quality in scientific assessments implemented at the Netherlands Environmental Assessment Agency (Janssen et al., 2005; van der Sluijs et al., 2008; Petersen et al., 2011, 2013). The latter systemizes critical reflection on uncertainty and quality in six crucial phases in the process of mobilizing knowledge for action: problem framing, stakeholder involvement, indicator selection, appraisal of the knowledge base, mapping and assessment of relevant uncertainties and communication of uncertainty information.

Because none of these existing frameworks is fully fit for application in a setting of co-production of climate services, in this paper we present a new tool for knowledge quality assessment—the *Collaborative Quality Assessment (Co-QA) framework*. Co-QA extends on Clark and Majones original comprehensive framework, tailored for deliberation support in the co-production of climate services in extended peer communities. The tool is documented in more detail in a scientific report (Van der Sluijs and Bremer, 2019). The framework assists in the co-production of relevant criteria to assess knowledges quality—fitness for purpose—relative to particular climate service projects, or instances when climate knowledge is used for responding to a discrete problem or question or task. It is not suited to a general assessment of climate knowledge, at a national scale for instance. Knowledge quality, as employed here, takes as its reference point the particular and contingent purpose or function for which climate knowledge is mobilized.

Co-QA is an open framework, which is collaboratively filled out by actors interested in a climate service during a focus-group. Alternatively (or in combination), actors can be interviewed individually to elicit quality criteria that are important from their perspective. The resulting framework is ultimately completed in cooperation with others, as a way of bridging knowledge quality expectations across all actors in a knowledge system. Inspired by Clark and Majone's (1985) framework, it distinguishes *critical*

TABLE 1 | The Co-QA deliberative tool.

Critical mode Critical role	Input (and context)	Process	Output	Use
Actor 1				
Actor 2				
Actor 3				
Actor 4				
…				

The table is filled in with criteria that are important from each actor's perspective for quality assessment of each of the critical modes of the climate service at hand. The rows represent different actors and quality assessment criteria that are important from their perspective. The columns represent the different critical modes.

roles and *critical modes*. The roles, referring to the ways different actors interact with a climate service, can vary from case to case and for instance include scientist, peer group, policy maker, funder, public interest group. It distinguishes the same critical modes as the Clark and Majone framework (input, process, output) but we have added a fourth critical mode: use, because our framework should not only address the step of the co-creation of climate services but should also include quality appraisal of their use in institutions in a knowledge system. This creates a two by two matrix with critical roles heading the rows, and critical modes the columns.

In filling out the framework (**Table 1**), actors discuss and register in the matrix cells their perspective on important quality criteria at each critical mode, or phase, of producing and using a climate service. Put another way, it dynamically unpacks the qualities that are layered on a climate service as information travels through and is used in institutions in a knowledge system. When used in a focus group, actors justify quality criteria before they are recorded, and challenge others on their criteria. The completed matrix is a product of negotiation, not a collage.

In a final step, the researchers and the actors involved jointly assess ("co-evaluate") the quality of a climate service using the resulting set of jointly developed or co-produced knowledge quality criteria, i.e., a filled out version of **Table 1**. This step, the assessment, can be done either in a group-interview, or in one-on-one interviews.

Having developed the Co-QA framework for comprehensively unpacking and assessing climate services diverse qualities—our first research aim—we sought to test this framework in two cases.

CASE STUDIES AND METHODS

In this section we expand on how we implemented the Co-QA tool for comprehensive knowledge quality assessment in two different cases; testing out the tool together with actors in knowledge systems associated with on-going (in Bergen) and planned (in Dordrecht) climate services. These two cases were chosen to study quality assessment and the Co-QA tool, as our second research aim.

The application of Co-QA in the cases can show to what extent the framework captures the diversity of ways that actors involved in co-developed climate services relate to "quality" and supports the assessment of climate services' fitness for purpose. The cases are unique but comparable. Both cases involve highly developed networks of climate scientists and users of climate information, practical experiences with climate services, and a growing focus on co-development of climate services. The selection of cases targeted novel experimental approaches to this co-development. They highlighted the widening interpretation in such co-development processes of what climate services are, and how they are developed [see e.g., Boon et al. (2021)]. The Klimathon in Bergen is an example of the widening interpretation of what a climate service is; less focused on tools and data and more on engagement and reflection between actors involved in climate adaptation. The place-based climate service design in Dordrecht is an example of changing approaches to climate service design, with local experiences and views on quality as a starting point of co-design. The Bergen case is an ex-post assessment, and the Dordrecht case ex-ante. This is notable because traditional approaches generally focus on ex post assessment only, while co-evaluation could be important for co-development of climate services at a much earlier stage.

In both case studies our two-step method started with the first step of *mapping specific quality criteria* using the Co-QA table in interviews (see **Table 1**). Here we conducted individual semi-structured interviews with actors connected with the climate service in different ways, trying to include diverse roles and perspectives among the group of interviewees. In the interviews we first discussed what the interviewee considered to be the main function(s) of the climate service, then, we proceeded to fill in the Co-QA table with quality criteria for each critical mode, relative to the stated function (one interview and actor thus making up one row in the table). Following the cohort of interviews, the second step reconvened a group of those same interviewees in focus group sessions for *collaboratively assessing the climate service according to an agreed upon short list of quality criteria*. These focus groups started by jointly discussing the main function(s) of the climate service, with a sheet of anonymized interview statements as points of departure. They went on to discuss a filled-out Co-QA table, which assembled all quality criteria elicited from the interviews, and worked toward agreeing on the most important criteria fitted to the function(s) of the climate service. The focus groups finished by conducting an assessment of the climate service according to the short list of criteria. This two-step process is designed to enable both a comprehensive mapping of specific quality criteria from different points of view, roles and modes. And a peer review process where different perspectives are presented to different parties and quality criteria are discussed, agreed upon and anchored; bridging quality expectations across different actors.

Ex Post Assessment of the Klimathons in Bergen, Norway

The Klimathon is a collaborative, "hackathon"[1] inspired seminar with participants from different fields, competences

[1] Hackathon is a composite of "hack/hacking" and "marathon" and was first used in the world of programming as a creative method for problem solving, often with a competitive element (Briscoe and Mulligan, 2015). The Klimathon has left out the

and specialties, sharing an interest in local climate adaptation. Participants are divided into "interdisciplinary and intersectoral groups [...] to design practical and strategic solutions to the challenges of planning and implementing climate adaptation at the local level" (Kolstad et al., 2019, p. 1424). As we write, the Bergen Klimathon has been held twice, as comprehensive "live" events, gathering 73 participants in 2018 and 98 participants in 2019 for two full days (Kvamsås et al., 2021). Many of those involved in the development and implementation of the Klimathons, a group of local practitioners and researchers, co-wrote an essay that might be seen as the Klimathon "origin story" titled "Trails, Errors, and Improvements in Co-production of Climate Services" (Kolstad et al., 2019), with the introductory statement—"An honest reflection on experiences in a climate service project is provided, with concrete recommendations on how to put ideas of co-production into practice" (Kolstad et al., 2019, p. 1). The Klimathon was developed to remedy some of the "errors" and is one of the "concrete recommendations."

The Klimathon developed from several years of cooperation between climate researchers and local municipalities and county administrators in different research and climate service projects[2] focusing on local climate adaptation in and around Bergen, with a "co-production" ambition (Kvamsås and Stiller-Reeve, 2018, Kolstad et al., 2019, Neby, 2020, Kvamsås et al., 2021). A recurrent experience and discussion concerned the challenges of *communication* and different problem framings, and a lack of understanding of each other's worlds (Kvamsås and Stiller-Reeve, 2018; Kolstad et al., 2019; Neby, 2020; Kvamsås et al., 2021). The Klimathon was an effort to create a new format and forum for dialogue, to address some of these challenges so that future processes for co-producing climate services for adaptation might run more smoothly. It is also a research method in itself, producing knowledge on local climate adaptation governance (Kvamsås et al., 2021). The main focus of the Klimathon is not to produce a climate service product like a scientific report or a concrete solution to a problem, though these are anticipated spin-offs. The focus is on developing insights and ideas on *how to work* successfully on climate adaptation governance. It aims to stimulate local-scale initiatives that bridge disciplines, and for the participants who are there to experience and reflect upon the challenges, and potential solutions, of working with climate adaptation; a complex problem at the interface of science and politics. For our purposes here it is an interesting case because it is difficult to assess according to either traditional criteria of *scientific robustness* or *plasticity of use* alone.

We facilitated a quality assessment of the Klimathon using the Co-QA framework as a guideline, following the two-step approach detailed above. We first conducted individual semi-structured interviews with eight Klimathon organizers and participants with different backgrounds, focusing on the goals of the Klimathon, and quality criteria according to the four critical modes. The individual interviews lasted approximately 1 hour, using the Co-QA deliberative tool as the interview guide (see **Supplementary Material**); eliciting overlapping perspectives on the Klimathon functions, and a list of 30 quality criteria (**Table 2**). All interviews were recorded and all but one was conducted face-to-face (conducted January to May 2020). We then invited these interviewees (four could attend) back for a 3-hour, face-to-face focus group session in June 2020, for discussing and validating the functions and criteria that came up in individual interviews and agreeing on a set of criteria for co-evaluating the Klimathons.

TABLE 2 | Knowledge quality criteria assembled from eight individual interviews.

Critical mode	Knowledge quality criteria recorded in interviews
Input and context	1. Political anchoring
	2. Diversity and interdisciplinarity in a balanced and purposeful group composition, both among organizers and the participants.
	3. Suitable tasks.
	4. Enough time, both for preparation, discussion, implementation, and follow-up afterwards.
	5. Sufficient funding
	6. Open minded participants
	7. Continuity (for building trust and strong relationships).
Process	8. Active participators
	9. Face-to-face interaction
	10. A process of discussion, learning, experiences, and discovery.
	11. Smooth and professional execution of the event
	12. Groups given a challenge and support for constructive problem-solving. Balance between openness and structure in group tasks.
	13. Available tools to support creative thinking and open discussions (drawing, pyramid dialogue, mind maps etc.)
	14. Acoustic comfort and sufficient space.
	15. Competent group moderation/facilitation
	16. Building trust
	17. That participants meet as equals
	18. Accessible templates for recording and presenting group ideas
Output and use	19. "Solutions" to defined problems
	20. New and improved ways for conducting routine work
	21. Concrete products like for instance an instructional booklet or webpage that contributes to daily routines in municipalities.
	22. Strengthen working relationships between public administration and local research communities
	23. Create and strengthen other useful networks
	24. Put climate adaptation higher on the political agenda in municipalities
	25. Inspire and give momentum for municipalities' climate adaptation
	26. Maintaining and updating knowledge.
	27. Learn about each other's roles in a knowledge system, and develop empathy for each other's work and challenges.
	28. Experience cross-disciplinary problem-solving
	29. Write a report, note, or policy brief to present to municipalities leadership.
	30. A dynamic event, "the goal" or focus should be changing and develop from year to year.

The wording is paraphrased, but criteria are in the critical modes where interviewees recorded them. Many interviewees grouped output and use, so we have too.

competitive element, but takes with it the elements of working in interdisciplinary groups, intensely and focused, on solving concrete problems in creative ways.

[2]Hordaklim: https://www.bjerknes.uib.no/hordaklim, R3- Relevant, Reliable and Robust local scale climate projections for Norway: https://www.norceresearch.no/prosjekter/relevant-reliable-and-robust-local-scale-climate-projections-for-norway. Hordaflom: https://www.norceresearch.no/prosjekter/hordaflom-bedre-beslutningsgrunnlag-for-risikostyring-i-flomsoner-i-hordaland.

This focus group agreed on six criteria that they saw as best fitted to assessing the Klimathons according to their three main functions (see **Table 3**). This was both a process of identifying what the group found to be the most important criteria, but also criteria that they found interesting to discuss further. So, for instance, while "sufficient funding" was deemed central it was not a topic that needed much discussion, and it had not been a limitation so far, thus it was not one of the criteria brought forward into the assessment part of the focus group session. Finally, the group assessed the Klimathons according to the six peer reviewed quality criteria (**Table 3**).

Recruitment of interviewees went through the organizers and snowballing[3]. This led to a group of interviewees where most had somehow been involved in organizing the Klimathons or had given input to the organizing process. In the group of interviewees there was a mix of natural scientists, social scientists and both municipal and county level administrators. These are the main groups represented at the Klimathon, and therefore the groups we wanted represented among our interviewees. The size and composition of the group of interviewees is a weakness of this case. A larger and more diverse group, with more actors that were "only" participants to the event (had not had a role in its organization) would have been desirable so as to get a more varied and less biased group, especially concerning the assessment of the events. Still, we find that the research material gives valuable insights into identifying the Klimathon goals and quality criteria, and works well for the purpose of testing out the Co-QA tool. Also, reports have been written from two of the Klimathons (Kvamsås and Stiller-Reeve, 2018; Neby, 2020) where results from the discussions and an online evaluation survey among participants carried out the day after the event is discussed. We used these reports to substantiate results from our own study.

Ex Ante Assessment for the Co-production of Climate Services in Dordrecht

The city of Dordrecht, the Netherlands, has been exploring climate-proofing and the co-production of policy and knowledge, together with a variety of neighborhood, local, regional, and national actors. The city is surrounded by rivers, close to the coast, and faces soil subsidence, groundwater issues, periods of heavy river discharge from the hinterland, heavy local rain showers, and heat stress, as well as various non-climatic issues such as socio-economic challenges, demographic change, and increasing demand for housing. Over the past 3 years, the CoCliServ project developed a bottom-up approach to climate service co-development, with Dordrecht as one of its case studies. The Dutch team involved the Municipality of Dordrecht, Utrecht University, KNMI Royal Netherlands Meteorological Institute (Dutch met office), CAS Climate Adaptation Services (climate service developer), and Studio Lakmoes (knowledge communication and design bureau). The case focused on the Vogelbuurt neighborhood, a low-lying area with much social housing that is scheduled for large scale urban renewal. Researchers collected narratives of local and regional policy actors as well as neighborhood residents on how they experienced weather, climate, and other changes (Marschütz et al., 2020). These narratives were used in a co-design workshop with 12 residents, policymakers, and researchers to draft future visions and scenarios for the neighborhood (Wardekker et al., 2020, p. 13–30), which in turn provided a basis to reflect on what climate services might be most useful to support "climate proofing" the area.

This process of designing novel climate services is currently ongoing. The Netherlands already has a significant infrastructure related to climate knowledge and climate services, but while very detailed and high-resolution, these are primarily focused on the national and regional level (Meinke et al., 2019, p. 33). The aim of the Dutch project team was to develop locally-specific, "place-based" climate services, based on local knowledge needs. An initial inventory of such knowledge needs was conducted during the co-design workshop. Currently, the project team is designing a concept for a local service that meets some of these needs. For the present paper, we argued that a reflection on knowledge quality criteria, before designing this new climate service, may be beneficial to guide this design process.

Here again our study was guided by the Co-QA framework, and following the two-step method detailed above. We built on the initial inventory of local knowledge needs developed during the co-design workshop with 12 residents, policymakers, and researchers (Wardekker et al., 2020, p. 13–30). We conducted semi-structured interviews, in individual and duo interview formats, with six actors who either participated in or helped organize the co-design workshop. These interviews aimed at eliciting knowledge quality criteria, associated with the four critical modes, which might guide the design of new place-based climate services. Following these interviews, an online discussion was held with ten of the co-design workshop participants (five of the interviewees plus five other workshop participants and co-organizers), focusing on starting the design process, with the knowledge needs and quality criteria in mind.

A key goal of the knowledge quality exercise was to inventory a relatively broad set of criteria that might be used as design guidelines in developing a novel climate service, rather than to evaluate existing services. The exercise took place before decisions had been made on the nature or audience of the service. Therefore, we present the full, uncondensed set of criteria. We focused the interviews and discussion on the CoCliServ partner organizations, as these were designing the new climate service and already included the key user, Municipality of Dordrecht. Interviewees included local policymakers, climate service specialists (public and private), policymakers, academics, and a design bureau. Interview questions roughly followed the interview guide used in Bergen, aiming at eliciting the potential goals and target audiences of a novel service, relation with inventoried local knowledge needs, and the implications of these for potential quality criteria. We used the tool implicitly to guide the initial questions, and explicitly in the inventory of quality criteria.

The individual interviews lasted between 1 and 1.5 h. All interviews were recorded and they were transcribed into a synthesis document. The online discussion lasted 1.5 h. General

[3]Lists of Klimathon participants were not available to us.

TABLE 3 | Assessing the first two Klimathon events.

Key assessment criteria	Qualitative peer assessment
Group composition: diverse, interdisciplinary, and intersectoral; both among the groups of Klimathon participants, and also among the group of organizers.	Good diversity of participants from within the "target groups," based on the Klimathons focus on the use of climate information for planning. Diversity was seen in terms of the different "roles" represented, and the geographic spread of attendees. Politicians were one under-represented group.
Continuity: for building trust and well-functioning networks, and for maintaining and updating knowledge.	Good continuity in that the Klimathon has become a regular event, and many attendees came back for the second event. Another consideration is whether conversations triggered at the Klimathon continue in the different organizations that attended, and there is some evidence they do. Also, new initiatives have come out of the Klimathon, like the "Rent-a-researcher" initiative and one other local "-athon" event.
Infrastructure for discussion: acoustic comfort, thoroughly thought through topics for discussion, capable moderators.	Infrastructure was in place that made group work go smoothly. There was some feedback about the balance between having open or structured group work, and this saw the format change from the first to the second Klimathon. Attendees who returned the second year were also more familiar with the concept, which further facilitated discussion.
An equal meeting ground: that participants are equal independent of background, and all have legitimate concerns for climate adaptation.	It is difficult to assess whether the Klimathon created a neutral meeting place for attendees, because there was no work to deliberately assess this. But the Klimathon was designed to assemble highly diverse groups, which went some way to creating "neutral ground." There were also "informal" facilitators to ensure all felt they had a voice, though this varied between different groups. The pyramid discussion technique worked well to give all a voice, and a positive atmosphere was reported.
Social learning: about each other and how to overcome differences. Learn about each other's roles and work life. Understand each other's challenges. Shared experience with working on cross-disciplinary problem solving.	Attendees have learned from each other, as appraised from immediate feedback at the event, through the continuity of discussions between attendees, and in the enthusiasm to take part in the event, with more applications to attend than available places. However, much of what was learned is background information that sits in the back of people's minds, so a follow-up survey could be an important way of assessing what was learned.
Concrete outputs: reports, policy briefs or a summary that can be brought back to municipalities and further "up the system" so that insights from the event can have an impact.	There was a report following the first Klimathon, but the anticipated "policy brief" was not delivered, nor the report following the second Klimathon. The Klimathon products have not been well-delivered because of a lack of time and money, and a change in personnel. There need to be more resources for follow-up, with deadlines and clear responsibility. In future, a final product in the shape of a report or similar should be delivered immediately following the event.

notes were taken to document aspects relevant to this paper. The synthesis document of the interviews on quality criteria provided the starting material for the discussion. The knowledge needs from the co-design workshop provided input for both interviews and discussion. Both interviews and the discussion were conducted online, as physical meetings were not possible due to the COVID-19 pandemic.

RESULTS: ASSESSING CLIMATE SERVICES AND THE CO-QA FRAMEWORK

In this section we present a comprehensive knowledge quality assessment of the two case study climate services facilitated by the Co-QA framework, as a demonstration of Co-QA "in action" (the second aim). We finish here by comparing experiences in both cases.

Applying the Co-QA Framework to the Klimathon

The Co-QA framework provided a focus for interviewees and focus group participants to reflect on the qualities of the Klimathon and appraise the event by these qualities. Though the framework is designed to elicit diversity, in using it participants were seen to converge on the main functions and related quality criteria of the Klimathons. Differences were mostly found in which goals and criteria the participants emphasized most. While agreement was strong across participants, the two participants from municipalities differed slightly from the rest of the group on some points. The small number of interviewees does not allow for generalizations, but the organizers also mentioned having encountered some of the same comments elicited in this process, in other evaluations and feedback.

Goals, Criteria, and Assessment

The main functions or goals of the Klimathon, discussed and agreed upon through the two-step process, were:

i *Knowledge development; developing common understandings of climate adaptation and climate services, and understanding of each other*
ii *Enact a framework for co-production*
iii *Develop concrete ideas for climate services and map information needs*

Another recurrently mentioned function of the Klimathon was to build supportive networks for participants. Though the goals are limited and largely agreed, they do demonstrate the multiple functions attached to climate services in a knowledge system, and the corresponding diversity of quality criteria, some of which are difficult to capture in metrics, like "common understandings."

Participants were seen to broadly divide goals or functions into two main categories, one related more to outputs, and one focusing more on the process itself and the experiences of the participants. In the focus group this was at one point discussed as "the concrete" and "the abstract" goals, where abstract meant the learning, experience and knowledge development and the process itself, and concrete meant outcomes like a report or a concrete new idea or solution, like "rent a researcher[4]". The group didn't necessarily find this vocabulary to be satisfactory, and it was used mostly as a shorthand in the discussion, but it is interesting for our purposes here to see that the group was searching for and trying out different vocabulary to express what they experienced as valuable in the Klimathon. A recurrent comment was also that the things they found valuable with the Klimathon were difficult to assess. We found support within the group for the need to developing new ways to discuss and assess climate services, with Co-QA as one option.

The goal "knowledge development" encompassed aspects like taking part in something challenging that broadens one's understanding, experiencing cross-disciplinary work, and understanding one's role in a larger knowledge system. It embraces a broad understanding of knowledge, including to "gain experience" and "develop understanding." Relative to the second goal, comments related to testing, developing and encouraging others to use the Klimathon framework or something similar, to nurture productive dialogue and prepare the ground for well-functioning collaboration on climate information and action; future co-production. The third goal, to come up with concrete solutions, tools or procedures, reports and documents, was one of the goals most stressed by the municipalities. While all goals were given importance, it was the topic of knowledge development that generated most excitement and enthusiasm during discussions and was most talked about, explained, and nuanced, in the interviews and focus group.

With the agreed upon goals in mind, we presented the focus group participants with a Co-QA framework "filled out" with the 30 different quality criteria assembled from the interviews (see **Table 2**). Stemming from the three goals, the group agreed on six over-arching quality criteria. Then the Klimathons were assessed according to these six co-produced criteria. We moved systematically, discussing each criteria in turn, with participants offering their own appraisal of the Klimathon supported by evidence for each criteria, and adding to or challenging the appraisals tabled by others. In this way, we arrived at a broad consensus about the Klimathon according to each of the six criteria, as presented in **Table 3**. Please note that since this focus group, a report has been released about the second Klimathon.

Reflection on the Co-QA Tool

Both the topic of how to assess climate services generally, and the Co-QA tool specifically, came up in most interviews without the interviewer prompting on this. This might indicate that it is a topic that climate service practitioners are concerned about. In addition, we directly asked for reflections on the Co-QA tool at the end of both the focus group and in the individual interviews. One participant saw Co-QA as important for "…thinking about co-production more thoroughly," in order to draw lessons for future practice; "there are some generalizable lessons there I think." Many of the participants raised what they felt to be a challenge, that while they did feel the goals of the Klimathon were important and valuable, they were also fundamentally difficult to document and assess. In this sense, a qualitative tool that gave space for nuanced and peer reviewed qualitative appraisals was seen as a good fit. One participant said, "I'm not so fussed about having [a framework with] 50 metrics and red, green, yellow lights (…) we have talked a little bit about the need for standardization (…) [but] I don't know that that is necessarily possible, there might be too many local factors." Some also mentioned they felt it was a general problem that climate services were rarely evaluated, and that to discuss and develop ways of assessing climate services should be an important issue for the climate service community.

There was positive feedback on the Co-QA tool for enabling mapping of different perspectives and for generating fruitful discussion about climate services. Many of the participants also reported that participation in the interviews and focus group was very useful for their own reflections, about both the Klimathon and climate services in general. It was particularly commented on as being a valuable tool in a *co-production* context. Still, most interviewees also found that this particular group was too biased and involved, not big and varied enough, and missing an outside perspective, for a totally comprehensive and meaningful *assessment* of the Klimathons to be made.

Applying the Assessment Framework in Dordrecht

Guided by the Co-QA framework, interviewees reflected on the potential target groups and roles for a novel service and quality criteria that could guide its design. Answers were highly similar; most aspects were mentioned by three or more interviewees, with differences in emphasis or details.

Audiences and Goals

Three key potential audiences were defined for new climate services: residents, municipal policymakers, and municipal operations staff.

Residents include the "general public," but for a specific location or neighborhood. They include resident organizations, with a distinction made between residents who have little knowledge or interest regarding this topic, and residents who are highly interested and well-informed. For residents, climate services should provide practical information. They may also

[4] ≪Rent a researcher≫ was a concrete idea that came up during the first Klimathon and that was actually carried through. A climate researcher working with the Klimathon and its associated projects, spent two weeks at a small municipality working with them giving guidance and advice on climate services.

focus on environmental communication, awareness raising and improving sense of urgency. This increases people's capacity and knowledge, allowing them to see connections (e.g., between local heat, flooding and green space), and highlighting the relevance of local adaptation to their lifeworld. A key role for climate services is to provide perspectives for action. Limiting services to raising awareness is insufficient if the service should lead to change.

Municipal policymakers focus on more strategic aspects. They use knowledge to design new plans and policies, and to inform the public. Information may be focused on current and future policy challenges, expected trends, and development options for the neighborhood toward the future. General educative material can also be useful for policymakers to enter discussions with residents and policymakers in other departments. Services might help people think about what information they need in relation to a specific issue, including connections to other issues, and information related to the current climate. Similar to residents, providing perspectives for action is a key role of a climate service.

Municipal operations staff, such as "neighborhood managers," municipal project managers, and implementation staff have a more practical focus. They require information on what's currently going on in a neighborhood, monitoring, detection/alerts in case of problems, or information related directly to the work that's being implemented. Climate services might have a "signal function" (for managers) or a "quick lookup or reference" that can be used in the field (for implementation staff). An action perspective was again mentioned as a key role.

Other potential audiences included: water boards (regional water management agencies), municipal health services, provinces, companies and industrial areas, environmental agencies, housing corporations, and project developers. Many climate services experience widening target audiences, whether horizontal (more actors) or vertical (higher/lower scale levels). This may or may not lead to different requirements for the climate service.

Quality Criteria

Application of the Co-QA tool yielded a list of quality criteria deemed relevant by the interviewees for different potential target groups of the novel climate service (**Table 4**).

For residents, information's accessibility and ease of use are paramount. This can involve, for example, the use of language, types of visualization, or the assumed level of background knowledge. Details are not always necessary; it is important to develop a good basis of understanding first. Credible developers—trusted as conducting their work appropriately and rigorously—are important, for example national science institutes, well-known consultancies, or municipal health services. The information should be clearly actionable. For most, that would focus on practical aspects at the scale of the home, street or neighborhood. One interviewee pointed to TEDx and a Dutch TV talkshow ("De Wereld Draait Door"), which tell "informative stories told in an enthusiastic way, which tickle people's curiosity." Recognizing diverse social groups in neighborhoods, services may need to be tailored to people's perspectives, or coupled to local topical issues to be meaningful. Finally, climate services would be open to user input (interactivity), especially when focused on specific neighborhoods.

For municipal policymakers, credibility of both the developer and the input data and data provider are highly important: "We should be able to count on it that this is the best there is. Not something someone cobbled together in his attic." A related point is that climate services sometimes involve biases or debatable assumptions because of the way they use, transform or combine data [see e.g., van der Sluijs and Wardekker (2015)], or how they present and visualize results. Climate services' biases and assumptions, and uncertainties should be made transparent and discussed relative to policymakers use. Providing actionable information, is again a very important criterion. Services should relate to policymakers' fields of work and current and future challenges. Continuity of service is important. Interviewees referred to experiences where services were developed in a research project, and then defunct a few years later, when the project was over. This is detrimental to their practical applicability. Finally, the interviewees stressed that while it is important that services meet user needs, there can be differences between stated needs and what they would actually need for their purpose, emphasizing the importance of iteratively co-develop climate services through continuous conversation.

Criteria for municipal operations staff were similar to policymakers, with differences in the details. Specific aspects were the involvement of sectoral knowledge institutes (e.g., RIONED, STOWA), providing technical know-how and serving as a recognizable "quality label" for these users. Practical aspects related to the use of services, e.g., coupling to existing management systems or approaches, or usability on smartphones, were also mentioned.

Finally, discussions were raised on other qualities of climate services. For example, should climate services have emotional impact? Might they be "slightly scary," or would that hamper legitimacy or backfire (e.g., induce denial). How prominent should a municipality's ambitions be embedded in a service? And should climate services also include things that municipalities have little knowledge on, or that are highly uncertain? This information may be relevant, but may backfire if people overinterpret it or consider it as "the truth."

Overall, the tool was easy to use in the context of designing quality criteria that might (pre-emptively) guide the co-design of novel climate services. The emphasis on different target groups matched participants' own experiences with quality in the sense of fitness for use. Several mentioned this even before being shown the framework. The phases were recognizable to participants when they were shown and briefly introduced. We had prepared a list of example criteria, and referred to this in two cases to stimulate discussion. Participants used the framework easily, to typify past experiences (good and bad) with quality of climate services and to identify quality criteria. One respondent remarked that the criteria did remind them of those in the theoretical literature. However, the resulting criteria were more rooted in respondents' experiences and practice.

TABLE 4 | Quality criteria for designing a novel climate service for Dordrecht.

Critical phase Target group	Input (and context)	Process (includes developing the climate service)	Output	Use
Residents	Open to interactivity and user input (?)	Credibility of developer (!) Consideration of different types of people Aimed at scale of house, garden, street, neighborhood	Tangible, visual Accessible in content, use, and findability (!) Form matches residents' needs, lifeworld, recognizability. Aimed at scale of house, garden, street, neighborhood Reliable	Has perspectives for action: practical, aimed at own environment and lifeworld (!) (?) Tickles curiosity, interesting, informative, entertaining. Timely information (warns when you need to do something) User-friendly Suitable for pallet of options ("honest broker")
Municipal policymakers	Credible input data and data provider (!) Correct combination of data (e.g., accounting for issues with integrating datasets and models with different time or spatial scales) Checked for potential biases due to data use	Credibility of developer (!) Cocreated, with or though conversation with users, iterative design Developer and user discussed how the service will be used Continuity of service; doesn't vanish after project is over (!) Tailored, uses detailed local knowledge instead of generic tools	Accessible, visual Form matches needs: usable at local scale, scale where problem manifests Checked for potential biases due to way of visualization, framing Easy to communicate to others in different field/sector Tailored, uses detailed local knowledge instead of generic tools Balanced information (regarding fields with much experience, blind spots) Clear what the tool does and doesn't show	Has perspective for action: aimed at policy development, strategic, future (!) Use matches design of service (content, bias, added value) and actual user goals User-friendly Suitable for pallet of options ("honest broker"). Helps weigh decisions without steering Transparent system, open access, think about unexpected use/abuse
Municipal operations staff	Credible input data and data provider (!) Correct combination of data (e.g., accounting for issues with integrating datasets and models with different time or spatial scales) Checked for potential biases due to data use	Credibility of developer (!) Continuity of service; doesn't vanish after project is over (!) Involvement of sectoral knowledge institutes (credibility; "quality mark") Cocreated, with or though conversation with users, iterative design Developer and user discussed how the service will be used	Accessible, visual Form matches needs: usable at local scale, scale where problem manifests Suitable for practical use Checked for potential biases due to way of visualization, framing Tailored, uses detailed local knowledge instead of generic tools	Has perspective for action: aimed at what's happening now, monitoring, concrete, recognizable, matches their practical situation (!) For managers: link to management system, decision-trees; usable on desktop computer For implementers: reference/lookup function, usable in the field e.g., on smartphone User-friendly

Criteria marked with (!) were mentioned as especially important, those marked with (?) were subject of discussion among participants.

Use in Developing Novel Services

CoCliServ participants decided to focus on a warning service for Vogelbuurt and neighboring residents for approaching heavy rain showers. They discussed aspects related to the quality criteria multiple times; often implicitly, but most aspects were covered. There are several local low-elevation points that experience problems during intense rain. Two recent extreme showers led to local flooding and considerable damage. Insurers refuse future compensation and the issue cannot be solved structurally. Both the Municipality and residents see this as an urgent issue. The Municipality wants to set up something that helps residents take timely action, for instance through temporary barriers or sandbags, but these will need to be staged over time. The climate service might provide timely warning and show potential actions and locations of materials. This relates directly to criteria "perspectives for action," "timely information," "aimed at house/street/neighborhood scale." A challenge is that such showers are very local and difficult to predict. Residents may be warned several times without being hit by the shower ("reliable"). Discussion will be held with residents on how many unnecessary warnings are acceptable. The format might be a smartphone app, with a warning and further information ("tangible," "accessible"). KNMI was seen as an ideal provider of the warning, or the information on which it is based, as people see the national met office as a trusted source ("credibility"). Another challenge is that KNMI, as a public institute, cannot provide services that could also be provided commercially, for legal/competition

reasons. Commercial meteorological bureaus and consultants may be involved.

The CoCliServ co-design workshops allowed for developing an initial sketch or demo. The issue of "consideration of different types of people" and diverging needs was also raised. Layered provision of information in the app may be possible (warning plus different levels of detail). An interviewee also questioned whether it would be free to download the app or not. CoCliServ partners are now developing proposals for further development. These referred explicitly to "user-friendly," "visual," "local/neighborhood level," and "interactive." Alternatives were also suggested by multiple partners: linking up with existing fora including e-mail and WhatsApp groups or neighborhood app ("accessible," "form matches needs/lifeworld/recognizable") and where residents and (KNMI-)experts ("credible") might exchange information. The service should avoid information overload ("accessible," "form matches needs") and be developed in conversation between actors ("cocreated"). Participants showed a high degree of awareness of the quality criteria in their discussions.

Comparison

The Bergen and Dordrecht cases applied the Co-QA tool to co-evaluate climate services in different situations. The Bergen case was ex post and aimed at a relatively novel type of climate service; a workshop series intending to stimulate reflection among relevant climate service actors. The Dordrecht case was ex ante and aimed at designing a more typical (though novel) climate service; an app on heavy precipitation events for local residents. In each case, we observed that the Co-QA tool allowed for both individual and collaborative reflection on quality. Both uses of the framework resulted in explicit discussion of the intended audiences and purposes of climate services, and how quality related to that. Diverse sets of quality criteria were generated, and while many of these bear similarities with theory-based criteria in the literature on knowledge quality, they were more detailed and better rooted in the daily realities and experiences of providers and users and other actors with a stake in climate services. In both cases, participants observed that the exercise in itself, while qualitative, stimulated them in explicitly taking quality considerations into account in their work on and with climate services.

Some differences were also observed between the cases. In Bergen, the resulting quality criteria placed emphasis on process-related aspects. Given that the Klimathon is a workshop series where the process itself is indeed key, we argue that the Co-QA tool adequately picked up on this as a key aspect of quality for this specific service. A traditional quality assessment may have retained a focus on the data, models and other tools that would be used in the workshops, rather than on the more nebulous factors that play a role in making the service a success. In Dordrecht, we observed a broad discussion along input, process, output and use of climate services, with the latter two in particularly emphasized by policymakers and tool developers, and the input primarily highlighted by climate scientists. This shows that it is important to include multiple types of actors in the co-evaluation, as different actors will have different "sensitivity" to each stage due to their background and experiences. We also observed that participants found the explicit discussion of such aspects useful and that they took it into account in designing novel climate services.

Jointly, the case studies show that in co-development of climate services in a knowledge system, a wide-ranging set of functions and goals, potential users and uses, and contextual factors play a role in determining quality; many of which are difficult to measure, evaluate and communicate using traditional quality assessment. Co-evaluation using the Co-QA framework helped actors in our cases to make these quality aspects more tangible and to intentionally include them in different phases of climate service design, refinement and use.

DISCUSSION

Co-QA and Climate Service Co-evaluation

We aimed to: (i) develop a new tool—the Co-QA—for comprehensively assessing the qualities of co-developed climate services relative to their particular functions; and (ii) test the Co-QA for assessing two climate services; an *ex-post* assessment of the Klimathons in Bergen, and an *ex-ante* assessment for guiding the design of a novel climate service (heavy precipitation warnings) in Dordrecht.

To the first aim, we developed the novel Collaborative Quality Assessment (Co-QA) framework. This framework builds on Knowledge Quality Assessment (KQA) scholarship, extending on the long-established framework of Clark and Majone (1985) and contributing to the stock of empirical evidence of how KQA is implemented in practice, and to what effect. To climate services scholarship, Co-QA provides a new tool for the comprehensive *co-evaluation* of services, in recognition that quality means different things to different people in complex knowledge systems, and that these diverse criteria need to be collaboratively weighed in any assessment. Co-QA resembles existing frameworks [see e.g., Wall et al. (2017)], but we see novelty in its (i) simplicity of use; (ii) low resource demands; (iii) openness to including diverse quality criteria of different types; (iv) ability to capture—"bottom-up"—actors contingent concerns in a particular knowledge system; and (v) facilitating discussion, justification and weighing of criteria in collaborative fora, as "extended peer review." Though climate services have seen a paradigm shift toward collaboratively producing (co-producing) information with interested actors, this collaboration has rarely extended to their assessment, which remains narrowly and technically defined. Co-QA shows what co-evaluation can look like.

To the second aim, we tested Co-QA and found it to be effective in both of the cases studies. These cases were chosen because they departed from classic climate models, tools and datasets, and were paradigmatic of the wave of co-developed and creative approaches to climate services, where lines between providers and users are blurred, and new actors are becoming involved. The openness and flexibility of Co-QA meant that

it could be deployed for assessing very different services—whether for an ex-post assessment of a learning process like the Klimathon, or an ex-ante assessment of an information product like a flood warning app—it is the actors themselves who decide which criteria are most relevant for assessing a particular climate service and its functions. As one participant in Bergen said, a qualitative framework like the Co-QA could be a better fit here than a pre-configured quantitative list of metrics, which may not capture what is actually experienced as important. This much noted, both cases also included (natural) climate scientists and elicited criteria that related to more technical and quantifiable scientific standards (e.g., checked for biases, transparency etc). In this way, the Co-QA framework is also suitable for more "traditional analysis" of scientific quality; it could for instance be used to map quality criteria across different disciplines and foster a cross-disciplinary dialogue on epistemic quality norms.

The categories in the tool, focusing on multiple actors and modes was recognizable to participants, and allowed us to start a dialogue on quality criteria based in participants' experiences and needs, rather than from theoretical work. This meant that the tool was fairly quick and easy to use, compared to some of the more formal KQA methods. Together the cases showed that Co-QA can work for comprehensively assessing co-developed climate services, but more case studies are needed before we can state this any stronger.

Three Broader Lessons for Climate Service Assessment Scholarship and Practice

These cases revealed the importance of studying climate services as emerging from and traveling through complex knowledge systems, and a corresponding need for comprehensive assessment that accounts for these diverse qualities. Accepting that these were atypical climate services, they did nonetheless show two instances of information products that came about through configurations of "linked actors, organizations and objects," operating across institutions with different logics. Indeed, one of the Klimathon's main goals was to mutually understand the complex landscape of public administrations and research organizations engaged in climate adaptation, by physically gathering these networks of actors and organizations in one venue. The Klimathon product was a self-reflexive understanding of the very system producing the Klimathon. Likewise, in Dordrecht, the process for developing a neighborhood-scale flood-warning product implicated various research and municipal institutions, including different professions, and a local community that is itself far from homogenous.

Both cases demonstrated the multitude of possible qualities attached to a climate service in a knowledge system, with 30 criteria distilled in Bergen, and 51 in Dordrecht. Looking at how these criteria differentially emerge in different institutional settings, the Dordrecht case teased out the different qualities important for different target groups: residents, municipality policy-makers, and municipality operations staff. There the credibility of product developers was a proxy for scientific robustness, and various quality conditions related to "use" were laid out. But beyond scientific quality and plasticity, other qualities arose. For example, information that diverse local communities can make sense of and maps onto their identities and daily lives. Or a service that is developed over a long time-horizon, since it can be through use that we understand what our needs are. There were also issues raised around how numerous and diverse quality criteria can cohere in a single product. On one hand, by discussing qualities in an *ex ante* design process like in Dordrecht, a product becomes an explicit composite of all these expectations. On the other hand, in Bergen, participants saw tensions between "concrete" and "abstract" expectations.

Distinguishing between the "concrete and abstract" raised another issue around how to put into words some of the qualities attributed to climate services. In Bergen, participants saw that what they found to be important and valuable aspects of the Klimathon were difficult to measure and to communicate to funders, public administrators and the research community. Both cases saw participants try out, or develop, new vocabulary to talk about what they find to be important goals and valuable aspects of climate services for them. Many criteria in our case studies might be interpreted under the classic headings of "credible, legitimate, salient, useful." However, because we approach these bottom up with knowledge system actors, the criteria are much more diverse, specific, place-based and purpose-specific, as well as much more recognizable to users who utilize them in the co-evaluation. For us, this shows the necessity of more comprehensive assessment that can accommodate the tangible and the less tangible understandings of climate service quality.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Marianne Høgetveit Myhren and Lis Tenold from NSD-Norwegian Data Protection Services (Project No. 60380). The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

SB, AW, EJ, and JS were engaged in: (i) developing the Co-QA tool, and/or (ii) implementing the Co-QA in case study research. All authors contributed to writing text in this article, and have agreed to submit this manuscript.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fclim.2021.627665/full#supplementary-material

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Understanding and Managing Harmful Algal Bloom Risks in a Changing Climate: Lessons From the European CoCliME Project

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This paper discusses the conceptual and methodological challenges to co-developing high-quality and transferable knowledge to understand and manage harmful algal bloom (HAB) risks as part of adaptation to changing aquatic ecosystems in Europe. Global HAB-climate change research efforts to date have focused on enhancing the *credibility* of scientific knowledge by conducting basic scientific research aimed at understanding the physical and biogeochemical drivers and mechanisms shaping HAB dynamics in order to predict their occurrence and prevent their societal and ecological impacts. However, the rapid and interconnected changes occurring in marine ecosystems worldwide necessitate a simultaneous shift toward enhancing the *salience*, *legitimacy*, *usefulness,* and *usability* of this knowledge for decision-making. To address this need, we present and discuss empirical findings from the marine-focused CoCliME project, which set out to co-develop user-oriented climate services to support HAB risk mitigation and adaptation in European coastal regions. We present lessons learned in relation to four areas of project implementation, across five regional cases, that emerged as essential for enhancing the quality of knowledge for managing HAB-climate risks: (1) Engaging stakeholders to understand their knowledge, experiences, interests and concerns; (2) Co-developing a shared terminology and framing of the "HAB-related problems"; (3) Advancing scientific understanding of drivers and interactions shaping HAB-climate risks and; (4) Co-producing prototype services that integrate social and HAB-climate data and knowledge to support decision-making. We find that efforts to reduce scientific knowledge gaps and uncertainties about HAB-climate linkages (efforts to enhance *credibility*), while important, risk overlooking key aspects of knowledge co-production and application that are necessary to render this knowledge more *salient*, *legitimate, useful,* and *usable*. Understanding the multi-risk decision-making context within which societal stakeholders appraise HAB and climate change risks and approaching knowledge co-production as a learning process, are vital lessons learned in this respect. Drawing on project learning, we highlight key priorities for enhancing the societal relevance and impact of HABs-climate research during the UN Decade of Ocean Science for Sustainable Development.

Keywords: harmful algal blooms, risk management, climate services, coastal adaptation, Europe

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INTRODUCTION

Climate change and anthropogenic pressures are modifying the world's ocean in an unprecedented manner (Pörtner et al., 2019). Increasing atmospheric and ocean temperatures, more persistent water column stratification, ocean acidification, and human induced eutrophication are already impacting coastal ecosystems (Bindoff et al., 2019; Pörtner et al., 2019). And while the long-term and interactive impacts of these trends are difficult to assess, if left unchecked, they are likely to cause major changes to marine ecosystem functions, with corresponding adverse ecological and societal consequences for regions that depend on coastal and marine environments and the economic, social and cultural values and service they support (Claudet et al., 2020). As recognized in the EUs Blue Growth strategy and highlighted in numerous national marine strategies, coastal regions, which support close to half (43%) of the population in EU countries, provide myriad opportunities for enhancing citizens' health, well-being and prosperity (European Parliament, 2015). However, these benefits coexist alongside hazards and risks that may be exacerbated by climate and anthropogenic pressures on coastal and marine environments (European Marine Board, 2013).

One of these hazards is the occurrence of harmful algal blooms (HABs), an important indicator of ecosystem health status. Harmful algal blooms are associated with particular combinations of physical, biological and chemical conditions in marine and coastal environments, and can be facilitated by human activities (for example eutrophication and ecosystem destruction). The term HAB refers to a biological event that occurs in marine, brackish and freshwater systems when certain macro- or micro-aquatic photosynthetic organisms proliferate above reference limits, causing adverse impacts for ecosystems or society (GEOHAB, 2001; Wells et al., 2020). HABs are natural phenomena modulated by anthropogenic, physical, biogeochemical and climatic factors. They are considered a hazard to aquatic ecosystems and many human marine activities including aquaculture, tourism, recreation, and human health due to the negative impacts that may result from the phycotoxins that are produced and/or oxygen limitation that occurs in the water due to the excess biomass when the bloom is active or decays.

Both warming ocean conditions, as well as eutrophication caused by human activities such as agricultural run-off, may favor the development of particular HABs. Yet the complexities in HAB life cycle stages, and biochemical and physical interactions involved indicate that the scientific community has yet to unravel the particular climate and non-climatic drivers modulating HAB dynamics (Gobler, 2020). Research suggests that shifting climatic conditions are influencing the biogeographic distributions and abundances of some HAB species and the temporal and spatial extent of blooms (Wells et al., 2020). The 2019 IPCC special report on the ocean states with high confidence that an increase in coastal HAB events has occurred in many parts of the world since the 1980s (Bindoff et al., 2019; Pörtner et al., 2019). Although regional efforts to reduce nitrogen run-off have been partially successful at controlling eutrophication in areas such as the Baltic Sea region, there has been a notable increase in reports of prolonged HAB events associated with marine heat waves in different parts of the world in recent years. Such marine heat waves are expected to increase as the climate continues to warm due to continued anthropogenic greenhouse gas emissions (e.g., Di Lorenzo and Mantua, 2016). For example, blooms of the neurotoxin-producing diatoms, *Pseudo-nitzschia australis*, such as that which coincided with a prolonged marine heatwave in the Pacific Northwest USA in 2015, are becoming more common, with major ecological and economic consequences for marine wildlife and resources, and communities that depend on them (McCabe et al., 2016; Trainer et al., 2020a and references therein). Strong alterations of the atmospheric and oceanic circulation dynamics in the southeastern Pacific Ocean, likely related to climate change, were also linked to massive HABs dramatically affecting salmon and shellfish aquaculture in 2016 (Trainer et al., 2020b). Of further concern and as highlighted by the 2019 IPCC report, many coastal communities will be exposed to future HAB risks, especially in areas where HAB monitoring is poorly implemented (Bindoff et al., 2019 and references therein).

The increasing prevalence of major HAB events in recent years corresponding with marine heatwaves (e.g., McCabe et al., 2016; Roberts et al., 2019) and other extreme events highlights the need for more robust and impactful HAB risk mitigation and adaptation strategies on a regional and global scale. Yet to date, there remains a paucity of high-quality and actionable knowledge to support HAB risk assessment and management in the face of climate change (GlobalHAB, 2017; Ritzman et al., 2018). To address this gap, we present and discuss conceptual and methodological challenges and lessons learned within the European research project "Co-developing Climate Services for Adaptation to Changing Marine Ecosystems" (CoCliME). This transdisciplinary project constituted a collaboration between natural and social science researchers and societal stakeholders from seven European countries across six European coastal regions and set out to enhance the co-production, integration and uptake of high-quality knowledge to support HAB impacts assessment, risk mitigation and adaptation strategies in European coastal waters in the face of climate change.

Harnessing High-Quality Knowledge for Adaptive Governance in European Coastal Regions

The transdisciplinary approach taken in CoCliME reflects increasing calls to improve the link between high-quality scientific outputs from marine based research and societal decision-making needs (Stenseth et al., 2020). Attending to the multiple drivers and consequences of coastal and marine ecosystem dynamics and changes—including those that contribute to HABs—requires that environmental decision-makers have access to the necessary knowledge to manage complex risks and changes in a flexible and adaptive manner (Cvitanovic et al., 2015). An adaptive management approach has been identified as vital for navigating these challenges; however, ensuring the necessary knowledge exchange and trust between scientists and environmental decision makers remains a significant obstacle (Cvitanovic et al., 2015; Stenseth et al.,

2020). Joint knowledge production processes involving scientists and societal decision-makers—also known as "knowledge co-production" —is increasingly advocated as a way to bridge the gap between the supply of and demand for scientific knowledge and to render scientific advice more actionable in practice (Lemos et al., 2012). Under the United Nations Decade of Ocean Science for Sustainable Development (2021–2030), for example, there are increasing calls for enhanced collaborations across scientific disciplines, geographic and political borders, and science-policy interfaces in order to improve the credibility, salience, legitimacy, and usability of ocean science (Claudet et al., 2020). It is within this timely context that we present lessons learned within the European CoCliME project, which aimed to address many of these challenges.

A number of authors have described the determinants of "high-quality" knowledge. In their seminal article: "Knowledge systems for sustainable development," Cash et al. (2003) draw on "lessons learned" from a series of cases to describe key qualities that enable knowledge systems to mobilize scientific and technological know-how to solve sustainability challenges. The authors show how success in connecting scientific information to decision-making is fundamentally linked to whether and how this "information is perceived by relevant stakeholders to be not only *credible*, but also *salient* and *legitimate*" (Cash et al., 2003, p. 8086). According to the authors, "credibility"…[refers to] "the scientific adequacy of the technical evidence and arguments" while "salience" refers to the extent to which the information that is produced meets the needs of targeted decision makers. "Legitimacy" has to do with the extent to which the production of knowledge, information or technology is inclusive and respectful of stakeholders' different values and beliefs and whether it is "unbiased in its conduct, and fair in its treatment of opposing views and interests" (Cash et al., 2003). Usefulness is defined by Lemos and Morehouse (2005, p. 63) as the extent to which knowledge and information are "provided in forms and at temporal and spatial scales that fit with user practices and needs." The related term of *usability* refers to whether stakeholders can "actually access and use the information in the form that it has been delivered," e.g., whether it is easily accessible online, in the local language of stakeholders, and in layman terms as opposed to scientific jargon (Lemos and Morehouse, 2005).

To date, global research efforts linking HABs and climate change have focused on enhancing the *credibility* of scientific knowledge through inter alia, conducting basic scientific research on the physical, biogeochemical and other drivers and mechanisms shaping HAB ecological dynamics. However, efforts to enhance the *salience, legitimacy, usefulness, and usability* of HAB research in the context of climate change have received comparably less attention. Yet HABs occur in coastal marine socio-ecological systems undergoing multiple sources of environmental, climatic, and socio-political changes, and are themselves driven by a complex interplay between anthropogenic and natural factors operating and interacting across scales. Addressing HAB risks to society, whether by reducing drivers such as eutrophication, mitigating impacts, or adapting to the consequences of marine ecosystem changes, therefore requires attention to the social, economic and governance—in addition to ecological—contexts that shape human-ocean interactions in particular contexts.

In the sections that follow, we outline the conceptual and methodological challenges we encountered in the project as we strove to generate *salient*, *credible*, *legitimate*, *useful,* and *usable* knowledge, information and services to support HAB-climate risk mitigation and adaptation activities in diverse geographic and sectoral contexts. Section Materials and Methods introduces the CoCliME project and regional case studies and describes the steps taken to document and synthesize project-wide "lessons learned." Section Results summarizes key lessons learned with respect to four areas of project implementation that correspond to the five knowledge quality criteria. Here we provide project-wide and case-specific examples of the main encountered challenges and our efforts at addressing them. Section Summary of Findings and Implications for the UN Decade of Ocean Science discusses the findings in light of the wider literature on knowledge quality criteria, climate and HAB risk management, and adaptive coastal governance and highlights the relevance of the findings for the UN Decade of Ocean Science for Sustainability. This section concludes with recommendations for enhancing the quality of knowledge and knowledge co-production processes to help society better understand, prepare for and manage HAB-climate impacts and risks in coastal and marine socio-ecological systems undergoing rapid changes where decision-making contexts are characterized by high uncertainties.

MATERIALS AND METHODS

Conceptual and Analytical Framework

To address the CoCliME objective of co-producing high-quality and transferable knowledge to help society better understand, prepare for and manage HAB-climate risks, we employ a conceptual and analytical framework that describes and links "lessons learned" within four key areas of project implementation to the five "knowledge-quality criteria" of *salience, credibility, legitimacy, usefulness,* and *usability* (described in section Harnessing High-Quality Knowledge for Adaptive Governance in European Coastal Regions) that have been identified as important pre-conditions for creating inclusive, robust, policy-relevant and actionable environmental research (Cash et al., 2002, 2003; Lemos and Morehouse, 2005). Specifically, our analysis focuses on lessons learned in relation to (1) Engaging stakeholders to incorporate their knowledge, experiences, interests and concerns (*legitimacy*); (2) Co-developing a shared terminology and framing of the "HAB-related problems" (*salience*); (3) Advancing scientific understanding of key drivers and interactions shaping HAB-climate risks (*credibility*) and; (4) Co-developing prototype services that integrate social and HABs-climate data and knowledge to support decision-making (*usefulness* and *usability*). The four areas correspond to key research objectives and activities that emerged as essential for improving the quality of knowledge for understanding and managing HAB-climate risks across five European regional cases (described further below). Our analyses are framed by a hybrid conceptual framework that draws on insights from the literature

on knowledge-quality criteria and discusses their relevance for HAB-focused climate services and HAB risk management and adaptive coastal and marine governance.

Since CoCliME investigated both the social and ecological dimensions of HAB-climate risks, "vulnerability" and "adaptation" in this article encompass both the ecological and social dimensions of these terms, while recognizing that they are understood and applied somewhat differently by natural and social scientists and in the fields of HABs and climate change research (see section Co-developing a Shared Terminology and Framing of the "HAB-Related Problems"). We therefore employ a broad definition of "vulnerability" that refers to the suite of factors that may render coastal and marine ecosystems, communities and associated sectors susceptible to sustaining harm from climate change, HABs, and their interactions. Similarly, and building partly on the IPCC (2014) definition of adaptation, in CoCliME, "adaptation" refers to socially- as well as biologically-adaptive strategies and actions taken in response to or anticipation of HAB and/or climate-related risks in order to moderate or avoid harm and/or exploit beneficial opportunities (see e.g., Field et al., 2014, p. 40). In the sense used in this paper, adaptation therefore also encompasses HAB risk prevention and mitigation strategies (see, e.g., Kudela et al., 2015). These definitions are consistent with the CoCliME interpretation of coastal and marine environments as constituting "coupled socio-ecological systems" (Whitney et al., 2017).

The CoCliME Project and Regional Case Studies

The transdisciplinary CoCliME project formed part of the ERA-NET Consortium "European Research Area for Climate Services," (ERA4CS), which was designed to boost the development of efficient climate services in Europe (http://www.jpi-climate.eu/ERA4CS). Under ERA4CS, "climate services" are defined as the "*user-driven development, translation and transfer of climate knowledge to researchers and decision-makers in policy and business. This includes knowledge for understanding the climate, climate change and its impacts, as well as guidance in the use of climate knowledge*". From the beginning, CoCliME set out to co-develop tailored, proof-of-concept and prototype HAB-climate services and a transferable framework to support HAB-climate risk management and adaptation decision-making in European coastal regions. The project focused on HABs as aquatic phenomena that are driven by a range of environmental (including climate) and anthropogenic factors, and their associated impacts on water quality, seafood safety, and different socio-economic sectors. To date, HAB-focused climate services remain in their infancy. For this reason, this pilot project drew upon and combined expertise from diverse scientific disciplines and intensive stakeholder dialogues with exploitation of existing data sets toward the goal of co-producing actionable knowledge to support HAB risk mitigation and adaptation decisions in specific contexts.

Our analysis in this paper draws on lessons learned across five regional coastal cases: the NE Atlantic (Ireland), NE Atlantic (France), Mediterranean, Baltic and North/Norwegian Seas. **Table 1** summarizes the geographic and sectoral focus, key stakeholders consulted and HAB issues addressed in each regional case. The cases are in turn briefly presented below.

NE Atlantic (Ireland)

Closures of aquaculture facilities are caused by *Pseudo-nitzschia* or *Dinophysis* biotoxin accumulated in filter feeding mussels and mortalities in fish farms are due to anoxic conditions produced by high biomass *Karenia* blooms. These blooms originate in offshore shelf waters and are carried to the inshore aquaculture sites by ocean circulation dynamics. In CoCliME a numerical physical hindcast and ocean climate model was developed and combined with *in-situ* biological information to investigate future possible changes and environmental linkages with HABs.

NE Atlantic (France)

Shellfish aquaculture in the area is threatened by *Alexandrium* spp. and *Dinophysis* spp. biotoxin-producing blooms. Research was undertaken on the biological aspects (food web structure) of the *Dinophysis* spp. that could be modulated by climate change, and on the economic losses of shellfish farm closures caused by the HABs.

Mediterranean Sea

In summer, recurrent blooms of *Ostreopsis* spp. are associated with acute respiratory and cutaneous disorders in beach users, workers and coastal inhabitants. Ongoing studies address the ecology, ecotoxicology, toxin aerosolization, epidemiology, economic impacts, and modeling bloom dynamics as a function of climate scenarios.

Baltic Sea

This semi-enclosed regional sea is characterized by limited wind mixing, low ventilation of deep water and multiannual eutrophication, which results in an excess availability of nutrients in the system. These conditions favor blooms of nitrogen fixing cyanobacteria in summer that cause problems for tourism and leisure activities and potential human health problems.

North/Norwegian Sea

In this area, the main HAB threats are posed by fish-killing microalgae (e.g., *Chrysochromulina*, *Pseudo-chatonnella*) that cause infrequent but massive mortalities of farmed fish in aquaculture facilities. HABs causing shellfish closures and recalls are also a recurring problem across the region. Research in this area is investigating the environmental conditions driving these blooms toward predicting their future dynamics, considering biogeographic shifts of HAB taxa and HAB risk periods.

The CoCliME Climate Service Co-development Approach

In CoCliME, co-development of case-specific proof of concept and prototype HAB-climate services was pursued with targeted stakeholders and end-users through an iterative process organized around project-wide "Engagement Points (EP)." The EPs (**Table 2**) were carefully designed to flexibly pursue co-discovery with relevant stakeholders in each case study in order to tailor and co-develop useful prototype services.

TABLE 1 | Summary of the CoCliME case studies discussed in this paper, the HAB taxa addressed, the sectors impacted and types of stakeholders consulted.

Case study	HAB taxa (impacts)	Sectoral focus	Types of stakeholders consulted
NE Atlantic (Ireland)	*Dinophysis* spp. (human health) *Pseudo-nitzschia* spp. (human health) *Karenia* spp. (fish-killing; ecosystem health)	Shellfish aquaculture and associated industries; Regional and local climate adaptation	Irish shellfish farmers, coastal adaptation planners, policy-makers and scientists in government agencies
NE Atlantic (France)	*Dinophysis* spp. (human health) *Alexandrium* spp. (human health) *Ostreopsis* spp. (human and ecosystem health)	Shellfish aquaculture associations and industry; Tourism	French shellfish farmers and regional shellfish associations; government authorities
Mediterranean Sea	*Ostreopsis* spp. (human and ecosystem health)	Tourism and health	Health and environmental authorities (France, Spain); local residents and tourists (France, Spain); transboundary environmental organizations (Monaco, France, Italy and Spain)
Baltic Sea	Cyanobacteria (ecosystem health)	Coastal and marine planning	Swedish coastal and marine planners and managers, and county water authorities
North/Norwegian Seas	*Dinophysis* spp. (human health) *Alexandrium* spp. (human health) *Chrysochromulina leadbeateri* (fish-killing)	Shellfish and fish farming industries; Tourism	Fish farmers, fishery authorities, HAB researchers and aquaculture-related interest organizations (Norway); Shellfish farmers and food safety authorities (Norway and Sweden); Water managers (Sweden); Conservation NGOs (Germany)

Table 1 provides an overview of the main types of stakeholders that were consulted in the different CoCliME cases. The EPs acted as a platform for the CoCliME partners to gather stakeholder input, discuss results, and further tailor product development to suit identified user needs. The EP format ranged in style from workshops, semi-structured interviews conducted in person or by telephone, to virtual online and/or one-to-one or structured group meetings and discussions and online surveys. Regular dialogue with key stakeholders was deemed important and carried out through established working relationships, partnerships, and professional forums/channels in many cases. The targeted stakeholders included co-developer partners identified at the start of the project, new co-developers, intermediary or end-user stakeholders identified during the course of the project, and scientific partners internal and external to the project.

RESULTS

Engaging With Stakeholders to Understand Their Priorities and Define the Focus of HAB-Climate Services

To ensure saliency and legitimacy, a climate service co-development process must take its starting point in thoroughly analyzing stakeholder priorities and decision-making contexts (Buontempo et al., 2017). Discussions and interviews with stakeholders at the start of the project (EP1) revealed that vulnerability and adaptation to and mitigation of HABs risks, are location- and stakeholder-specific and depend on a range of contextual factors. Characteristics of the bloom such as the timing of the onset, and the duration and location of blooms relative to the main periods of economic activity (e.g., during peak tourism season in the Mediterranean Sea, or during the fish growth period from smolts to adults in aquaculture pens in the North/Norwegian Seas), has a significant effect. Economic factors related to business activities that affect vulnerability and adaptive capacity to HAB risks include the size of firms and levels of integration and/or collaboration across them (with smaller firms typically, though not always, being more vulnerable), the extent of economic diversification across geographic areas, species and markets, the potential for substitution (i.e., sourcing fish or shellfish from other locations), the flexibility of operations (e.g., the potential to move planned maintenance activities to periods of closures, delay harvesting, and the flexibility of the workforce), and the extent of economic support mechanisms such as insurance or other compensation measures in the event of prolonged closures or large-scale mortalities of farmed fish. Technological factors such as access to, and ability to implement, mitigation options, such as raising or lowering fish cages, and the use of physical control methods such as "bubble curtains" (e.g., Gallardo-Rodríguez et al., 2019) also play a role. Finally, aspects related to the social infrastructure, including the extent of local networks and cooperation for monitoring, mitigation, and emergency preparedness and response, shape stakeholders' vulnerabilities, and adaptation to HAB risks and their ability to mitigate impacts (e.g., Le Bihan et al., 2013; Guillotreau et al., 2017). For example, CoCliME interviews conducted with Norwegian aquaculture stakeholders that were affected by a devastating bloom of *Chrysochromulina leadbeateri* in northern Norway in 2019 revealed that close cooperation between family-owned salmon farming firms in the affected region was decisive for managing the effects of the bloom.

The perceived importance of HAB risks, relative to other risks, moreover varies according to the occupational and professional roles and knowledge and background of different

TABLE 2 | Focus and aims of the project-wide Engagement Points (EP).

EP	Short name	Focus and aims
EP1	"User needs and experiences"	Document stakeholder knowledge, interests, concerns and needs related to HABs and climate change risks; enhance CoCliME partner understanding of stakeholder adaptation and mitigation options and potential need for HAB-climate services
EP2	"Ambition with climate services"	Map existing HAB-climate services and technology readiness levels (TRLs); establish TRL ambitions; refine stakeholder and scientific focus in the different cases
EP3	"Stakeholder feedback" *Originally entitled: "Future risks and adaptation options"*	Present and discuss preliminary results that could feed into a prototype HAB-climate service with targeted stakeholders; discuss the format and content of potential services and gather and/or synthesize social, economic, statistical, ecological and other data needed to develop the service
EP4	"Implementation"	Co-develop, test and/or implement prototype HAB-climate services; identify and discuss implementation and sustainability opportunities and challenges with stakeholders
EP5	"Dissemination and evaluation"	Presenting project results; identify wider dissemination pathways for CoCliME prototype services

stakeholders. In cases having shellfish aquaculture as a focus, some stakeholders have extensive experience and well-developed adaptation strategies for dealing with regularly occurring HABs on a seasonal or cyclical basis. In other cases, sporadic, major bloom events that occur with no forewarning and cause massive mortalities of farmed fish are a key concern. Economic risks and impacts from pathogens that cause shellfish mortalities are a more important concern than HABs in some regions while in others, predation by starfish, jellyfish and eider ducks are key concerns. In cases where the linkages between HABs and human health are not obvious or well-established, local residents and tourist stakeholders may not be fully aware of potential HAB risks.

Stakeholder perceptions and concerns about climate change in relation to HABs moreover varied widely. Some stakeholders in the NE Atlantic (Ireland) and North/Norwegian sea cases expressed specific concerns about potential risks associated with new invasive HABs species, driven by climate change. Most stakeholders however, noted that climate change is only one among multiple factors driving HABs, and recognize that large uncertainties are involved when trying to project HABs into the future. To meet stakeholder needs and interests, CoCliME researchers had to maintain a high level of flexibility. For instance, in the Irish case, regional policy makers asked specifically for a climate information service in the form of outreach material for local authorities and the public. To accommodate this request, CoCliME activities were realigned, and the scientists worked with the co-developer and a designer to produce graphics and climate information suitable for the target audience. Co-creating outreach material from technical results with the end-user was a helpful exercise and highlighted the importance of addressing end-user's interests and needs and working together to produce useful decision support products.

In summary, experiences in CoCliME suggested that stakeholders have varied understandings, awareness and priorities when it comes to HABs and climate change risks and their management that affect the perceived saliency of a HAB climate service. These factors needed to be assessed thoroughly in a co-design process, where stakeholders' knowledge, experiences, interests, and concerns constituted the starting point for finding the appropriate focus and entry-points for service development. The EP format in the project was therefore tailored in each case to support co-design and co-development of prototype services at local scales that were differentiated according to case study-specific parameters and stakeholder needs and realities. Stakeholders' varied climate-change perceptions and understandings, HAB and climate service knowledge, interests and priorities, and their perceived vulnerability and strategies for avoiding, adapting to and managing HAB risks formed an important backdrop for co-developing a shared terminology and framing of the "HAB-related problems" to be addressed in each case, to which we turn in the section below.

Co-developing a Shared Terminology and Framing of the "HAB-Related Problems"

Conceptually, "framing" refers to "a process by which actors construct and represent meaning to understand an event, process, or occurrence" (Lugen, 2020, p. 2). The act of framing includes the definition of scientific terminology whereby "individual disciplines and their associated academic networks can be understood as communities of practice which "make meaning" by creating and reinforcing a shared frame around their research topic" (ibid). The framing of scientific problems reflects shared assumptions and values within a scientific community as expressed in research methodologies, hypotheses, and in specific forms of expert language. For example, the term "harmful algal bloom" is essentially a "societal term" (Smayda, 1997) that is species-specific and defined normatively according to what society judges to be "harmful." As a transdisciplinary project involving multiple cases and disciplines and seeking to integrate different forms of scientific and lay expertise, the implicit assumptions, discourses, terminology, language and epistemological, conceptual and methodological approaches employed within and across the project differed substantially. Differences in the terminology and scientific approaches employed within and across the consortium were not always openly discussed or communicated at the start of the project. It moreover became clear early on that scientist and stakeholder understandings and framings of the importance of HABs and climate change for decision-making and salient problems to be addressed differed substantially in some cases. This led to

plural understandings of how to approach climate service co-production and created some challenges for integrating and connecting knowledge and data at later stages of the project.

Language and Terminology

Two examples illustrate the diversity of ways in which CoCliME scientists approached key language and terminology. The first example concerns the terms "mitigation," "adaptation, "adaptive capacity" and "resilience." The term "mitigation" in a HAB context refers to human actions taken to reduce the ecological or societal impact of a HAB event, while for climate change, it refers to efforts to reduce local and global emissions of greenhouse gases. Examples of HAB mitigation activities at the firm level include moving fish cages away from a patchy high biomass bloom or transferring shellfish into depuration tanks to remove accumulated biotoxins that can harm consumers if eaten. Governments may facilitate HAB mitigation through the provision of subsidies or compensation measures to individual firms that limit the potentially devastating local consequences of major bloom events.

From a social science perspective, adaptation, adaptive capacity and resilience refer to how an individual, a company or firm, a community, sector or even a country acts to achieve health and well-being in the face of complex socio-economic and environmental change processes (Smit and Wandel, 2006). Societal vulnerability, adaptive capacity, and resilience are interlinked, context-specific, socially differentiated, and shaped by a range of social, political, institutional, economic and environmental aspects and interactions (Engle, 2011). Since coastal and marine environments constitute "coupled socio-ecological systems," there is a need to incorporate and address both the ecological and social dimensions of these terms (Whitney et al., 2017).

From an ecological point of view, "adaptation" and "adaptive capacity" refer to biologically adaptive strategies to ensure survival and reproduction of the organisms within any ecosystem (Whitney et al., 2017). For example, the microscopic biotoxin-producing microalga *Dinophysis* is a predator that feeds on other microorganisms (ciliates called *Mesodinium rubrum*), which in turn feed on smaller microflagellates such as *Teleaulax amphioxeia*. *Dinophysis* blooms are dependent on food sources (prey) that are sensitive to marine environmental factors that vary with changes in physical parameters (e.g., temperature, pH and light). Thus, in CoCliME, laboratory studies were conducted with these microorganisms to explore their potential *adaptive capacity* to climate change scenarios. Related to the ecological definition of "adaptation" is the concept of "ecological niches," which are the ensemble and ranges of environmental conditions (physical and biogeochemical) that define where an organism has adapted to live.

A second example is the term "climate services," a relatively new term for which there are a number of definitions operating in research, policy and practice. While CoCliME adopted the definition of climate services employed by the ERA4CS (see section The CoCliME Project and Regional Case Studies), natural and social scientists in the project interpreted the term depending on their particular perspectives. For physical oceanographers focused on open sea environments such as the Baltic Sea and the North Seas, climate services consisted of providing hindcasts and forecasts of the marine environmental properties that influence the occurrence of high biomass HABs. In this case, well-organized and technically supported numerical modeling tools were necessary to develop the climate services. In the NE Atlantic (France) case study, the target for climate services was *Dinophysis*, a highly toxic HAB species, that even at low biomass can contaminate shellfish and cause shellfish poisoning if consumed by humans. For the natural scientists in this case, a key focus was on filling knowledge gaps on small scale ocean processes affecting the bloom and clarifying the adaptation of essential *Dinophysis* food web components to changing light, temperature and pH conditions (Gaillard et al., 2020). Knowledge at this small scale can be combined with physical oceanographic numerical modeling of future scenarios to progress climate service development (Ralston and Moore, 2020). On the social science side, economists worked to develop a harmonized database of shellfish farming closures in order to assess the economic impacts of the closures. Both types of data are needed in order to provide actionable information to decision makers working to reduce the economic and health impacts of *Dinophysis*-related shellfish farming closures in the area.

Establishing Salience: Understanding the Reason for Concern

One of the key challenges we faced as a project from a scientific point of view was to develop HAB-related data products that contribute to services that can help the end user(s) to make decisions. On the natural science side, the entry-point for service development was on addressing knowledge gaps that prevent connecting and integrating information about HABs with information about climate change. On the social science side, interactions with stakeholders during engagement points generally revealed that HABs are only one part of a complex multi-risk picture and may not be the most important or impactful risk that they need to consider in their decision-making.

Several examples from stakeholder engagements undertaken during the project highlight this point. For instance, shellfish and fish farmers are usually concerned with factors that affect mortality of shellfish or fish since these lead to direct losses that cannot be recuperated by delaying harvesting, and often cannot be foreseen through monitoring or other efforts. Other factors affecting mortalities that were identified by shellfish and fish farmers in the North Sea and Norwegian Sea case study included marine pathogens, oxygen depletion, predation by other species (shellfish), sea lice and other diseases (in the case of fish). In the Baltic Sea case study, it became clear that HABs are one aspect or indicator of ecosystem health and water quality that need to be considered by marine spatial planners, alongside numerous other factors. For food safety authorities, HABs are one aspect of monitoring and regulation of harmful substances in seafood consumed by people in Europe and globally (see for example the European Food Safety Agency webpage, https://www.efsa.europa.eu/en). In addition to well-known seafood poisoning risks caused by harmful algae, care

is taken to protect consumers from emergent poisonings, such as those associated with the tropical genus *Ostreopsis*, which produces potent toxins that can be transferred through the food web and can cause respiratory and cutaneous irritations on beach users, inhabitants and workers exposed to marine aerosols during the summer vacation period (e.g., Berdalet et al., 2016; Vila et al., 2016 and references there in) with implications for both human health and tourism in affected regions. The challenges for the scientific stakeholders involved in *Ostreopsis* monitoring in the Mediterranean Sea case study in CoCliME included adequately informing the population without causing alarm, while also communicating with health authorities to distinguish between microalgae-induced respiratory problems and similar disorders caused by virus or bacteria, which may require specific types of treatment. Like other HABs, *Ostreopsis* blooms moreover appear to be driven by a combination of climate (e.g., ocean temperature-related) factors as well as alterations of the coastal zone due to factors such as infrastructure development in coastal areas and beach erosion caused by violent storms. For health authorities, bacteria and chemical contamination due to sewage and agricultural runoff are further concerns which may increase in the future due to climate change-induced alterations in the frequency and intensity of extreme weather.

In Ireland, the Climate Action Regional Office (CARO) with whom CoCliME scientists partnered is responsible for coordinating regional climate action and providing guidance, advice and support to local governments and the communities they serve on national climate change policy. During interviews and discussions, they explained that coastal communities in Ireland are especially in need of climate services that can assist them to adapt to extreme weather events such as floods and storms, as well as longer-term processes such as sea-level rise and associated impacts such as submergence, flooding, shoreline erosion, salinization and wetland change. Since local authorities provide hundreds of services ranging from roads, planning, housing, economic and community development, environment, recreation, and amenity services, libraries and fire services, HABs were not considered by the CARO to be a primary concern for communities. However, community adaptation strategies are currently being developed under Ireland's Climate Adaptation Framework, with a view to identifying what functions are at risk from climate change and what action is needed to adapt and build resilience. This requires an understanding of the multiple risks and impacts of climate change across many categories (social, economic, cultural, infrastructure, ecosystems etc.) with HABs constituting one of the many hazards to consider.

Our findings thus point to the need to take a more holistic approach to the concept of "service development" as encompassing more than HABs. This resonates with scholarship on the links between climate change and societal vulnerability and adaptation, which has long recognized that people are not vulnerable or adapting to climate change risks independent of other hazards or risks. Climate change is only one type of change and "stressor" (and not always the most important one) to which people are responding Leichenko and O'Brien (2000).

In summary, in CoCliME scientists and stakeholders brought different conceptual and methodological entry-points, expertise and concerns to the table in seeking to study and address the complex interface between climate change and HABs. The plural definitions and ambiguity in the concepts and language used by scientists and stakeholders affected how HAB-climate change risks were understood, framed and approached scientifically and in practice. The fact that HABs are one of many challenges facing operational stakeholders and coastal decision-makers poses particular challenges for efforts to co-design services that link the two.

Advancing Scientific Understanding of Drivers and Interactions Shaping HAB-Climate Risks and Societal Impacts

CoCliME experiences highlighted that, in general, transdisciplinary research linking physical climate, marine ecology, and social science approaches with information about salient societal information needs can guide the process toward co-developing credible HAB-climate services. CoCliME aimed to co-develop HAB-related climate services and thus needed to anticipate future trends of HABs and their societal and ecological impacts. The partners identified existing tools and knowledge that could contribute to co-develop a wide range of prototype HAB-related climate products and services (see **Table 3**). Overall, efforts to generate a credible knowledge base resulted in important scientific advancements. However, several critical knowledge gaps remain, including the link between environmental changes and HAB responses, and the interactions between HABs and essential climate variables. These gaps are linked to the complex environmental interactions of HAB dynamics, limitations in data availability, and lack of statistical and modeling expertise in the project. These challenges and their implications for the co-development of credible HAB-climate services are discussed below.

Gaps in Basic Knowledge to Determine HAB Species Ecological Niches

Despite increasing scientific knowledge, there remain large uncertainties about the precise linkages between climate change and specific HABs due to the complexity of biogeochemical-climate interactions for different HAB types and locations (Wells et al., 2015). In many cases environmental drivers of HABs are not fully understood (e.g., see Hallegraeff, 2010; Wells et al., 2015 and references therein). While underlying conditions necessary for HAB events are often described in the literature (e.g., Raine, 2014), it is acknowledged that the presence of such "HAB suitable" conditions may not lead to a bloom event. There is also a miss-match between observed HAB numbers and recorded toxicity that is in some cases attributed to differences in the production of biotoxin by different phytoplankton species of the same genus, or toxic and non-toxic strains within a species (e.g., Trainer et al., 2012), or environmental control (temperature, nutrient availability) of biotoxin production. In other cases, the reasons are still poorly understood. Phytoplankton can have a rapid (within days) response time to changing environmental conditions. It is therefore reasonable to compare HABs to environmental

TABLE 3 | CoCliME prototype HAB-related climate products and services.

Cases	CoCliME products and services
NE Atlantic (Ireland)	Scientific data products and hindcast and ocean climate models (SW Ireland) to share with researchers (intermediary service) CoCliME co-created graphical illustrations to be used by the project partners and co-developers to raise awareness about ocean climate change and HABs as a downstream service for policy makers and the general public
NE Atlantic (France)	Harmonized database on shellfish farm closures and economic impacts Transnational ocean particle tracking modeling in the NE Atlantic which can be made available to future projects Biological model on *Dinophysis* prey available to modelers HAB datasets incorporated into REPHY monitoring
North/Norwegian Seas and Baltic Sea	Hindcast and ocean climate projections for the Baltic Sea Analyses of cyanobacteria time series data Tools for analyzing and visualizing model and observational results (Python and R-scripts) Molecular HAB detection training for national monitoring programme scientists Proposed method to include harmful algae blooms in a marine spatial planning tool (Symphony) Proposed linkage of HAB monitoring and development of an early warning system for the Kattegat-Skagerrak region Co-development of a national website (one-stop shop) to connect and share HAB-related observations and early warning information (Norway)
Mediterranean	CoClimer package (package for the statistical description and analysis of HAB-forming organisms time series) *Ostreopsis* dataset in the Catalan coast CoCliME *Ostreopsis* climate service v0.1 (Predicted maps of present and future abundances of *Ostreopsis* cf *ovata* along western Mediterranean shores) Co-design of and training for a Mediterranean *Ostreopsis* monitoring programme

conditions at the same point in time and environmental conditions several days prior to HAB observations. It is also possible for HABs to have a slower response time or that pre-Spring bloom environmental conditions have significant effects on whether HABs will develop later in the year or not. It is also possible that there is a mismatch between the location where HABs are observed and the environmental drivers. This means that underlying environmental conditions that stimulate HAB growth are missed at unmonitored sites where HABs develop unobserved before being transported in ocean currents to the monitoring sites where they are recorded (e.g., Anderson et al., 2019).

Limitations of Data Availability

High quality, comparable, long-term environmental and HAB data are essential to assess and manage HAB risks over a range of timescales. HAB events are generally only recorded at fixed locations such as at shellfish harvesting sites or popular tourist destinations. Fluctuations in marine algae and plankton are a natural—and also essential—part of marine ecosystem dynamics and food web structure. Toxic or harmful algae may be present in marine ecosystems, but go undetected, or may not result in an algal bloom that is associated with negative societal impacts, complicating detection and assessment of ecological impacts. Due to limited resources, HAB records might only be available seasonally, at few sites and at a fixed water depth or as depth integrated samples. Data on ecological impacts are normally not recorded in a systematic way; surveys are generally only carried out on an *ad-hoc* basis, in response to HAB events that have caused economic impacts (closures of shellfish harvesting sites, death of farmed fish), with fragmented reports and accounts of the ecological impacts. Key drivers of phytoplankton succession, such as nutrients, prey and competition are missing for many case studies. Monitoring of HABs was insufficient in some CoCliME regions (e.g., enhanced monitoring was needed to address an exceptional fish killing bloom in Norway). While the partners worked with policy makers to address these issues, the important lesson here is that individual champions and formalized, cross-border collaboration and funding are required to sustain such activities in the long term. Similarly, a lack of historical high quality sustained ocean observing data needed to do trend analysis posed challenges to generating credible data in some cases. A lack of long-term observational data can lead to flawed decision-making due to insufficient understanding of natural and anthropogenic-imposed variability over time (Stenseth et al., 2020). The relatively short time series inhibited progress in the data analyses activities in all of the cases. Climate change is measured over centuries, with at least 30 years of data needed to calculate climatological averages, while most biological HAB datasets are only 20 years in length. While some trends were observed, the high interannual biological variability made it difficult to identify statistically significant trends in many of the available datasets. A substantial share of the project time was therefore spent on gathering baseline information on environmental, social and climate variables to create credible knowledge about the links between environmental change and HABs.

Limited Statistical and Modeling Expertise and Short Duration of the Project

Lack of numerical and statistical experts, and bottlenecks related to accessing modeled data in the right format for biologists to use in data analyses posed additional challenges. European downscaled ocean climate models were, unfortunately, unavailable from data repositories at the start of the CoCliME project. This inhibited progress in some areas as only a few partners had funds to develop ocean models for specific regions. Fortunately, more downscaled ocean models are becoming available in this area of research; this is welcomed by the community. The modelers in the project responded to a need expressed by the biologists to develop a data extractor to condense numerical model information into usable formats. A CoCliME expert hosted training courses and shared an application to facilitate time series analyses. However, time limitations within the project proved to be one of the biggest challenges in CoCliME, as it takes time to do basic scientific research. While this inhibited progress in areas of basic science

that are critical to advancing HAB-climate services, the modeling approaches used in HAB projections were shared between partners in order to help build capacity within organizations and the information generated will be made publically available to enable learning in the wider scientific community. In addition, CoCliME was involved in documenting the best practice on how to create a weekly HAB bulletin to assist other regions (Leadbetter et al., 2018; Pearlman et al., 2019).

Challenges in Assessing HAB Impacts

HAB socio-economic impacts include both tangible and intangible economic, and non-economic impacts related inter alia to shellfish and/or beach closures and mortalities of farmed fish (Trainer, 2020). To date, a lack of comparative methodologies to study these impacts, which are often case-specific, complicates efforts to derive more general lessons about the costs of HAB events and the costs and benefits of measures to mitigate these impacts (ibid). While intangible and non-economic impacts of HABs are less studied and may be more difficult to assess quantitatively, recent studies indicate that they may nonetheless be substantial, and may include impacts such as psychological and mental stress, loss of traditional ways of life, recreational opportunities, spiritual and aesthetic experiences in nature, sense of individual and collective identities and cultural attachment and place-belonging (Ritzman et al., 2018; Willisa et al., 2018). The economic and social impacts of shellfish closures may extend beyond coastal and marine-based harvesting activities and into other sectors, such as tourism.

In terms of human health impacts, many HABs produce biotoxins that affect human health through food-borne poisonings, or exposure to aerosols, or direct contact with water (as indicated above). While most HABs are natural phenomena and unavoidable up to a certain point, their impacts on human health can be prevented. However, misdiagnosis and underreporting are common concerning HAB-related health impacts. Emerging biotoxins are moreover less well-characterized and constitute new challenges.

Assessing and Communicating HAB-Climate Risks

Assessing and communicating HAB-climate risks to the public and determining the vulnerability and adaptive capacity of various societal actors, sectors and communities to coupled HAB-climate risks is complicated by several factors. First, despite increasing scientific knowledge, there remain large uncertainties about the precise linkages between climate change and specific HABs due to the complexity of biogeochemical-climate interactions for different HABs and locations (Wells et al., 2015). This limits the informative value of marine ecosystem- or climate indices or indicators in predicting the exposure of societal actors to climate-induced changes in the frequency, intensity or spatial occurrence of HABs. Second, the presence of potentially toxic HAB species or environmental conditions favoring their presence, does not necessarily translate into observable ecological, social or economic impacts. Third, the potential for direct and indirect economic, health, and/or intangible impacts of HABs are mediated by how HAB risks are determined scientifically and legally (e.g., biotoxin threshold levels above the EU regulatory limits) as well as how such risks are communicated, experienced and perceived by different actors. For example, precautionary measures taken to reduce the potential impact of HABs on public health, such as closure of beaches in areas where there is a projected threat, can have major economic impacts on tourism, irrespective of whether the HAB risk materializes. In a similar vein, but, with respect to health, residents may choose to ignore warnings about potential shellfish poisoning or beach closures in their area, due to subjective perceptions of vulnerability and higher levels of risk tolerance. These examples illustrate that there is not a simple, linear or causal relationship between the detection and communication of HAB risks, actions taken to avoid, reduce or adapt to them, and efforts to evaluate HAB impacts.

In summary, we find that sustained investments in long-term HABs and environmental modeling, in securing social and economic expertise, and in training and capacity building to connect different communities of practice, are a prerequisite for co-developing credible and actionable HAB-climate services. The fact that large scientific uncertainties remain regarding the biophysical drivers of HABs, the outcomes of different climate scenarios, and the societal vulnerabilities, impacts, adaptive capacities and risk perceptions of particular communities and sectors, highlights that renewed investments are needed in transdisciplinary HAB science and in continued maintenance and optimization of existing HAB monitoring programmes to provide long term datasets and test the validity of models (Ralston and Moore, 2020). Enhancing understanding of the risk perceptions, institutional, business and decision-making contexts and adaptation processes of different end-user groups further requires dedicated social science expertise and is necessary in order to ensure that salient, credible and timely advice is included in HAB and climate risk mitigation and adaptation plans.

Co-developing Prototype Services That Integrate Data and Knowledge to Support Decision-Making

Co-developing prototype services that incorporate and integrate different sources and types of data and knowledge in order to inform HAB risk mitigation and adaptation decisions in diverse contexts posed particular challenges in CoCliME. Below, we discuss key lessons learned relating to scientific integration, knowledge co-production and service co-development and propose potential strategies for making HAB-climate information more useful and actionable.

Integration Across Disciplines, Cases, and Types and Scales of Data

CoCliME drew upon and sought to combine a wide range of natural and social science expertise covering oceanography, marine biology, ecology, numerical and statistical modeling, chemistry, economics and geography as well as combining traditional, science-focused, and applied research organizations. The diversity in conceptual and methodological approaches and epistemologies with respect to applied, vs. basic research was substantial, and posed challenges at times to meaningful

integration. The CoCliME project design was moreover highly ambitious in targeting numerous HAB taxa over several geographic regions, with multiple sectors, stakeholders and impact areas to address. The diversity of HAB taxa and their ecological niches and societally relevant impact areas necessitated approaching the study of HABs from multiple perspectives and at different scales simultaneously. Accordingly, the events and processes studied within the project ranged from adaptive cellular processes (namely, biotoxin and cell growth) of individual HAB species to environmental changes (defining ecological niches), to the impacts of HAB events on ecosystems, local and regional economies and human health. Exploratory investigations were in some cases also carried out into how society may adapt to changing marine ecosystems, considering local, regional and global-scale ocean climate projections and their uncertainties. Finally, because the ocean has no borders, some HABs were analyzed from a transboundary perspective where similarities and differences in administrative, ecological, physical, sectoral, or other boundaries had to be considered in order to mitigate potential HAB and climate change impacts and their interactions. While addressing multiple objects of study increased the salience of the research, this context-specific approach prevented making systematic comparisons across cases.

As highlighted in section Advancing Scientific Understanding of Drivers and interactions Shaping HAB-Climate Risks and Societal Impacts, a lack of comparable, long-term data, and difficulties in accessing and processing data in some cases posed further challenges to knowledge integration. Existing historical data sets come with a legacy in that they were collected for a specific purpose (e.g., EC Directive-driven national biotoxin and HAB monitoring programmes) and not necessarily for climate change studies or climate service development. Difficulties arise when climate models are only available in offshore waters and nearshore areas are unresolved. Key lessons learned in this respect relate to the need for long-term and interconnected environmental monitoring systems, for consistent social science, modeling and statistical expertise in the different cases, and for FAIR (findable, accessible, interoperable and reusable) and open data policies to facilitate data transparency and retrieval.

From Knowledge to Services: Translating Science into Usable Knowledge

Co-producing actionable, high-quality HAB-climate services through a process that is perceived as meaningful to stakeholders requires consideration of the relevant time-horizons for decision making and managing stakeholder diversity and expectations.

Short- vs. Long-Term Data

In discussions with stakeholders, it proved useful to conceptually distinguish between short-term and long-term climate service needs. In the short-term, the focus typically lies on mitigating risks associated with specific extreme HAB events, for which climate services such as improved monitoring and early-warning systems are required. In a longer-term perspective, where the focus is on enhancing resilience and adaptive capacity, a climate service may aim to support ecological and social adaptation to multiple stressors and reduce concurrent anthropogenic pressures on the coastal and ocean environment, such as reduced eutrophication in the Baltic Sea, or reduced coastal development in the Mediterranean.

Overall, most operational stakeholders expressed a preference for short-term information such as real-time, early-warning information or information about potential HAB developments for the coming season or year. Establishing, maintaining, and enhancing HAB monitoring systems in the short-term is needed to form a basis for providing "early warnings" of HABs, but could also inform medium- to long-term decisions connected to marine management.

Diverse Stakeholders

At an early stage of the project, investigations revealed a highly diverse set of stakeholders, ranging from national and local government agencies, to the tourism industry, to individual shellfish farmers and researchers (see also **Table 1**). The diversity in stakeholder types translated into varying knowledge and capacity, information needs, and different levels of prior or ongoing working relationships between scientists and stakeholders. In some cases, such as in the North/Norwegian sea, this made it difficult to identify a clear direction for developing the content of particular services. To address this complexity, stakeholder mapping exercises were carried out for each of the case studies, using interest/influence matrices (adapted from Mendelow, 1981) to identify appropriate target audiences for the climate services to be co-developed (see **Figure 1**).

Further, early stakeholder assessments revealed that there was often limited overlap between stakeholders with high influence and high interest in HABs climate services. Notably, efforts to engage government representatives were often time-consuming, partly due to lack of interest in the proposed services. To some extent, this was mitigated by adjusting the methods of stakeholder engagement, for example by switching from larger workshops or online surveys to one-on-one interviews and meetings and regular engagements. In addition, the limited interest in the originally perceived climate services required a change in scientific focus within the project in some cases to better address stakeholder knowledge, interest and concerns. While this was possible in several cases, maintaining flexibility remained a challenge given that the scientific consortium and scientific focus were already to a large degree set.

Managing Stakeholder Expectations

With generally low TRL levels for the co-developed climate services, managing stakeholder expectations proved a challenge. The knowledge base on HABs was often limited, which required transparent discussions with end-users about limitations, uncertainties, and data resolution, to clarify the potential usefulness and reliability of the climate services as decision-support. Feedback from stakeholders in a number of cases, however, revealed that non-tangible outputs of the co-development process, such as improved relationships, networking, trust, access to scientific expertise and capacity building may be of equal importance as the data and information provided to stakeholders, and constitutes a solid foundation for further science-practice collaborations.

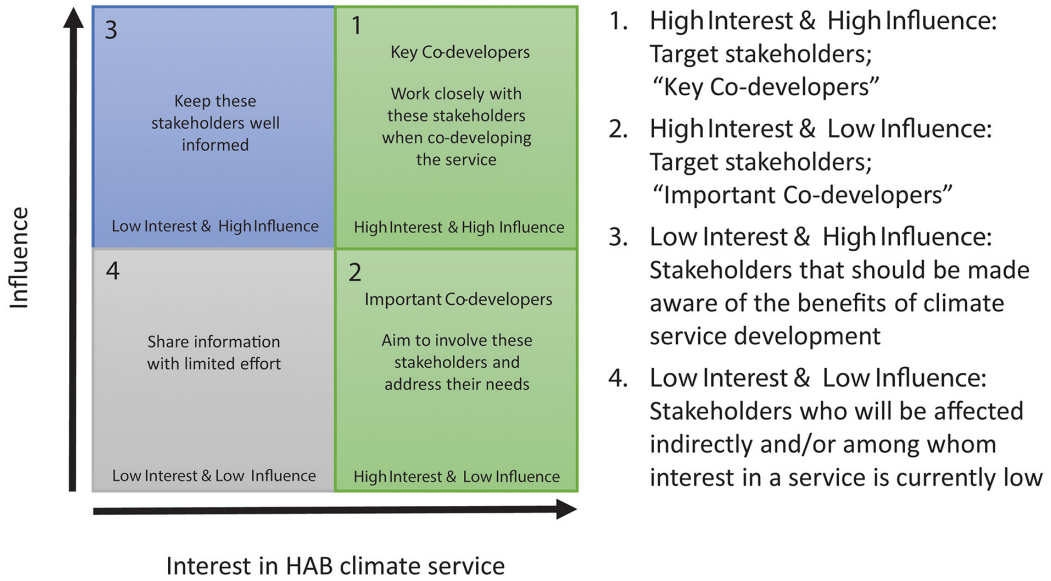

FIGURE 1 | Stakeholder interest-influence matrices were created for each of the case studies. The position of stakeholders in the matrix reflects the identified stakeholder group, their interest in the proposed climate service and their influencing power. Modified version of Mendelow (1981).

Maintaining momentum and stakeholder engagement over the course of the project was also sometimes difficult because the research processes were time-consuming and at times delivered inconclusive results that were not useful to stakeholders. A possible way forward is to focus on enhancing adaptive capacity of ecosystems and institutions to deal with a range of uncertainties, scenarios and changes, irrespective of how specific HABs will develop in the future. Experiences from CoCliME have shown that there is a need to focus on improving or modifying existing services such as HAB monitoring systems, reducing concurrent anthropogenic pressures on the marine environment, such as controlling eutrophication and preventing habitat destruction or modification in coastal areas, as well as focusing on the need to enhance decision-making under uncertainty. Another way forward would be to focus on improving marine planning and governance by placing HABs in a multi-risk context. In CoCliME's Baltic Sea case study, this was addressed by preparing to integrate HABs data into a marine spatial planning tool called Symphony, which includes data on a range of human-driven impacts of importance to marine spatial planners, including marine pollution, fishing, shipping, and climate change (Hammar et al., 2020).

Our experiences also point to the value of building on or connecting to pre-existing climate services, to increase their usefulness, narrow the scientific focus, and identify relevant stakeholders. For instance, in the Baltic Sea case study, shifting focus toward a climate service that could feed into an existing marine spatial planning tool clearly ensured interest and reduced the risk of stakeholder fatigue. Another option is to focus on piloting a service on a small scale, to maintain flexibility and ensure that adjustments can be made to meet stakeholder needs. For example, approaches that engaged stakeholders in easy and simple monitoring in coordination with scientists, as conducted to detect *Ostreopsis* presence and blooms in Mediterranean beaches, proved successful and encouraging.

SUMMARY OF FINDINGS AND IMPLICATIONS FOR THE UN DECADE OF OCEAN SCIENCE

Lessons learned during the process of implementing the transdisciplinary CoCliME project suggest that progressing and connecting fundamental science with societal needs, understanding the multi-risk decision-making context within which different stakeholders comprehend, appraise and frame HAB and climate change risks, attending to the short- and long-term aspects of HAB-climate service development, and approaching knowledge co-production in transdisciplinary projects as a learning process are all necessary to generate more *salient*, *legitimate*, *credible* and *useful,* and *usable* knowledge. Below, we discuss these key findings and their relevance for enhancing the quality of HAB-climate knowledge and services and addressing key challenges and outcomes that have been prioritized under the UN Decade of Ocean Science for Sustainable development 2021–2030 (UNESCO, 2020), hereafter referred to as "the UN Ocean Decade."

Understanding the Multi-Risk Decision-Making Context for HAB-Climate Risk Mitigation and Adaptation

Enhancing community resilience to ocean hazards has been identified as a key priority under the UN Ocean Decade (UNESCO, 2020, p. 11). Findings from CoCliME concur with other studies that understanding the operational, sectoral, social and economic decision-making contexts and capacities in HAB risk management is essential in order to co-produce high-quality and actionable knowledge to inform societal adaptation decisions (Buontempo et al., 2017). We find that enhancing community resilience to ocean hazards such as HABs requires knowledge of the biology and ecological dynamics of the different harmful organisms, and attention to the different spatial and temporal scales, frequency and severity of harmful impacts and risks faced by diverse stakeholders, regions and sectors. Our findings further show that different stakeholders and scientific disciplines understand, frame and appraise HABs and climate change risks, and adaptation and risk mitigation options in different ways. Developing a shared understanding and framing of the salient problems to be addressed in research involving complex socio-ecological systems and change processes is a challenge that is widely highlighted in the literature (e.g., Djenontin and Meadow, 2018). The way problems are framed, shapes the approaches to studying them and the solutions generated to address them. Experiences in CoCliME therefore underscore the need for involving stakeholders and their knowledge, and for including mechanisms to facilitate inter- and transdisciplinary communication and understanding, early in the project. These findings echo calls for interdisciplinary and transdisciplinary approaches, broad involvement of stakeholders, and active engagement of social and behavioral sciences in ocean research under the UN Ocean Decade (UNESCO, 2020). They are further in line with those of Dilling and Lemos (2011) and Sarewitz and Pielke (2007) and many others who highlight the importance of stakeholder involvement in knowledge co-production processes in order to bridge the knowledge-usability gap. Including a strong social science component, investing time in developing interdisciplinary communication and allowing for methodological and ontological pluralism in transdisciplinary projects are additional lessons learned in CoCliME that echo findings from other studies (e.g., Lowe et al., 2013; Klenk and Meehan, 2015) and that should continue to inform scientific efforts under the UN Ocean Decade.

To be *credible*, *salient,* and *legitimate*, decisions concerning investments in basic science, early warning systems, monitoring and various HAB mitigation and risk management measures should take their starting point in understanding stakeholders' multi-risk decision-making contexts and information needs, the key scientific knowledge gaps, and the expected costs and benefits of implementing different risk mitigation measures (Le Bihan et al., 2013). Acknowledging that enhanced precision and credibility of scientific information does not always translate into immediate or short-term action (Dilling and Lemos, 2011) and that decision-making under uncertainty is the norm in climate adaptation, the costs of investing in different HAB risk mitigation and adaptation measures need to be weighed against the potential societal risks that HABs pose, and the benefits that high-quality information can provide to different public and private-sector stakeholders (Trainer, 2020).

Need to Progress and Connect the Basic Science With Societal Needs

The UN Decade of Ocean Science underscores the need for a safe ocean, "where people are protected from ocean hazards" and a predicted ocean, whereby "society has the capacity to understand current and future ocean conditions" (UNESCO, 2020, p. 10). Experiences gained from the co-production processes undertaken in CoCliME highlight that in order to advance the *crediblity* of HAB-climate services, there is a need for investments in both basic research, and transdisciplinary research to connect HAB-focused marine ecosystem and climate science with society. Despite the progress made within CoCliME to advance scientific understanding of HAB dynamics, and the consequences and risks for society, large uncertainties and knowledge gaps remain, particularly concerning how climate change may affect these dynamics (Anderson et al., 2019; Wells et al., 2020). Such uncertainties and gaps make it difficult to assess potential future societal exposures, vulnerabilities, and adaptation and mitigation needs, posing challenges to the salience, credibility and legitimacy of future research, stakeholder engagement and service co-development efforts.

There is therefore a need to improve basic scientific understanding of HAB-climate links (Griffith and Gobler, 2020). Without a basic foundation of long-term data and observations for generating credible scientific information, the utility of this information for decision-making will remain low (Anderson et al., 2019). High quality, comparable, long-term environmental and HAB monitoring data are essential to assess and manage HAB risks over a range of timescales. Monitoring provides the basis to establish and understand long-term environmental and HABs trends, contributes to enhanced basic scientific understanding of HAB ecology and bloom dynamics, and is necessary to develop "real time" and early warning system information about evolving HAB risks to the public. Long-term observations of key environmental parameters are needed in order to develop indicators of HAB ecological impacts. Identifying and establishing "supersites" or "sentinel sites" where complete water column (planktonic and benthic) and multidisciplinary monitoring is conducted, and into which HAB monitoring is integrated, would enable the development of a more complete picture of ecosystem changes and impacts over time and their interactions with multiple climate stressors (Anderson et al., 2019; Griffith and Gobler, 2020).

The increasing imperative of "usability" in sustainability science and in calls for co-production of knowledge (Lemos et al., 2012; Djenontin and Meadow, 2018) therefore needs to be accompanied by progress in more fundamental areas of basic science that are required to establish credible and usable services to meet stakeholder needs. This in turn will require ample time and funding. In CoCliME, it became clear that a 3 year project is insufficient to address basic scientific

gaps, engage key stakeholders, connect data and knowledge, and develop new HABs-focused services in the novel area of marine ecosystem-focused climate services. For example, a short term (3 day) HAB warning system in Ireland took over 20 years to develop into a scientifically credible and operational programme (Leadbetter et al., 2018). Nonetheless, and echoing the findings reported above, we call for targeted HAB ecological research and investments in basic science that take their starting point in an understanding of stakeholders' multi-risk decision-making contexts and that address the specific knowledge gaps that are necessary to inform effective mitigation and adaptation strategies to deal with current and emergent HAB risks.

Need to Focus on Opportunities for Both Short- and Long-Term HAB-Climate Services

"Delivering data, knowledge and technology for all" and developing early warning systems are highlighted under the UN Ocean Decade (UNESCO, 2020, p. 11). In this respect, the findings from CoCliME suggest that there are multiple avenues and potential entry-points for addressing marine and coastal hazards such as HABs. Engagements between scientists and stakeholders during the project led to the identification of a range of entry-points for prototype HAB-climate services. The first entry-point is to focus on low-hanging fruit such as improving or connecting existing HAB monitoring services as a basis for short-term HAB risk mitigation. The second focuses on reducing concurrent and cumulative anthropogenic pressures on the marine environment in order to enhance the adaptive capacity of ecosystems and human societies to respond to multiple stressors. The latter reflects a need that was identified in the project for longer term, adaptive management strategies in coastal regions that take an integrated risk management approach. This approach aims to reduce socio-ecological vulnerability and enhance resilience to concurrent and cumulative human pressures in changing marine environments in order to mitigate HAB impacts and enhance societal adaptive capacities in the face of marine biological and other hazards. For example, continuing to implement existing policies, including the EU Water Framework Directive and the Marine Strategy Framework, that aim to reduce eutrophication and destructive habitat actions can help to decrease the incidence and consequences of HABs in coastal areas. Integrating HAB risk management into adaptive management strategies, multi-hazard perspectives and transboundary marine governance frameworks will require connecting high-quality knowledge about HABs to relevant societal and decision-making contexts and integrating and mobilizing knowledge across disciplines, regions, sectors and scales. These findings are relevant for the UN Ocean Decade Challenge 2 which aims to "understand the effects of multiple stressors on ocean ecosystems, and develop solutions to monitor, protect, manage and restore ecosystems and their biodiversity under changing environmental, social and climate conditions" (UN Decade implementation plan 2.0; https://oceanexpert.org/document/27348).

Need to Approach Knowledge Co-production Processes in Transdisciplinary Projects as a Learning Process

Lessons learned during the process of implementing the transdisciplinary CoCliME project indicate that generating high-quality and actionable HAB-climate services requires dedication as well as realism at the start of a project to determine what can be accomplished when there are large gaps in foundational knowledge upon which HAB-climate services can be built and where the issues and stakeholder needs to be addressed are potentially many. Setting aside ample time to learn about the skills and expertise that different disciplines bring to the project and for developing an in-depth understanding of users' decision-making context and needs would enable identifying and prioritizing key areas of added value for climate service co-development, and novel and innovative ways for scientists and stakeholders to work together. A flexible scientific and management approach with a solid foundation in credible science is important while ensuring sufficient time to build trust, develop shared understandings, and connect and transfer knowledge across disciplines and communities of practice. An appropriate balance between natural and social science expertise (and involvement of communication experts and knowledge brokers) in projects aiming to co-develop marine-focused climate services is further needed in order to enhance the salience, legitimacy and usefulness and usability of the research process and outputs.

Cash et al. (2003) argue that the attributes of salience, credibility and legitimacy are "tightly coupled, such that efforts to enhance any one normally incur a cost to the others" (Cash et al., 2003, p. 8086). Lessons learned in the CoCliME project support this hypothesis. On the one hand, we find that access to long-term environmental and biological datasets, continuous sustained ocean observations and laboratory tests are a basic foundation for generating credible scientific information and for understanding the potential interactions between the effects of climate change on HAB risks and hazards in the future. When combined with an understanding of stakeholders' decision-making contexts and priorities, this information can be used as a basis for dialogue about potential future HAB-climate risks and how they might be addressed in the context of wider marine ecosystem changes.

At the same time, establishing long-term monitoring takes time and adequate financing (Anderson et al., 2015). A large body of social science scholarship further shows that improving the availability and quality of knowledge alone will not guarantee its uptake in practice (Lemos and Morehouse, 2005; Lemos et al., 2012). Efforts to reduce scientific knowledge gaps and uncertainties about HAB-climate linkages (efforts to enhance *credibility*) therefore need to be accompanied by more holistic efforts to reduce societal vulnerability and support adaptation to HAB, climate and other concurrent risks facing coastal and marine environments, where there are high stakes and high uncertainties on both the social and environmental sides (Cvitanovic et al., 2015; Whitney et al., 2017).

All of these lessons are relevant for, and should inform, the implementation of the UN Ocean Decade. Making progress toward addressing these lessons will require open-mindedness, a commitment to transdisciplinarity and involving appropriate scientific and stakeholder expertise. Building conceptual, methodological and organizational flexibility into projects is essential to encourage iteration and capacity building and to incentivize the creation of products and services that suit evolving stakeholder needs and priorities. Since most scientists are not trained in conducting holistic assessments of coupled socio-ecological coastal and marine systems (Stenseth et al., 2020), this will require broader transformations in the organization, funding and incentive structures in marine science and education akin to those that are called for in order to address the societal challenges posed by climate change (Fazey et al., 2020; Shrivastava et al., 2020). In addition, it will require overcoming "fear of failure" and documenting and sharing not only project successes, but also key lessons learned about what "did not work" (Catalano et al., 2019).

To conclude, CoCliME contributed to the main pillars of the UN Ocean decade by inter alia, co-developing high-quality, interdisciplinary, science-based knowledge on HAB risks in Europe, providing tools for understanding and modeling HAB trends and understanding their potential societal and ecological impacts under climate change, undertaking capacity building activities, and connecting science and society toward the sustainable management and use of coastal and ocean resources. The lessons learned while implementing this pilot European project should help to inform and progress transdisciplinary research practices toward improving the health and well-being of our ocean and societies; working toward getting "The Science we need" for "The Ocean we want" in the UN Decade of Ocean Science.

DATA AVAILABILITY STATEMENT

The data analyzed in this study are subject to the following licenses/restrictions: Requests to access datasets related to this publication should be directed to caroline.cusack@marine.ie.

AUTHOR CONTRIBUTIONS

JW and EB contributed to conceptualizing the research project and to leading various project work packages. CC led and managed the project consortium and coordinated the overall project deliverables. JW drafted the paper. All authors contributed to conceptualizing the paper, gathering and analyzing data, and writing, reviewing, and improving the final manuscript.

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A Changing Climate for Knowledge Generation in Agriculture: Lessons to Institutionalize Science-Policy Engagement

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Effective science-policy engagement efforts are crucial to accelerate climate action. Such efforts should be underpinned by high-quality knowledge generation that enhances salience, credibility and legitimacy of research results. This is particularly important for the agricultural sector. Agriculture has been identified as a priority for climate action. The sector also constitutes well-established institutions set up to help achieve food and nutrition security. Institutionalizing high quality knowledge generation for climate change adaptation within these institutions presents a major opportunity to catalyze climate action within the sector. To contribute to insights about this institutionalization, we draw on and develop Cash et al.'s 2002 success conditions for enhancing salience, credibility and legitimacy: (1) increased accountability, (2) use of boundary objects, (3) participation across the boundary, (4) mediation and a selectively permeable boundary, (5) translation, and (6) coordination and complementary expertise. We examine how these success conditions apply in a major global case of agricultural research for development under climate change: the CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS). We explore these success conditions in the wider context of CGIAR reform and response to climate change as the international system for Agricultural Research for Development (AR4D). Our results specify and confirm the practical relevance of the six success conditions for institutional design and reform, but also point to the need to complement these with two inductively-derived success conditions: effective leadership and presence of incentives. To institutionalize these success conditions among AR4D institutions, there is an urgent need to create a conducive environment that enables the development of context-specific science-policy engagement strategies, along with leadership development and efforts to break traditional disciplinary silos which constrain user-oriented knowledge production.

Keywords: science-policy interfaces, climate change, institutions, knowledge generation, research management, climate change adaptation, agricultural research for development

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INTRODUCTION

In its special report on Climate Change and Land, the Intergovernmental Panel on Climate Change (IPCC) has said that food security has been affected adversely by climate change and future food security is at risk from a warming climate (IPCC, 2019). Meanwhile, the report also highlights the opportunities for land-based actions to combat climate change and the need to accelerate knowledge transfer (IPCC, 2019). In 2015, countries submitted their Nationally Determined Contributions (NDCs), which form the basis of the Paris Climate Agreement intended to keep global warming to <2 degree Celsius. These NDCs overwhelmingly prioritize agriculture as a sector for adaptation and mitigation actions (Richards et al., 2016; Strohmaier et al., 2016). One hundred and thirty-one countries have indicated adaptation in the agriculture sector to be a priority (Strohmaier et al., 2016). Among developing countries, this priority is all the more distinct, with 93% of developing countries prioritizing adaptation in the agricultural sector (Strohmaier et al., 2016). These priorities include actions pertaining to crops, livestock, fisheries and aquaculture, irrigation, water, knowledge transfer, diversification, soils, early warning systems, agroforestry, indigenous knowledge, financial mechanisms etc. (Richards et al., 2015), indicating that virtually all agricultural activities are at risk due to climate change.

In the context of climate change, many agree that new models of knowledge production with an emphasis on generation of societal outcomes are needed (Cash et al., 2003; Sayer and Cassman, 2013; Kläy et al., 2015; Popa et al., 2015; Van Der Hel, 2016; Dinesh et al., 2018). Such models will be crucial for adaptation in the agricultural sector, to enable countries to translate priorities set out in their NDCs into tangible actions which benefit rural communities. However, efforts to facilitate adoption of such actions at scale are affected by a number of factors. These include the enabling policy environment, institutional coordination and capacity, engagement among different stakeholders, research and development systems, and market development (Lybbert and Sumner, 2012; Biagini et al., 2014; Long et al., 2016; IPCC, 2019). Therefore, new models of knowledge production need to be developed, not only at the level of individual researchers or research projects, but also to be institutionalized to effectively address systemic limitations. In global environmental governance, the development of new institutions as well as the redesigning of existing institutions is a prominent need (Biermann, 2007; Young et al., 2008). Within the agricultural sector, experts have called for efforts to significantly change the approach to Agricultural Research for Development (AR4D) and to design transdisciplinary innovation ecosystems (Meinke et al., 2006; Barrett et al., 2020; Herrero et al., 2020; Steiner et al., 2020).

Global investment in agricultural research for development is significant. The World Bank has estimated that around USD 56 billion was spent on agricultural research and development in 2011 (Fuglie et al., 2020). Collectively over almost 50 years (1962–2011), it is estimated that over USD 1.1 trillion has been spent on public agricultural research and development alone (Fuglie, 2017). Ensuring that the significant public resources devoted to AR4D enable climate action in the sector therefore provides an opportunity to deliver enhanced societal outcomes from these investments. Among institutions developed for agricultural research and development, the CGIAR, originally the Consultative Group for International Agriculture Research (CGIAR), is a key player as the network of international agriculture research centers (Pingali and Kelley, 2007; Ozgediz, 2012), which invested USD 824 million in agricultural research and development in 2018, and about USD 60 billion over the past five decades in present value terms (Alston et al., 2020). The CGIAR's focus on smallholder farmers in the global South—most often at the frontline of climate change impacts—makes it a key institution for adaptation in the agriculture sector, and Bill Gates, Co-Chair of the Global Commission on Adaptation and the Bill and Melinda Gates Foundation said, *"for poor country farmers, the CGIAR system is the only hope we have"* (Gates, 2019).

There is growing recognition within the CGIAR of the impacts of climate change on its clientele (smallholder farming communities), and **Table 1** outlines the evolution of climate change research within the CGIAR in the context of wider reforms. In this context, studying and improving the CGIAR's knowledge generation models in relation to climate change offers an opportunity to identify best practice for institutionalization, and thereby enable the sector as a whole to more effectively support adaptation actions. As the international system for agricultural research, the CGIAR reform process has attracted the attention of various scholars (Mccalla, 2014, 2017; Kamanda et al., 2017; Leeuwis et al., 2018; Byerlee and Lynam, 2020), and in addition to scholarly research, the reforms have also been reviewed by leading international experts as part of CGIAR's evaluation processes (Beddington et al., 2014; Birner and Byerlee, 2016). While Byerlee and Lynam (2020) have argued that the formation of the CGIAR is *"the major institutional innovation of the 20th century for foreign assistance to agriculture,"* they note that in order to retain its leadership, longstanding organizational and funding issues will need to be resolved (Byerlee and Lynam, 2020). While the reform process brought greater impact orientation and coordination, it has also been critiqued for governance ambiguities, prioritization of research, transaction costs and research quality (Leeuwis et al., 2018). The challenges of institutionalizing new approaches to research within the CGIAR has also been noted (Douthwaite et al., 2017).

Over the past decade, climate change efforts within the CGIAR have been led by the CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS) which made a conscious shift from "research in development" to "research for development," by taking a theory of change approach to making research more outcome oriented (Vermeulen et al., 2012; Thornton et al., 2017; Dinesh et al., 2018). CCAFS works in four flagship areas: (1) priorities and policies for Climate-Smart Agriculture (CSA); (2) Climate-smart technologies and practices; (3) Low emissions development; and (4) Climate services and safety nets. In addition to the flagships, two cross-cutting areas also exist, gender and social inclusion and scaling climate smart agriculture. Across the flagship areas, outcome targets have been set (CCAFS, 2016), and it is envisaged that these targets will be met through projects under each

TABLE 1 | Evolution of climate change through reforms in the CGIAR.

Year	Description
2007	World Bank Vice President and CGIAR Chair, Katherine Sierra proposes to intensify climate change research in the CGIAR at COP13 of the UNFCCC in Bali CGIAR, 2007.
2009	CGIAR Challenge Program on Climate Change, Agriculture and Food Security established, as a new Challenge Program of the CGIAR CCAFS, 2009, in addition to other thematic programs which were initiated in 2002 in response to calls for reform in the CGIAR Douthwaite et al., 2017.
2011	CGIAR Research Programs launched as an alternative to Challenge Programs, including the CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS) CCAFS, 2011b; Roy-Macauley et al., 2016.
2014	CGIAR commits to devote 60% of its research to tackle climate change at the UN Climate Action Summit CGIAR, 2014, 2016.
2017	New phase of CGIAR Research Programs announced, with CCAFS as an integrative research program linking multiple CRPs and centers CCAFS, 2016.
2019	New phase of reforms initiated to transition to One CGIAR, with a focus on responding to the climate crisis CGIAR, 2019.

flagship as well as synthesis and science-policy engagement activities. In 2019, CCAFS spent USD 53.6 million (CCAFS, 2020) in over 50 projects across all flagships. These projects mobilize not only the expertise from within the CGIAR, but also advanced research institutions, national agricultural research systems, and development partners. To ensure that the research results address the needs of target stakeholders, CCAFS has developed a regional approach, with programs established in South East Asia, South Asia, East Africa, West Africa and Latin America. In each region, impact pathways have been developed in consultation with partners in the region (Schuetz et al., 2014). A matrix management approach is taken to design and manage projects, wherein projects are designed and managed jointly by flagships and regions, and this is at the crux of its model of "research for development." In this context, we seek to open up a new pathway for interdisciplinary research for development linking institutional design with science-policy engagement, to help conceptualize what impact-oriented AR4D would mean in an era of climate change. We do this by examining CCAFS' efforts to enhance credibility, salience and legitimacy in knowledge generation for its key stakeholders. We aim to provide insights relevant for theories of institutional design (e.g., Biermann, 2007; Young et al., 2008; Ostrom, 2011), not only for the benefit of the CGIAR, but also the wider knowledge system for agriculture under climate change, as there has been increasing focus on transforming knowledge systems to catalyze a transformation in food systems (Fanzo et al., 2020; Herrero et al., 2020; Klerkx and Begemann, 2020; Loboguerrero et al., 2020). We also aim to contribute to the literature on science-policy engagement, addressing a prominent knowledge gap, being the systematic empirical study of knowledge systems for sustainable development. While much conceptual work on this topic been done, the systematic empirical unpacking of "what works" in different empirical domains is of a more recent date (Hegger et al., 2020). This paper adds to these emerging empirical examples an institutional perspective on how science-policy engagement efforts are institutionalized in a key international institution and a player in the knowledge system on agriculture and climate change. This also includes literature on boundary work drawing on multiple communities of expertise to support decision making in highly different contexts ranging from participatory R&D to political bargaining and earlier insights on boundary work within the CGIAR (Clark et al., 2016).

To achieve the research aims, the following steps will be taken. Section Conceptual Approach and Methods outlines our conceptual approach and methods. Section Results presents the results. This is followed by a discussion (section Discussion) and the conclusion (section Conclusion), focusing on key issues and commonalities as well as potential next steps.

CONCEPTUAL APPROACH AND METHODS

Conceptual Approach: Institutional Analysis for AR4D

In their seminal (2003) paper, Cash et al. have coined the notions of credibility, salience and legitimacy as indicators of quality of knowledge for science-policy engagement efforts to inform societal outcomes (Cash et al., 2003). Credibility refers to the adequacy of scientific information, salience to its relevance to decision makers, and legitimacy the extent to which the information is considered to have been respectful of divergent views (Cash et al., 2003). These notions provide the foundation for improving research for sustainable development and resonate with CGIAR's interpretation of research quality, wherein the principles of relevance, scientific credibility, legitimacy and effectiveness are key attributes of quality of research (Belcher et al., 2015; ISPC, 2017). In an earlier, related, paper, Cash et al. (2002) propose strategies to institutionalize efforts to enhance salience, credibility and legitimacy in boundary organizations. These strategies have potential applicability in institutional design and reform in the context of climate change.

We use the success conditions based on Cash et al. (2002) and specify these to fit the context of climate change and agriculture in order to understand the patterns of interactions leading to enhanced credibility, legitimacy and salience in knowledge generation. These success conditions are shown in **Table 2**, where we have described, validated and operationalized these against the wider literature. Based on this process, the success conditions provide a conceptual starting point to study the CCAFS program. The concepts proposed are not final and empirical research helps us to specify them.

TABLE 2 | Framework for examining program efforts to enhance salience, credibility and legitimacy.

Success conditions	Description of the condition and outline of the assumed relationship with credibility, salience and legitimacy
Accountability	Research institutions are accountable to both sides of the boundary (i.e., research and action), helping ensure **legitimacy** Guston, 2001; Cash et al., 2002; Kristjanson et al., 2009. This includes efforts to facilitate participation, transparency, evaluation of results and managing critique Whitty, 2010
Use of boundary objects	Actors involved in science-policy interactions co-produce boundary objects like assessment reports, models, maps and briefs, which enables research institutions to overcome the science-non-science divide and produce more **salient** research, and build **credibility** and **legitimacy** Cash et al., 2002; Kristjanson et al., 2009.
Participation across the boundary	Research institutions effectively mobilize participation from both sides of the boundary to ensure the production of **salient, legitimate** and **credible** information to guide action Cash et al., 2002; Kristjanson et al., 2009; Popa et al., 2015; Clark et al., 2016.
Mediation and a selectively permeable boundary	Research institutions actively mediate to reduce the potential trade-offs and conflicts between increasing **salience, credibility** and **legitimacy** Cash et al., 2002. It includes efforts to address concerns which can be practical, political or cultural. Meanwhile, having a selectively permeable boundary Kislov, 2018 enables institutions to effectively engage across the boundary.
Translation	Research institutions translate research for users, helping enhance the **salience** of research results Cash et al., 2002, enabling researchers and users to understand each other's' concepts, and address real world problems Lang et al., 2012.
Coordination and complementary expertise	In addition to enhancing the scale and scope of research Poteete et al., 2010, research institutions actively coordinate among entities with complementary expertise and mandates, provide more **salient, legitimate** and **credible** research results, leading to more harmonious actions Cash et al., 2002.

Adapted from Cash et al., 2002.

Methods

We adopted a case study approach (Mills et al., 2010), and information on CCAFS' performance in relation to the criteria is gathered from the literature, independent external evaluations of the program, and complemented with key informant interviews. The CGIAR has a focus on evaluation and impact assessment, therefore a number of evaluations have been conducted on CCAFS. These include an evaluation of the program's themes by regions (Ash, 2013), a management and governance review (Robinson and Flood, 2013), a review of the low-emissions development activities (Smith, 2014), a review of work on climate services (Feinstein, 2014), a comprehensive external evaluation of the program commissioned by the CGIAR Independent Evaluation Arrangement (Anderson et al., 2016), and two reviews commissioned by the European Commission (Jobbins and Pillot, 2013; Pillot and Dugue, 2018). These external evaluations have a number of findings which are relevant to our study, for example Anderson et al. (2016) examined CCAFS role as a knowledge producer, and found that the program has struck a balance between production of science based knowledge and local application and scaling (Anderson et al., 2016). In another example, Smith (2014) focused on CCAFS work on low emissions development and found that the work was relevant to set objectives, effectively managed, sustainable and efficient. It noted that the scientific impact varied across outputs, and the development impact was likely to be moderate, although it was still too early to make a definitive statement (Smith, 2014).

We relied on external evaluations to ensure the greatest possible reflexivity. At the same time, the authors were in a good position to interpret the findings since the author team comprises researchers with multiple roles. The first author is employed by CCAFS but also has an academic affiliation and has conducted the current study as part of his latter work. The third author leads a project funded by CCAFS, but is an academic together with the second and fourth authors who are in the position to view the empirical field from critical distance.

Twelve key informant interviews with stakeholders were conducted using a semi-structured approach (**Appendix 1**). These interviews served to help interpret the findings from the document study, in particular to validate the way in which we linked the content of the evaluations to Cash et al.'s success conditions. In so doing, we tried to eliminate subjectivity to the greatest extent possible. Four of the interviewees were engaged in CCAFS's Independent Steering Committee (formerly the Independent Science Panel), three of the interviewees were engaged in the CGIAR's Independent Science and Development Council (formerly the Independent Science and Partnership Council), four of the interviewees were in the CCAFS and CGIAR management, as well as two external experts who have published on science-policy interfaces in the CGIAR.[1] These interviews give insight into decisions on institutional design and oversight, which would otherwise have been absent. The interviews were transcribed and key lessons corresponding to the criteria where identified by qualitatively analyzing the transcripts. We also checked if inductive coding pointed us at additional success conditions, which were distinct from those already identified by Cash et al. (2002).

RESULTS

In this section we present results from our literature review and interviews with key informants, wherein we examined the applicability of the success conditions presented in **Table 2** in the CCAFS context.

[1] Two of the interviewees have had multiple roles within CCAFS and CGIAR.

Accountability

Key mechanisms to enhance accountability within CCAFS are the development of impact pathways, efforts to enhance transparency, external evaluations and impact assessments, and effective leadership. CCAFS has endeavored to integrate accountability in its project design process through impact pathways for each project, which correspond to regional and thematic impact pathways at the program level. These impact pathways ensure a route to societal impacts, while also ensuring that activities address major knowledge gaps (Schuetz et al., 2014). Participation of stakeholders from both sides of the boundary, i.e., researchers and decision makers are facilitated in the project design process (Schuetz et al., 2014), with the aim to ensure that research projects as part of the CCAFS portfolio address the needs of decision makers, as well as the knowledge gaps identified by researchers. Conformance to the project designs is monitored through monitoring, evaluation and learning efforts (Schuetz et al., 2017).

Transparency of the program's efforts is provided through annual reporting as well as public facing pages of its projects through which individual projects' progress can be monitored. Evaluation of the program's results have been conducted at different stages of implementation, including evaluation of thematic activities (Ash, 2013; Feinstein, 2014; Smith, 2014), management and governance (Robinson and Flood, 2013), and program level evaluations (Jobbins and Pillot, 2013; Anderson et al., 2016; Pillot and Dugue, 2018). Efforts seem to have been made to address critique as each evaluation has received responses from the management, including on key actions to address recommendations. For example, following the 2016 evaluation (Anderson et al., 2016), the CCAFS management published its responses to all recommendations put forward by the evaluators (CCAFS, 2016). This includes a recommendation to increase its policy informing role, which the management agreed to do, focused on the development of NDCs as well as engaging with regional groupings in climate negotiations. Similar responses to other evaluations are also available.

In addition, a number of impact assessments have also been conducted, to evaluate impact of the program's efforts to end users (Gill, 2014; Aryal et al., 2015; Murendo and Wollni, 2015; Reddy, 2015; Hariharan et al., 2020). The program's accountability to facilitating outcomes also received favorable review in the program-wide evaluation, wherein accountability within the CCAFS program was considered to be enhanced as a result of the results based management and the associated approach of developing theories of change (Anderson et al., 2016). But, the review also called for further strengthening accountability by strengthening the theory of change and impact pathways at the regional and flagship levels (Anderson et al., 2016). The reviewers suggest that the assumptions and risks in these theories of change needs to be defined better and converted into hypotheses which can be tested during implementation (Anderson et al., 2016).

According to those involved in program design, efforts to ensure accountability were crucial, as one of the interviewees who was part of the Independent Science Panel (ISP) noted, *"accountability was critically important for us and we took that very seriously at each of our meetings. I think we put the leadership team of CCAFS under enormous pressure early on in terms of the reporting requirements, and not just in terms of their financial reporting but also in terms of how people were appointed, how people were treated, what the culture was like in the organization, and ultimately whether they were able to deliver on the promised results"* (Interviewee-T, 2020). This means that formal processes need to be complemented with informal processes and efforts (Interviewee-O, 2020), and a key aspect of ensuring this is through recruitment of suitable staff. The program's approach of hiring staff accountable entirely to the program as opposed to participating centers was found to be an effective approach (Robinson and Flood, 2013). Interviewees also noted the importance of competitive hiring (Interviewee-O, 2020), strategic leadership (Interviewee-W, 2020), incentives for researchers (Interviewee-X, 2020) and the developing country focus of staff. It was however noted that in maintaining accountability, CCAFS and the wider CGIAR can be affected by shifts in donor priorities (Interviewee-Y, 2020), trust deficits within CGIAR governance processes (Interviewee-Y, 2020), and changes to governance processes (Interviewee-V, 2020). It was also noted that efforts to enhance accountability should ensure that the program is accountable to the right stakeholders and the selection of stakeholders is not influenced by power dynamics, and bias toward current partners and research interests (Interviewee-P, 2020; Interviewee-U, 2020). An example in the CCAFS context to enhance accountability is the focus on gender equality, which was found to be under-developed in the 2016 review (Anderson et al., 2016), and subsequently a new strategy and leadership was brought in (Anderson and Sriram, 2019).

One of the interviewees identified an area of improvement to be accountability and interactions with funders, which can help make the funding environment more conducive for boundary work (Interviewee-T, 2020). This is important because in contrast to academia, scientists in the CGIAR need to be accountable to working for the poorest of the poor, while also publishing articles, and fundraising (Interviewee-Q, 2020), which requires the support of funders.

Use of Boundary Objects

Boundary objects developed in the CCAFS context include models, briefs, websites, conferences etc. which are targeted at practitioners. Key approaches to improve the use of boundary objects are to link these to science-policy engagement processes, capacity building efforts, and participatory knowledge production processes. While the use of boundary objects has not been explicitly noted as a strategy by CCAFS, this appears to be the case and the 2016 review noted that CCAFS produced a number of boundary objects, including briefs and info notes, working papers, reports and conferences (Anderson et al., 2016) next to specific participatory processes. CCAFS put quite a lot of emphasis on boundary objects and communication, as an interviewee on the program's ISP noted, *"We needed to have credibility in the science community, so peer reviewed journals and articles were absolutely crucial without that we would not have succeeded but it's not sufficient of course. That's why we developed*

the policy briefs for example and other types of publications to reach out to other audiences" (Interviewee-W, 2020). Interviewees found that CCAFS had been fairly successful in the use of boundary objects, particularly when engaging a target audience or process (Interviewee-O, 2020; Interviewee-W, 2020). This was approach was also reiterated by a science-policy expert interviewee, who said, *"to me there's an engagement process and in that engagement process it may be useful to use boundary objects as one of the tools in your engagement process. All of those things are part of what you need to do in order to be effective with your research*" (Interviewee-R, 2020). With regard to targeting specific processes and outcomes, the utility of boundary objects was perceived to be higher when focused at the supranational or national scales (Interviewee-S, 2020; Interviewee-V, 2020). Provision of capacity building and sequencing the production of boundary objects with participatory knowledge production was another important factor (Interviewee-T, 2020).

In producing boundary objects, the emphasis should not only be on briefs and info notes: events and processes are equally important. For example an interviewee noted *"an event, where the partner deeply buys into it, is much more successful than perhaps an info note produced solely by the research provider"* (Interviewee-O, 2020). Participatory scenarios were identified as another innovative boundary object (Interviewee-Y, 2020). In this case, CCAFS developed participatory scenarios with stakeholders (Chaudhury et al., 2013; Palazzo et al., 2017) and a review of these efforts (Carey, 2014) noted that the process had *"evolved from an academic approach to a bespoke product to meet the needs of the actors CCAFS wishes to engage."* One of the interviewees also noted this, *"I'd say one of CCAFS' great strength, is how to bridge that divide between science and policy and I would I think the scenario process is a really important boundary object for that"* (Interviewee-Y, 2020).

Producing boundary objects relevant to the context is not simple, and at times this happens in the midst of challenges, as an interviewee noted, based on her experience in the wider CGIAR, *"There's such a deep-seated attitudinal issue around needing to be in front, needing to be visible as an individual player and not as part of a bigger team"* (Interviewee-X, 2020). While this comment was not specifically about CCAFS, it is important to note that within the wider institutional landscape the need for attribution can be a risk to producing collaborative boundary objects. Capacity was another key challenge noted, as capacity to produce boundary objects cannot be taken for granted as scientists may not necessarily have the right skills to tell the story in a way that it appeals to the users (Interviewee-W, 2020). It was also noted that since the CGIAR has multiple entities producing boundary objects, users tend to receive too many boundary objects and information, and greater coordination and user orientation is needed within the CGIAR (Interviewee-U, 2020).

Participation Across the Boundary

Key mechanisms to improve participation across the boundary included a "partnerships and participate" approach to deliver outcomes, regional engagement and engaging stakeholders from the beginning of the research process. The 2016 external evaluation noted that CCAFS was actively partnering with institutions on the delivery of knowledge (Anderson et al., 2016). The approach to project design, including the design of the impact pathways of projects, together with the matrix management approach involving flagships and regions facilitate participation across the boundary (Anderson et al., 2016). CCAFS also has a strategy in place for engagement and communications, to facilitate participation across the boundary (CCAFS, 2013), and the approach adopted in partner classification and delivery of results was identified as a good example in the CGIAR wide evaluation on partnerships (McLeod et al., 2017). While engagement of partners to deliver outcomes has been noted in the external review (Anderson et al., 2016), particularly at the regional level. Partners in turn perceived the outcome focus adopted by CCAFS as a clear competitive advantage (Anderson et al., 2016).

In the course of the interviews it was noted that participation is a key part of the CCAFS approach (Interviewee-W, 2020), which comes upfront in the research process (Interviewee-T, 2020). One of the interviewees observed that CCAFS in comparison to the wider CGIAR has done well on participation, but that performance across CCAFS was not uniform, with certain scientific leaders being far more open to equal relationships than others (Interviewee-X, 2020). Setting up regional programs with senior leaders was perceived as a success factor (Interviewee-X, 2020). In addition to participation downstream with farmers and stakeholders, upstream participation, i.e., partnerships to achieve scale is important (Interviewee-V, 2020). One interviewee noted this as "*partner and participate approaches*" (Interviewee-S, 2020), since the quality of the participation is enhanced through high quality partnerships that enable outcome delivery. One of the interviewees noted that within the CGIAR, the classic approach has been that partners came in at the end of the research process for scale, but CCAFS deviated from this approach and engaged partners right from the beginning, to understand their needs and co-designing research questions (Interviewee-X, 2020). This is important as balancing participation with strategic research is inevitable to manage tradeoffs of time and resources (Interviewee-Y, 2020). However, care must be given so that participation is fair and equitable and participants are actively engaged, and have a voice in deciding what the questions are (Interviewee-P, 2020; Interviewee-Y, 2020).

Mediation and a Selectively Permeable Boundary

Key mechanisms for mediation include exchanges based on trust based relationships and inputs from external experts. In terms of permeability of the boundary, facilitating transdisciplinary research was identified as a key mechanism, together with efforts to coordinate across institutions. Mediation as a tool to balance credibility, salience and legitimacy is not explicitly referred to in external evaluations of CCAFS. However, the interviews confirmed that while mediation as a tool has not been used explicitly (Interviewee-O, 2020), implicit mediation does occur in participatory processes which involve partners. These are addressed through trust-based relationships and exchanges with

partners. As one interviewee noted based on his experience in science-policy engagement processes, "*in a political process, it's a negotiation process and you have to allow some things in order to get the bigger picture.*" (Interviewee-S, 2020).

It was also found that trade-offs between salience and credibility were common when endeavoring to do high quality research and achieve outcomes at the same time (Interviewee-X, 2020). Potential tradeoffs between legitimacy and credibility were also highlighted (Interviewee-R, 2020). CCAFS has a matrix-based management approach in place, and this system seeks to provide a mechanism to mediate and achieve such a balance. An additional dimension to mediation which came out prominently in interviews was the internal "science politics" within the CGIAR, wherein ongoing reforms and governance processes erode trust within the system, and have required mediation, for example by bringing in external experts (Interviewee-S, 2020). An interviewee noted, *"the CGIAR is one of the most over governed organizations that I've ever been involved in. And they haven't done that very effectively, a lot of the governance processes that are set up for some opaque reasons and often do not result in any sort of desirable outcomes"* (Interviewee-T, 2020).

In terms of the permeability of the boundary, there are two dimensions, boundaries among institutions and boundaries among disciplines. The CCAFS approach is one that enables permeability in both, however, within the wider institutional landscape, permeability of the boundary may cause overlap and competition among institutions. For example, within the international agriculture landscape, the CGIAR is responsible for research, FAO for policy and IFAD for funding, but in practice there is tremendous overlap among all these organizations and competition for funding (Interviewee-Y, 2020). With regard to disciplinary boundaries, an interviewee noted that this was a strength of CCAFS, *"they've always been very accommodating of those different strands and not just within the physical sciences but also between social science and the physical sciences. They were open to bringing in people from different backgrounds and give them an enabling environment in which they could make meaningful contributions."* (Interviewee-T, 2020).

Translation

Key mechanisms for effective translation of research include ensuring a two directional process to secure stakeholder input and changing the culture to ensure a more long term and impact oriented view of translation. Translation of research into usable formats is a big part of the CCAFS approach (Kristjanson et al., 2014), and a dedicated research area focused on translation, with emphasis on innovative research and communications, gender and social inclusion and future scenarios. The approach to translation was one wherein the users of research results were engaged at the outset to define the scope of research and thereafter throughout the research process (Kristjanson et al., 2014), which helps ensure salience of results. This is important as noted by one of the interviewees as translation needs to be a two directional process as opposed to scientists talking to users (Interviewee-P, 2020).

Challenges in this area included the timelines, wherein the impact was not visible during project cycles of 2–3 years, and difficulties in forming and maintaining non-research partnerships. The interviews also noted that translation cannot be a one way process, and needs to have the strong buy in of the target users, as an interviewee noted, *"translation needs commitment also from the target audience to read the research and a willingness to be informed*" (Interviewee-Y, 2020). This means that researchers need to have the right skills and capacity to be able to take that on (Interviewee-S, 2020). Cultural issues need to be addressed too, for example within the CGIAR communications is not understood as a tool for science-user engagement, communications is understood as a tool for advertising and fundraising (Interviewee-X, 2020). These deep seated cultural issues need to be overcome to be more effective in translation and this seems to have been the case in CCAFS (Interviewee-W, 2020).

Coordination and Complementary Expertise

Key mechanisms for effective coordination and mobilizing complementary expertise include mobilizing expertise from outside the CGIAR, more effective internal coordination of expertise, and a transdisciplinary approaches to address the needs of policy makers. At the time of CCAFS inception, CGIAR was lagging behind on global research for climate change as it had retained a very strong disciplinary focus, particularly on plant breeding without branching out into the broader areas that needed to be addressed in food systems and were important to policymakers (Interviewee-Q, 2020; Interviewee-T, 2020). CCAFS was initiated as a partnership between the CGIAR and the Earth System Science Partnership (now Future Earth) which had expertise in climate change research, which would complement the CGIAR's work (Interviewee-Q, 2020). CCAFS was being designed specifically to address policy needs, as one of the interviewees on the Independent Steering Committee (ISC) noted, *"when we transitioned CCAFS from what used to be a challenge program into a CRP under the new structure, we did that very much keeping in mind that we wanted to create an entity that firstly connects sensibly across all of the core disciplines within the CGIAR. But at the same time becomes really influential in providing evidence-based policy support at various levels. Because that's where clearly the need was"* (Interviewee-T, 2020). CCAFS has the mandate to coordinate across the CGIAR on climate change issues and mobilize complementary expertise toward societal outcomes. In addition to the intra CGIAR role, CCAFS also has a focus on mobilizing partners out with the CGIAR, where capacity is lacking within the system. The external evaluation noted that CCAFS has made progress with integration, but greater integration and linking is needed (Anderson et al., 2016). The approach to mobilizing expertise from advanced research institutes in areas where the CGIAR system had limited expertise was noted as key feature (Anderson et al., 2016; Pillot and Dugue, 2018).

This coordination and mobilization of complementary expertise is all the more relevant in the context of transdisciplinary research (Interviewee-R, 2020), and a former member of the ISC noted, *"everybody talks about the importance*

of inter and transdisciplinary research, but very few organizations know how to engender that and how to provide the supporting networks that are actually necessary for that" (Interviewee-T, 2020). Often, institutional structures and incentives do not encourage such collaboration (Interviewee-O, 2020), and in the end the onus falls on "*a relatively small group of people that are really competent, dedicated and committed to the same outcome*" (Interviewee-O, 2020). This seems to have been the principle behind the design of the core CCAFS team (Interviewee-Y, 2020).

Coordinating climate change research in the CGIAR has not been an easy task, an interviewee associated to CGIAR management noted, "(Interviewee-T, 2020) *The prevailing view across CGIAR is that there is no need for any specialist knowledge on climate. Climate is not associated with any kind of specific skill sets or knowledge sets. And what this leads to is that climate change is used as an additional justification, a rationale for research projects. But then the research proposed is the same as it would have been, you know, prior to any awareness of climate change*" (Interviewee-X, 2020). In this context, another interviewee noted, "*my perception is that CCAFS focus on maintaining its coordination internally is very strong, much more than with the other CG centers or as a system*" (Interviewee-Y, 2020).

Additional Success Conditions Identified

In addition to insights about the success conditions from Cash et al. (2002), we inductively identified additional success conditions from the evaluations and during interviews, which were not contained in the initial Cash et al. framework.

Role of Leadership

Key mechanisms to enable effective leadership include selection of results oriented and strategic leaders, skills development, ensuring regional and national focus, funding allocation to enable efforts, and facilitating a shift in culture. It is evident from the evaluations and interviews that selection of the right leaders has been a key success factor in the CCAFS context. This means strategic leadership, as one interviewee noted, "We need leadership that has a clear vision on an outcome-oriented approach. Clear vision that you should almost work backwards, you know what is the target and then put the research in place that's needed to achieve their target" (Interviewee-O, 2020). Good leadership can help to ensure that best practices are effectively institutionalized. Leadership should also be relevant to regional and national issues as noted by an interviewee based on the success of regional programs in CCAFS, *"I think one of the things that have helped with CCAFS, has been the permanent presence of the regional program leaders in the regions"* (Interviewee-X, 2020). At the same time, it is important for leaders to steer clear of bias (Interviewee-R, 2020).

However, it may not be assumed that strategic leadership skills exist within the system, and where this is the case, skills development is important (Interviewee-S, 2020). In a complex environment such as that of the CGIAR, good leadership was noted as being, "*more bottom-up leadership, you are empowering people within the system to do good things as a leader rather than leading from the top down"* (Interviewee-S, 2020), and such skills need to be developed. Competitive hiring is another approach to fill skills gaps and secure leaders who are highly practical but also able to navigate the complexity of the CGIAR system, stakeholders and research challenges. Multiple interviewees engaged in CCAFS design and selection of leadership noted that leaders were selected based on their ability to navigate complexity and deliver results (Interviewee-Q, 2020; Interviewee-T, 2020; Interviewee-W, 2020). CCAFS also made a conscious attempt to recruit leaders from developing countries due to its focus on the Global South, this also helped, as an interviewee noted, *"I do think that with leadership, that does make a difference, If you come from a background where you identify with the partners"* (Interviewee-X, 2020).

Selecting good leaders is not sufficient, funding allocation needs to be in place to support leaders to take a strategic approach, as noted, *"I would say the most important thing to pay attention to is who controls the purse strings and who is accountable for making the results happen from those investments and expenditures"* (Interviewee-X, 2020). Supporting mechanisms, i.e., management is important to ensure that processes reflect the intentions at the governance level and making sure that people are on board and get the view (Interviewee-U, 2020). Institutionalizing high-quality knowledge generation requires a shift in culture, and leadership and supporting mechanisms need to be in a position to support this shift, as a former member of the ISC noted, *"Culture eats strategy for breakfast, so you can have all the strategy in the world, but the culture will just squash it, so it is essential to have leadership that is absolutely consistent with the culture that you're trying to head towards"* (Interviewee-Z, 2020). Another interviewee also noted, *"I feel the problem is very deep in the culture of CGIAR and it's a way of working, and CCAFS has been quite radical in trying to break out of that CGIAR only model and be far more open to partnership, bringing in partners even to run parts of the program, being very open to being an equal or even junior partner. And I guess that was established by the kind of attitudes across CCAFS leadership that could sort of break open that CGIAR culture a little bit"* (Interviewee-X, 2020).

Role of Incentives

Key incentives can be provided at the level of funders (long term commitment to boundary work), program level (linking project performance to achieving outcomes), and individuals (offering a career track for boundary scientists and incentives for achieving outcomes). One of our interviewees noted, "*in research as in many other areas of life, people have habits and it's very difficult to make them change their habits*" (Interviewee-Q, 2020). In order to change habits and realize impact, AR4D institutions should provide incentives to staff (Interviewee-P, 2020; Interviewee-X, 2020). Currently within the CGIAR the incentives for boundary work are limited, as an interviewee noted, *"There is no career track for the true boundary scientists or science policy interface people or whatever you want to call them. The people who are about research into action, who are there for the development part of AR4D. There are no jobs and that's zero, it's not taken seriously at all and is considered to be a kind of an add on, done by the scientists."* (Interviewee-X, 2020). The CGIAR has been very

dominated by crop breeding as a legacy of the green revolution (Interviewee-U, 2020), but there are examples of incentives being established to generate greater engagement in other institutions (Interviewee-S, 2020), which can offer lessons to the CGIAR.

Incentives are needed at the programmatic level from funders, as one of the challenges noted in the interviews was the changing expectations of funders and the unpredictability in funding cycles as one interviewee noted, *"CCAFS did have influence and managed to get agriculture on the global agenda on climate change. I think it's one of those major breakthroughs, but it has not been very effective in engaging the funders of the CGIAR in such a way that there would be comfortable to continue with that model"* (Interviewee-T, 2020). The current phase of CGIAR reforms are therefore going in the direction of funders wanting more line-of-sight in terms of investment and the outcomes and results, but the interviewee noted, *"this is going against the very nature of a boundary organization because in a boundary organization, you actually don't have that clear line of sight and often the attribution of those outcomes is incredibly difficult because so many other factors are involved in it"* (Interviewee-T, 2020). At the level of individual scientists, incentives can be offered through annual appraisals, salary levels etc. (Interviewee-X, 2020). An example that was highlighted from CCAFS was the approach to reporting and evaluating outcomes (Interviewee-X, 2020), which was established early on in the program and results were a key factor that determined performance of projects and associated staff (Interviewee-O, 2020). Incentives should also go beyond rhetoric, as one interviewee noted, *"there's a lot of rhetoric about partnership, in reality we usually have to do it on a shoestring and I think that's one of the key problems that CCAFS is also experiencing"* (Interviewee-T, 2020).

TABLE 3 | Success conditions and lessons for institutionalization.

Success conditions	Key lessons for institutionalization
Accountability	- Formal systems for developing theories of change and impact pathways are important, but need to be complemented with informal efforts which rely on individual researchers and research leaders.
Use of boundary objects	- Boundary objects need to be linked to impact pathways, partners, and policy-engagement processes to realize maximum impact. - Focus should not only be on boundary objects but also boundary processes.
Participation across the boundary	- The quality of participation can be enhanced if combined with partnership efforts, i.e., an approach to partner and participate. - Participation should be fair and equitable, enabling stakeholders to have their say in the process.
Mediation and a selectively permeable boundary	- Efforts must be taken to manage trade-offs between salience and credibility which may arise in a negotiation process. - Mediation also becomes essential in the "science politics" space especially in a complex institutional environment such as the CGIAR.
Translation	- Translation should be a two way process, with the target audience engaged early on in the process.
Coordination and complementary expertise	- Establish incentives which promote efforts to coordinate and mobilize complementary expertise.
Leadership	- Identify appropriate leadership and empower leaders to change culture. - Develop leadership at the regional level for better engagement with stakeholders.
Incentives	- Establish incentives for science-policy engagement efforts that enhance salience, credibility and legitimacy. This can be through linking performance with delivery of outcomes.

DISCUSSION

Success Conditions for Institutionalizing Efforts to Enhance Salience, Credibility, and Legitimacy

Based on the results, which illustrate how the Cash et al. (2002) success conditions relate to CCAFS in the context of wider CGIAR reforms, we revisit the conditions. Our results indicate broad applicability for these success conditions in efforts to institutionalize high-quality knowledge generation that enhances salience, credibility and legitimacy, thereby supporting science-policy engagement efforts. However, we also identified a need to specify the conditions for the domain of climate change, agriculture and food security and we identified additional success conditions through the CCAFS case study, which pertain to leadership and incentives. These point to the need to extend Cash et al.'s original framework. Cash et al. (2002) do allude to the importance of leadership in the context of accountability, when leaders are chosen to be accountable to both sides of the boundary, but our results show that the role of leadership goes beyond being accountable, to ensuring that knowledge generation also enhances credibility and salience, manages trade-offs and supports science-policy engagement efforts. The effectiveness of empowered and competitive leadership, and indeed the success conditions identified by Cash et al. (2002) will also depend on the incentive structures which are in place, and this is the second additional success condition that we have identified. In **Table 3**, we revisit the success conditions proposed at the outset, together with additional success conditions identified from the results. Using this framing, we have identified key empirical lessons for institutionalization of each of these success conditions.

Creating an Environment for "Enlightened" Boundary Work

In 2011, the global agricultural research and development expenditure was USD 56 billion (Fuglie et al., 2020), in the same year, CCAFS annual budget was only USD 62 million (CCAFS, 2011a). Therefore, for lessons derived to be institutionalized at scale, greater commitment from research funders and leadership is needed. As one of the interviewees noted, *"It's hard for isolated project outputs to get traction in the policy space. It needs a broader more cultivated space if you like a more fertile ground that's been cultivated more at the programmatic or institutional*

level" (Interviewee-Z, 2020). In endeavoring to drive changes to the wider knowledge system, researchers need to be cognizant that they are in the "science in politics" space, and without enormous commitment on their part, they end up, intentionally or not, serving the already empowered in the globalization of food systems. Clark et al. (2016) provides a useful framework on how boundary work can support "enlightenment," decisions, and negotiations. Enlightenment is framed as being about advancing basic understanding around key issues without concerns for short term application (Clark et al., 2016), and mobilizes multiple disciplines and thus true integrative research and development. While efforts within CCAFS focus on the use of knowledge to support decisions and negotiations, a greater focus on this kind of enlightenment is needed across the knowledge system. In the context of AR4D, effective science-policy engagement efforts can be found at the level of individual projects or programs, but there is a need to go beyond these in order to reach the enlightenment stage.

As science-policy engagement moves from informing decisions and negotiations in the short term to a systematic approach to enlightenment, research efforts will be characterized by enhanced credibility, legitimacy and salience. At this stage, the roles of different actors which are currently clearly differentiated, e.g., knowledge producers, intermediaries, users etc., may merge. In the CCAFS case, we do indeed see these roles merging, with the same institution producing knowledge, translating it, and facilitating partnerships for greater uptake. While the advances in research on the roles of institutions which have specialized roles is welcome, the Cash et al. (2002) success conditions provide a helpful framing for institutions which may have multiple roles. As an interviewee noted, "*what you're aiming for is that sweet spot where a very well thought out and delivered theory of change comes together with excellent leadership capabilities, a really strong vision, and with that ability to engage a whole range of different stakeholder communities*" (Interviewee-T, 2020). Such blurred boundaries need to be taken into account also for the CGIAR reform processes, to enable the CGIAR to more effectively deliver outcomes. As one of the interviewees noted, "*We now understand that there are multiple kinds of boundaries and it's quite likely that it's different kinds of boundary work, still guided by the notion it's a two-way exchange, still guided by the notion of accountability and so on.*" (Interviewee-P, 2020). Therefore, the emphasis needs to be on enabling boundary work within the institution, through institutional arrangements, norms, and procedures to support evidence-based policy making (Cash et al., 2002). Getting the institutional arrangements right, i.e., boundary settings (Mollinga, 2010) is crucial for the production of high-quality knowledge that enhances salience, credibility and legitimacy.

To catalyze institutional reform at scale and move toward enlightenment for science-policy interactions, efforts are needed in the wider institutional landscape for AR4D. Firstly, a shift in institutional governance which promotes a culture of evaluation and reflexivity amongst actors' is important. Such a culture can be achieved through strategies including facilitating participation, transparency, evaluation of results and managing critique (Whitty, 2010). Our interviews show that the CCAFS governance mechanisms placed a huge emphasis on accountability, but within the wider CGIAR, trust deficits were noted in governance processes, which can undermine efforts to ensure accountability. A multi-scale approach to accountability (project, program, institutional), can help enhance legitimacy of knowledge produced over and beyond an individual project or researcher.

We find that that several of the success conditions proposed by Cash et al. (2002): the use of boundary objects, participation across the boundary, mediation and translation, are not universal in applicability. Their applicability is dependent on the context, linking to policy engagement efforts and goals. To facilitate the development of context-specific approaches, institutional governance mechanisms need to foster a suitable environment where efforts to achieve impact are valued and incentivized, and capacity and skills are developed to enable researchers to make this shift.

The leadership of AR4D institutions needs to show commitment to knowledge generation which is credible, salient and legitimate, helping advance policy outcomes and impact on the ground. Such leaders need to be identified and appointed through competitive hiring processes, empowered to make decisions, and bring an entrepreneurial approach to science-policy engagement and achievement of outcomes. In the CCAFS context where the focus is on the Global South, regional leaders and those with developing country experience was found valuable. However, care must be taken so that the leaders thus selected are not overly involved in policy making processes causing research efforts to be biased.

Cash et al. (2002) have proposed coordination and complementary expertise as a key strategy. In the context of climate change adaptation in agriculture, this becomes all the more pertinent, and there is a need to break silos which may exist to make generate high quality and usable knowledge for decision makers. Strategies to do this can include developing partnerships, building transdisciplinary teams, and offering incentives for transdisciplinary work, which corroborates findings derived in the context of spatial climate adaptation in the Netherlands (Hegger and Dieperink, 2014). These have applicability in the CGIAR as well as other transdisciplinary research institutions operating to help adapt to climate change. These efforts can improve interactions among stakeholders, leading to better outcomes for salience, credibility and legitimacy.

The actions which have been highlighted here imply a change in culture within AR4D institutions, and this culture change needs to underpin actions as institutionalizing high quality knowledge generation for climate change is not just about policies and procedures within an institution but about changing the cultural foundations to address climate change.

Opportunities for Institutional Analysis

The lessons on institutional mechanisms to enhance salience, credibility and legitimacy have implications for theories on institutional analysis in the context of institutional design and reform. The Institutional Analysis and Development (IAD) Framework developed by Ostrom et al. (Ostrom et al., 1994; Ostrom, 2011), is a useful framework to unpack the lessons

for institutional design. Within the context of climate change impacts on agriculture, which enhances the risk of resource poor rural farmers, institutional arrangements are crucial to support farmers in climate change adaptation. Action research on climate change, agriculture and food security such as that conducted by CCAFS may be viewed as an "*action arena*" for institutional design. The CGIAR as the international entity responsible for agricultural research and through its ongoing reform to address climate change may be considered to be the "*action area*," which involves actors in this area including the CGIAR leadership, governance processes, funders, and users. With the CGIAR's emphasis on enhancing credibility, salience and legitimacy, as acknowledged by its interpretation of research quality (ISPC, 2017), institutional analysis of this arena and area, and effective institutionalization of success conditions identified, offer a major opportunity to advance theory and action. The IAD framework has been developed to study institutions in different contexts (e.g., Nigussie et al., 2018), but its application to knowledge production could offer new insights for theory and practice.

CONCLUSION

This paper focuses on a pressing knowledge gap: the need for more systematic empirical studies into the institutional design of knowledge action systems in the field of climate change and agriculture. We find that the success conditions proposed by Cash et al. (2002) are relevant to the CCAFS context, although CCAFS as a program was not designed using these as the basis. We see this as an indication that the success conditions are useful guidance for the design and reform of institutions to enhance their ability for science-policy engagement and to deliver societal outcomes. However, though our analysis shows the strengths of the success conditions and their ability to enhance salience, credibility and legitimacy, these success conditions can be strengthened through the addition of two additional conditions - leadership and incentives. These were found to be crucial in the CCAFS case.

The refined success conditions for institutional design can help advance literature on science-policy engagement, offering perspectives on institutionalizing efforts. We have expanded empirical studies of science-policy interactions, offering practical perspectives and applied it to an issue area that is in urgent need of more and more systematic attention of scholars, namely AR4D. While papers which laid the foundation for studying science-policy interactions including Cash et al. (2003) and Clark et al. (2016) draw on CGIAR case studies, the sector has been understudied, and we seek to further build on these foundations offering fresh perspectives around institutionalization. These perspectives on institutionalization also draw upon and contribute to the literature on institutional analysis and development. Our in-depth study of CCAFS has also led to novel insights on how to create an environment conducive to high-quality knowledge generation. It would be useful for future research to pursue such in-depth and interdisciplinary studies in other domains and issue areas.

The success conditions also have practical application in the design and reform of institutions for AR4D. Specifically, the CGIAR is now going through another round of reforms, which will see it transition to "One CGIAR" a more cohesive international institution with climate change as one of the key priorities. The fact that the success conditions also relate to the CGIAR perception of research quality further enhances their credibility to be applied in institutional design for agricultural research for development under climate change. Applying these success conditions in the CGIAR reform process can further enhance the CGIAR's ability to advance action in the context of climate change. Moreover, addressing challenges within the CGIAR for applying these success conditions including trust deficit, accountability, transaction costs etc., can help the reform process. These lessons also have applicability in the reform of other institutions, amidst the growing call to transform agricultural innovation systems (Fanzo et al., 2020; Klerkx and Begemann, 2020; Steiner et al., 2020). This requires a systemic shift in the institutional landscape, to create a suitable environment to apply the success conditions, by creating a culture of evaluation and reflexivity amongst actors, building capacity and skills to undertake science-policy engagement, transformative leadership that emphasizes boundary work, and transdisciplinary research to address climate change issues.

DATA AVAILABILITY STATEMENT

The datasets presented in this article are not readily available because qualitative data was collected through semi-structured interviews, however in order to protect the anonymity of interviewees, this data is not made available. Requests to access the datasets should be directed to d.dinesh@cgiar.org.

ETHICS STATEMENT

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. Written informed consent for participation was not required for this study in accordance with the national legislation and the institutional requirements.

AUTHOR CONTRIBUTIONS

Material preparation, data collection, and analysis were performed by DD. The first draft of the manuscript was written by DD and all authors commented on previous versions of the manuscript. All authors contributed to the study conception and design, read, and approved the final manuscript.

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APPENDIX 1: INTERVIEW QUESTIONS

1. Accountability

1.1 In order for research results to be credible, salient and legitimate, research institutions need to be accountable to both sides of the boundary (i.e., research and action). In your view, how important is this? Do you have an example to illustrate your answer?
1.2 In your view, how does CCAFS fare in terms of being accountable to both sides of the boundary?

2. Participation across the boundary

2.1 What are your views on participation across the boundary as a strategy to institutionalize high quality knowledge generation?
2.2 How effective do you think CCAFS has been in mobilizing participation from both sides of the boundary? Are there key successes/shortfalls that you would like to mention?

3. Use of boundary objects (briefs, info notes, working papers, conferences, maps, models etc.)

3.1 What are your views on the use of boundary objects to institutionalize high quality knowledge generation?
3.2 In your view, how well is CCAFS using boundary objects to do more outcome oriented research? Do you have any examples of boundary objects produced by CCAFS which were very good or bad, why?

4. Translation

4.1 Translating research for users, helps enhance their salience. How well do you think CCAFS is translating research for users? Is there an example you would like to share?

5. Mediation and a selectively permeable boundary

5.1 Mediation is a tool to balance credibility, salience and legitimacy. Have you found this to be important? Please illustrate with an example.

5.1.1 Is this something you have observed in CCAFS?

5.2 Do you find that CCAFS design and management enabled a selectively permeable boundary to advance action?

6. Coordination and complementary expertise

6.1 In addition to enhancing the scale and scope of research, active coordination among institutions with complementary expertise produce more effective actions. In your view how does CCAFS perform on coordination and mobilizing complementary expertise? Can you provide an example?
5.2 The external evaluation noted that CCAFS has made progress with integration of climate change research in the CGIAR, but greater integration and linking is needed. What is missing in terms of integrated climate change research across the CGIAR?

7. Interactions

7.1 What role does interactions among different actors (e.g., through CGIAR/CCAFS governance processes) play to ensure or deter the success conditions discussed above?
7.2 What role does CCAFS leadership play in outcome orientation of the portfolio?

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Advancing Relevance, Credibility, Legitimacy, and Effectiveness as a Heuristic for Local-Parallel Scenarios

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The parallel scenario process provides a framework for developing plausible scenarios of future conditions. Combining greenhouse gas emissions, social and economic trends, and policy responses, it enables researchers and policy makers to consider global-scale interactions, impacts and implications of climate change. Increasingly, researchers are developing extended scenarios, based on this framework, and incorporating them into adaptation planning and decision-making processes at the local level. To enable the identification of possible impacts and assess vulnerability, these local-parallel scenarios must successfully accommodate diverse knowledge systems, multiple values, and competing priorities including both "top down" modeling and "bottom-up" participatory processes. They must link across scales, to account for the ways in which global changes affect and influence decision-making in local places. Due to the growing use of scenarios, there is value in assessing these developments using criteria or, more specifically, heuristics that may be implicitly acknowledged rather than formally monitored and evaluated. In this Perspective, we reflect on various contributions regarding the value of heuristics and propose the adoption of current definitions for Relevance, Credibility, and Legitimacy for guiding local scenario development as the most useful as well as using Effectiveness for evaluation purposes. We summarize the internal trade-offs (personal time, clarity-complexity, speed-quality, push-pull) and the external stressors (equity and the role of science in society) that influence the extent to which heuristics are used as "rules of thumb," rather than formal assessment. These heuristics may help refine the process of extending the parallel scenario framework to the local and enable cross-case comparisons.

Keywords: boundary work, climate change, cross-scale, integrated assessment models, local-parallel scenarios, multi-scale, research evaluation, SSPs

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INTRODUCTION

The multi-scale and systemic nature of climate risk requires greater consideration of the ways in which responses to climate impacts and anticipated risks can be affected and influenced by conditions at the global, regional, and national scales (Simpson et al., 2021). The parallel scenario framework is a sophisticated, global-scale architecture involving representative concentration pathways (RCPs) of greenhouse gas emissions, shared socio-economic pathways (SSPs), and shared policy assumptions (SPAs) (Ebi et al., 2014). Since 2014 the framework has been used to develop

long-term futures, providing insight into the potential effects of climate change on social-ecological systems, the effectiveness of adaptation and mitigation, and the policies necessary to reduce climate-related risks (O'Neill et al., 2014). The framework provides a set of boundary conditions for constructing internally consistent, plausible representations of diverse futures. Elaborating futures scenarios enables researchers, policymakers, and practitioners to explore interactions and feedback mechanisms between large-scale drivers of global change, and to identify and assess possible pathways for change (O'Neill et al., 2020).

This global scenario architecture provides a versatile and flexible structure that can accommodate diverse applications, at different scales, and provide insight into potential impacts and implications. In this, the three interrelated parallel pathways; the RCPs, SSPs and SPAs explore the impact climate change will have on social-ecological systems, the degree to which mitigation and adaptation policies can avoid and reduce those risks, and the costs and benefits of various policy mixes (Ebi et al., 2014). An emerging trend in impacts, vulnerability, and adaptation research, therefore, is to improve the links between the global and sub-national (hereafter local) level by extending the parallel scenario framework and incorporating outputs into applied adaptation decision-making processes (Campos et al., 2016; Cradock-Henry et al., 2018, 2020; Aguiar et al., 2020; Schmitt Olabisi et al., 2020). Such extended SSPs have been developed for a range of settings and problems, including specific sectors and activities such as agriculture and forestry (Daigneault et al., 2019; Mitter et al., 2020; Lehtonen et al., 2021), and scales and places (Frame et al., 2018; Lino et al., 2019; Chen et al., 2020; Gomes et al., 2020; Pedde et al., 2021).

Extending the basic architecture of the global parallel scenarios developed by the climate change research community to the local level also continues the trend in adaptation research, of researchers working with stakeholders—including communities and regions, policymakers and practitioners—to co-produce knowledge (Bremer and Meisch, 2017). Co-production processes seek to better understand local conditions, assess current and anticipated impacts and implications, and explore adaptation options (Ford et al., 2014; Boon et al., 2019; Cradock-Henry et al., 2020; Hill et al., 2020; Cradock-Henry, 2021). These local-parallel scenarios typically combine elements of top-down and bottom-up data derived from probabilistic or econometric models, or through interviews and other participatory methods, respectively.

Local scenarios can improve understanding of the types and magnitude of change, explore sensitivities, and evaluate ways of managing risks. Often these scenarios are used as part of an adaptive planning or pathways process that begins with a comprehensive understanding of the current situation, and then bounds future uncertainty within a manageable set of conditions (Cradock-Henry et al., 2018; Frame et al., 2018; Aguiar et al., 2020). However, development of these scenarios assumes seamless ways to coordinate and apply the frameworks from the global through the regional and national to the local while accommodating new directions. However, as O'Neill et al. (2020, p. 1,079) highlight, "At present, there is no commonly agreed practice regarding methods for downscaling the SSPs" and more detailed Integrated Assessment Models are needed (Pereira et al., 2021; Rosen, 2021).

The rapid growth in the application and development of decision-making tools and processes for adaptation is prompting reflection on the value of heuristics. These are seen as a "branch of study" that seeks to "understand the methods and rules of discovery and invention" (Pólya, 1990). Heuristics can expedite conceptual and methodological development by stimulating thinking. In this essay we use the word "heuristic" to refer to a rule of thumb. Following Starfield et al. (1994), "a heuristic is a plausible or reasonable approach that has often proved to be useful." In so doing, we build on and extend recent work in the field, focusing on one of the most common heuristics in sustainability and climate science: relevance, credibility and legitimacy.

The relevance, credibility, and legitimacy heuristic (hereafter RCL) has been associated with desired attributes for information at the boundary between science and policy communities. It has been used extensively in the literature on adaptation (and climate change more generally), due in part to its origins in assessing the usability of seasonal climate forecasts for decision-making (Cash et al., 2006). We use RCL as our anchor point from the literature (e.g., Cash et al., 2002, 2003, 2006; Sarkki et al., 2014; Belcher et al., 2016, 2019; Cash and Belloy, 2020). We find this workable in practice at the local level, especially when there is a need for something that, while academically rigorous, can be easily understood by non-technical, on-the-ground practitioners. Or, to phrase it differently, we see the use of a heuristic to be of greater practical benefit than a formal evaluation methodology (Nalau et al., 2021). However, as Elsawah and colleagues point out, while conceptual papers such as that by Cash et al. (2006) are often quoted, their "recommendations are rarely used beyond the point of acknowledging that they exist" (Elsawah et al., 2020, p. 13). Our aim here is to consider the various formulations of criteria and attributes in the literature and propose a simple, reproducible formulation that can be used across local case studies.

In this Perspective we reflect on developing and applying local-parallel scenarios as part of adaptation planning. Findings have been generated inductively based on our own experience, and deductively from a review of the literature. We begin by summarizing the process of nesting the local in the global (section Nesting the Local in the Global), before describing the various RCL formulations (section What Is Meant by Relevance, Credibility, and Legitimacy, and What Is Effective?). In section Tradeoffs and Stressors in Developing Local-Parallel Scenarios we discuss how these criteria can accommodate internal and external stressors when working at the science–policy interface. We conclude by proposing how developing local-parallel scenarios might use these criteria most effectively.

NESTING THE LOCAL IN THE GLOBAL

There are many examples of adaptation planning and decision-making ranging from adaptation pathways to resilience and vulnerability assessment. Here we restrict ourselves to the

growing use of scenarios at the local level, and the corresponding increase in case studies (Nilsson et al., 2017; Lino et al., 2019; Zandersen et al., 2019; Butler et al., 2020; Lehtonen et al., 2021). Scenarios are narratives describing plausible future worlds. They are a strategic planning method developed to make flexible and robust long-term plans in response to complex and uncertain futures. Scenarios were initially developed by mid-nineteenth century European military intelligence specialists, but since the 1960s they have been used in a variety of contexts and scales, including business and trade (Berkhout et al., 2002), conservation and development (Peterson et al., 2003; Daconto and Sherpa, 2010; Pereira et al., 2021), community development (Rawluk and Godber, 2011), and adaptive infrastructure management (Hamilton et al., 2013). Due to the uncertainties surrounding the magnitude and effects of climate change, natural variability, and the extent to which human societies will adopt mitigation and adaptation, scenarios are used extensively to explore the effects of certain decisions on climate change.

The global-scale parallel scenario framework, however, is unable to model the localized effects of climate change (Ebi et al., 2014; O'Neill et al., 2014). Precipitation, timing, and intensity of weather events, the role of local geography, or the specific socio-economic factors that affect local decisions on adaptation and mitigation in regions and communities therefore need to be elaborated on and bounded in other ways (O'Neill et al., 2020; Pereira et al., 2021).

At the regional or local level climate scenarios have tended to fall into two broad categories. The first involves emulating the parallel process by collecting and refining expert data and projections into relatively complex scenarios for specific regions. These scenarios are then used with planners, policy makers, and others to synthesize large amounts of scientific data, compare and contrast policy options, and inform decision-making. The second approach uses more community-development-type approaches by working with local communities to co-create scenarios that prioritize local knowledge and memories and community aspirations (Mistry et al., 2014). An emerging third way is the use of local socioeconomic and climate scenarios as a tool for exploring plausible future conditions and how these may influence adaptation strategies (Nilsson et al., 2017; Zandersen et al., 2019; Reimann et al., 2021). These local-parallel scenarios use the basic architecture of the global framework to provide a set of boundary conditions. The combination of emissions, policy mixes, and socioeconomic pathways is contextualized for local conditions through stakeholder knowledge and experience. The resulting narratives represent alternative trends, with a loose or soft linkage to national and/or global conditions (Lino et al., 2019).

Developing and applying such scenarios involves developing quite specific artifacts, such as narratives or other representations of plausible future conditions. These, in turn, may challenge established norms and values, and cut across other place-specific issues. For local stakeholders at least, these have as much, if not more, importance in the short-term decision-making on such issues as infrastructure investments, the viability of primary production, and employment (Cradock-Henry et al., 2018). Consequently, for any scenario development process to be effective at the local scale, it has to successfully engage and negotiate with local concerns (Cradock-Henry et al., 2020; Cradock-Henry and Frame, 2021). Also, as discussed next, useful heuristics are needed that provide guidance on the extent to which this has been achieved.

WHAT IS MEANT BY RELEVANCE, CREDIBILITY, AND LEGITIMACY, AND WHAT IS EFFECTIVE?

Cash et al. (2002, 2003, 2006) established the key concepts of "credibility, salience and legitimacy" as attributes for information at the boundary between science and policy communities. These acknowledged the science and policy interface as a complex terrain requiring skilful navigation, the dynamics of which, within a rapidly changing world, are becoming increasingly challenging (Cash and Belloy, 2020). The terms evolved as a heuristic means to evaluate the boundary between research and policy without necessarily delving into the politics of the situation, or to challenge underlying assumptions (Preston et al., 2015; Nalau et al., 2021). Such research is effectively transdisciplinary, where high-level modeling is likely to be of limited value and datasets are likely to be incomplete or inconsistent (Carlsen et al., 2016; Bosomworth and Gaillard, 2019; Cradock-Henry et al., 2020).

In other words, "credibility, salience, and legitimacy" provide criteria that link the processes of developing climate change information and its usefulness within the transdisciplinary research world, and that other world experienced by end-users, including policymakers. While the heuristic has been widely used to describe the science–policy boundary (White et al., 2010; Kunseler et al., 2015; Dannevig and Hovelsrud, 2016; Cash and Belloy, 2020), various alternative formulations have been proposed. "Salient" was considered to be analogous to "relevant," which led to use of the term CRELE (credible, relevant, and legitimate), which has morphed into relevant, credible, and legitimate, resulting in the acronym, RCL. This, as discussed by others, is what appears to be gaining traction and which we adopt as the preferred terminology (Belcher et al., 2016, 2019; Dunn and Laing, 2017).

Other terms have also been proposed and include, for example, iterativity (Lemos and Morehouse, 2005; Dilling and Lemos, 2011), defined as "a continuous multi-directional interaction that goes beyond simple repetition, building on previous practices, learning from success and failure, and fostering evaluation itself among all participants at the interface and between science-policy interfaces and external audiences" (Sarkki et al., 2015, p. 507) which led to CRELE + IT. While this is useful in terms of transdisciplinary research, it can, for use in local scenarios, be seen as an essential requirement absorbed into the overall concept of effectiveness, as discussed later. Dunn and Laing (2017) suggested that CRELE is not suitable to describe policymakers' needs because it is more focused on information supply rather than information demand. They recommended the use of applicability, comprehensiveness, timing, and accessibility. This, and to a lesser extent CRELE, was criticized by Tangney

(2017) as flawed, though with the latter acknowledging the criteria that should be prioritized for the use of evidence in decision-making (Hansson and Polk, 2018).

To this lexicon, Maier et al. (2016) added terms to describe multiple plausible futures: deep uncertainty, global/local uncertainty and volatility, uncertainty, complexity, and ambiguity. Interestingly, with reference to the development and application of the parallel scenarios, O'Neill et al. (2020) use the term "credible, reproducible, and consistent methods for the use of the SSPs across scales" (p. 6), which perhaps lacks enough rigor. All of this suggests that a formal and broadly accepted formulation would be helpful as the process of extending scenarios gains momentum globally.

The systematic review by Belcher et al. (2016), and its subsequent refinement (Hansson and Polk, 2018), led to definitions for the principles and criteria for assessing the quality of transdisciplinary research. We propose the use of their working definitions for the development of extended parallel scenarios at the local level, as follows:

- *Relevance:* the importance, significance, and usefulness of the research problem, objectives, processes, and findings to the problem context
- *Credibility:* the research findings are robust and the sources of knowledge are dependable—this includes clear demonstration of the adequacy of the data and the methods used to procure the data, including clearly presented and logical interpretation of findings
- *Legitimacy*: the research process is perceived as fair and ethical—this encompasses the ethical and fair representation of all involved, and the appropriate and genuine inclusion and consideration of diverse participants, values, interests, and perspectives.

Belcher et al. (2016) also included the principle of effectiveness. This is, in this case, an assessment criterion to be considered *ex ante* at the proposal stage, with actual effectiveness determined *ex post* through the use of appropriate assessment tools. Thus, effectiveness defines the extent to which research generates knowledge and stimulates actions that address the problem and contribute to solutions and innovations. As a result, Belcher et al. (2019) placed this effectiveness heuristic outside the bounds of the adaptation processes, and we do not include effectiveness to assess adaptation processes prior to their application.

TRADEOFFS AND STRESSORS IN DEVELOPING LOCAL-PARALLEL SCENARIOS

Internal Tradeoffs

Sarkki et al. (2014) used empirical data to identify and explore four internal trade-offs at the science–policy interface, which they described as:

- The *personal time* trade-off between the commitment required by those involved to cover the highly complex, multi-faceted terrain of adaptation vs. commitment to an existing discipline or process
- The *clarity–complexity* trade-off between simple, strong, clear messages (relevance) vs. thorough treatment of uncertainties and systemic dimensions (credibility and legitimacy)
- The *speed–quality* trade-off between timely and rapid responses to policy needs (relevance) vs. time-consuming quality assessment (credibility) and/or consensus building (legitimacy)
- The *push–pull* trade-off between following strong policy demand (relevance) and more supply-oriented research strategies to enable identification of emerging issues or development of innovative solutions (credibility and legitimacy).

Sarkki et al. (2014) also identified issues relating to trust and inclusion of other worldviews, which are considered as external stressors.

External Stressors

Cash and Belloy (2020) describe four external stressors in the global context which address criticism that RCL does not fully address socio-political aspects, distributive justice, and the rapidly changing knowledge–action landscape. First there is the challenge of engaging with quite different forms of knowledge when working across scales, and the need to ensure trust is created in the process. Second there are equity issues, which are both urgent and complex and include ethical dimensions, populations with existing vulnerabilities, issues of privilege, as well as historically disadvantaged populations. Third there is the degradation of the role of science in society and the trust placed in science in the "post-truth" world where trust in science has become corroded with an increasing emphasis on personal or political preferences. This is most clearly exhibited through perspectives such as climate change denialism and resistance to evidence-based responses to the COVID-19 pandemic (Jasanoff, 2021). Finally, there are issues related to the production of knowledge through digital technologies across multiple platforms, including ease of access to shared information, which blurs the citizen–science boundary, and the ways in which social media is used by institutions, community groups, and businesses to influence opinions.

While these originated through consideration of global developments, we seek here to consider them specifically in relation to local scenario processes. That is to say, we consider the use of the RCL heuristics primarily through the first of these dynamics—working across scales. We then look at how this affects issues of equity and science in a post-truth society and with digital transformations only playing a relatively minor role. We do so based on our experiences with impacts, vulnerability, and adaptation at the local level in Aotearoa—New Zealand (New Zealand) that will be highly contextual and place-specific, but also seek to provide a more general perspective (Cradock-Henry et al., 2018, 2020; Frame et al., 2018; Ausseil et al., 2019; Cradock-Henry and Frame, 2021).

Equity

Cash and Belloy (2020) describe four aspects of inequity in contemporary society: historically disadvantaged populations;

those with existing vulnerabilities; those in post-disaster recovery; over-arching ethical considerations of human and non-human ecology. Of these, the historically disadvantaged and those with existing vulnerabilities are, currently, the most pertinent to our discussion. In the New Zealand context we propose that the first relates solely to the indigenous population, with the latter covering other disadvantaged groups.

Aotearoa—New Zealand is a bi-cultural nation, with indigenous Maori retaining governance rights and management responsibilities for ancestral land through Te Tiriti o Waitangi (the Maori version of the Treaty of Waitangi, 1840)—New Zealand's founding document, framing the relationship between Maori and the Crown. In addition to their lands, many iwi (Maori tribes) have commercial agribusiness and forestry interests. They also live in or near coastal margins, which are likely to be exposed to the effects of climate change. Ideally, scenarios would be developed using kaupapa-based Māori methodologies (Smith, 2012); i.e., designed by and for Māori, addressing Māori concerns, conducted predominantly by Māori researchers and based on Māori cultural values. In practice, available technical capability and capacity can, currently, be a limiting factor. To ensure a Māori perspective, any local consultation process must involve iwi or hapu as an equal partner. This cannot be considered an optional add-on but must be seen as a central component. If this is not undertaken in a sincere and comprehensive manner, then success in achieving a legitimate result is greatly diminished.

Our experience also suggests it is both critical and difficult to negotiate and balance the power dynamics between ostensibly equal stakeholders (Cradock-Henry et al., in press). As with geopolitics, there are strong players and silent players. For example, there can be wealthy landowners with extensive business interests, positions in local-body politics, and strong, long-term family connections who may be able to exert a disproportionate influence on decision-making processes (sometimes over-stated as "oligarchs"). This authority needs to be made relatively transparent and the opportunity for alternative perspectives enabled.

If "oligarchs" are potentially over-privileged, then there is an equal risk of under-privileging local, "silent," voices. These are groups or individuals who are potentially less able to form coherent and consistent opinions than those endowed with politically relevant resources. Exclusion of silent voices reduces the relevance and legitimacy of local scenarios. Consideration therefore also needs to be given to how participatory scenario processes unfold; for example, who participates, and to what extent local hierarchies of social difference (age, gender, class, ethnicity, etc.) shape how scenarios are facilitated, and the actions that emerge out of them (Stirling, 2008).

Science in Society

Expert-led scenario development tends to prioritize the knowledge and involvement of professionals over local communities and is usually expensive and resource intensive. However, experts can introduce information and identify opportunities not readily available to local communities. Nonetheless, scenarios can be perceived as derived from and delivered by experts telling local people what they need to do. In other words, the role of the external knowledge provider is perceived as privileged, with the potential to dominate the local. While this has been a topic within the science and technology studies field for several decades (e.g., Wynne, 1991, 1992), it is not always widely understood in practice by biophysical researchers or local authorities. Failure to accommodate this, or to have resources available to address this, could lead to early failures, which then place climate change as even less of a legitimate issue. This is exacerbated in the post-truth world, as highlighted through populist campaigns such as climate change denialism (Harvey et al., 2018; Bloomfield and Tillery, 2019; Bowden et al., 2019; Kovaka, 2021) and resistance to immunization programmes for the COVID-19 virus (Jaiswal et al., 2020; Uscinski et al., 2020).

In the context of developing local scenarios through participatory and co-production processes, this can result in the wider project being perceived by some locals as an extension of "government," with researchers being seen as "suits from the city." This has led, in our experience, to being advised against mentioning specific topics (in the rural New Zealand context this includes the use of toxins for predator management and proposed bans on fossil fuel mining) that can be particularly contested and divisive. Until recently, work on adaptation in New Zealand—particularly with farming communities—was fraught, with stakeholders' conflating mitigation and adaptation (Reisinger et al., 2011; Cradock-Henry, 2017) and opposition to taxes on carbon or greenhouse gas emissions (Cooper and Rosin, 2014). Attitudes, trust in science, and knowledge sharing have become politically polarized, with people rejecting scientific evidence that misaligns with their personal or political preferences, requiring greater sensitivity and diplomacy when managing participatory deliberation and analysis. It is essential therefore, to acknowledge and reflect on one's role in the scenario process. Assuming the role of the "honest broker" (Pielke, 2007; Sarkki et al., 2020) in scenario development can help navigate the tension between scenario types: what *could* happen vs. what *should* happen (Börjeson et al., 2006).

Participatory scenario development processes are more likely to reflect local people's experiences and aspirations. These should include important knowledge missed by experts, and include multiple stressors, and through this process build local agency to enact appropriate and socially acceptable solutions (Bohunovsky et al., 2011; Mistry et al., 2014; Wesche and Armitage, 2014; Flynn et al., 2018; Guaita García et al., 2020). However, they are often not spatially explicit, can miss important expert knowledge, are not robust enough and connected to national/global drivers, and can be resource intensive for participants (Guaita García et al., 2020). This tension between local and professional knowledges and experiences needs to be carefully facilitated.

CONCLUDING COMMENTS

Climate change adaptation processes are one possible intervention in the complex assemblage of climate risk management. However, they are deeply enmeshed in wider

social contexts, including the exercise of authority and agency, irrespective of scale. The arguments about this at the global and national level are well-rehearsed (O'Neill et al., 2020; Rosen, 2021) and we propose, these are equally valid at the local level.

For the global parallel-scenario process to connect to local contexts in culturally meaningful ways, scenarios should be formally reviewed during their development to assess the extent to which they are relevant, credible, and legitimate for local stakeholders, and not just for researchers. They need to be made relevant by ensuring expert knowledge is contextualized for local concerns, conflicts, and aspirations. The processes cannot privilege the expert over the local and must provide credible and legitimate ways in which the future can be plausibly negotiated. We propose that the consistent use of heuristics, rather than formal definitions, for assessment criteria are important, and that the definitions produced by Belcher et al. (2016) and restated earlier provide a means of creating consistency between case studies. Inevitably these will be subject to review over time, as they have already. However, a consistency of approach in practical examples appears the most useful next step.

It is the local's inherent complexity that makes the political so critical to an overarching understanding of adaptation options. Accommodation of this complexity must address not just the rigors of sound research but also the trade-offs and stressors described. While absolute definitions for criteria have an obvious attractiveness, the dynamic around the terms used and the concerns their use seeks to address (see Cash and Belloy, 2020 for a deeper discussion) reinforce that these should be seen as heuristics which, as demonstrated so clearly by Nalau et al. (2021) must retain a high degree of flexibility. That does not, however, imply a casual approach. Only by consistently applying these heuristics can we counter Elsawah et al.'s critique (Elsawah et al., 2020, p. 13) that such concepts are developed but not used.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author/s.

AUTHOR CONTRIBUTIONS

NC-H and BF: conceptualization, writing—reviewing, and editing. NC-H: funding acquisition. All authors contributed to the article and approved the submitted version.

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Inclusiveness, Equity, Consistency, and Flexibility as Guiding Criteria for Enabling Transdisciplinary Collaboration: Lessons From a European Project on Nature-Based Solutions and Urban Innovation

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The structural research programmes of the European Union dedicated to advance the sustainability sciences are increasingly permeated by the notion of transdisciplinarity (TD). A growing body of literature residing at the intersection of research methodology and sustainability studies can guide researchers to adopt appropriate research approaches in their projects. However, how to implement the transdisciplinary approach in multidisciplinary and multi-stakeholder projects that develop in different countries for several years is still relatively undocumented. This study seeks to fill this gap by sharing the experience of a group of researchers and stakeholders involved in the Horizon 2020 research and innovation project Nature-Based Urban Innovation (NATURVATION). The article discusses the monitoring and evaluation strategy that employed four criteria of transdisciplinary research quality as "reflexive devices" to enable a systematic reporting on the project's most important collaborative activities. By examining how the four criteria captured transdisciplinary quality, new insights were produced for improving this monitoring and evaluation strategy for future transdisciplinary research, allowing a number of concrete recommendations to be formulated.

Keywords: transdisciplinary research-design, research quality principles, inclusiveness, equity, flexibility, consistency

INTRODUCTION

The structural research programs of the European Union (EU) dedicated to advance the sustainability sciences have been increasingly influenced by the notion of transdisciplinarity (TD). A case in point is the Horizon 2020 Responsible Research and Innovation Action, which is oriented toward "promoting inter- and transdisciplinary solutions"

(European Commission Horizon 2020 Programmes, 2021, *online*). One explanation for the "institutionalization" of this methodological approach is the "quest for legitimate knowledge" (Basta, 2017) that underpinned the epistemological debate of the past decades on the roles of science *in* and *for* society (e.g., Owen et al., 2012). This debate contributed to the advancement of research practices where researchers, policymakers, and stakeholders collaborate in inclusive processes of knowledge production (Jasanoff and Wynne, 1998; Hirsch-Hadorn et al., 2008; Wyborn, 2015). The assumption that motivates these research practices, and that seems to have determined their growing acceptance on the side of the scientific community and research funding agencies worldwide, is that "transdisciplinary teams can generate new knowledge to address complex problems while integrating multiple disciplines and stakeholders" (Harris and Lyon, 2014).

As the science of "complex problems" *par excellence*, the sustainability sciences have been particularly receptive to relevant methods of "co-production" of scientifically grounded and, at the same time, transformative knowledge (Lemos and Morehouse, 2005; Godemann, 2008; Brandt et al., 2013; Gaziulusoy et al., 2016; Norström et al., 2020). As a consequence, at the intersection of research methodology and sustainability studies, a hybrid literature has emerged on which quality principles and operational criteria could support the design and evaluation of collaborative and integrative research practices (Schramm et al., 2005; Wickson and Carew, 2006; Pohl and Hirsch Hadorn, 2008; Carew and Wickson, 2010; Jahn et al., 2012; Belcher et al., 2016; Wall et al., 2017).

Generally accepted quality principles include relevance, credibility, legitimacy, and effectiveness of the knowledge production process (among others, Belcher et al., 2016). The challenges commonly faced by the multidisciplinary and multi-stakeholder teams seeking to operationalize these principles in their work are also widely studied. These include the combination of the different knowledge bases of research participants into a shared problem formulation (Pohl and Hirsch Hadorn, 2008); enabling dialog and building trust among researchers and stakeholders with different backgrounds and goals (Harris and Lyon, 2014); and more generally, minimizing the gap between the "ideal conditions" for effective knowledge co-production and synthesis, and the reality in which research projects normally develop (Lang et al., 2012; Verwoerd et al., 2020).

These practical challenges, and the guiding principles that assist in dealing with them, are indeed well-documented in the literature. However, how to tackle these challenges when the operationalization of these principles occurs in the framework of projects that develop in different countries over several years—that is, the typical setting of large EU research projects—is still relatively undocumented. In particular, there is a dearth of studies that combine the adoption of the transdisciplinary guiding principles of relevance, credibility, legitimacy, and effectiveness with the systematic reporting on their operationalization in the framework of large international projects. This research seeks to fill this gap by discussing the self-assessment of a transdisciplinary monitoring and evaluation strategy developed in the Horizon 2020 research and innovation project Nature-Based Urban Innovation (NATURVATION). As participants within the project, we reflect on the operationalization of transdisciplinary research quality principles in the context of one of the project's key activities, namely, conducting various knowledge co-production events on the benefits and implementation of nature-based solutions (NBS) in local urban plans. The events were organized on the basis of the common agenda of the six Urban–Regional Innovation Partnerships (URIPs) active in NATURVATION's consortium. These local partnerships included academics, researchers, urban professionals, and stakeholders involved in the common search for nature-based solutions to pressing urban challenges. As such, the six URIPs constituted the local "transdisciplinary teams" of NATURVATION's consortium.

Our self-assessment of the monitoring and evaluation strategy was tailored to assess the transdisciplinary quality of the URIPs' knowledge co-production events. It reflects on the pathway taken from the adoption of the aforementioned transdisciplinary quality principles to the identification of four operational criteria. The latter were used as "reflexive devices" for reporting on the events and gauging their transdisciplinary quality. The objective of the article is therefore two-fold. The first is methodological, and regard the development of our monitoring and evaluation strategy as an exemplary case on how to operationalize transdisciplinary research quality principles in large international projects where multiple transdisciplinary teams operate at a local level to advance project objectives. The second objective is reflexive and consists of self-assessing the efficacy of our strategy to inform the transdisciplinary quality of the collaboration within the URIPs.

This article is divided in four parts. Section The challenge of building transdisciplinary capacities in large European Union projects: nature-based urban innovation methodological approach, and the perspective of this study describes NATURVATION's objectives, organizational setup, and the notion of transdisciplinarity that informed the project's research design. This part provides a snapshot of the research context in which we developed and assessed the monitoring and evaluation strategy of the project's transdisciplinary quality. The section Materials and methods: literature review, Urban–Regional Innovation Partnerships' Summary Reports, and our collaborative self-assessment then describes the materials and methods that inform our study, and also provides a short account of the different proposals of implementation of the TD approach in NATURVATION that led to the definition of our strategy. The Discussion: What the Analysis of the Urban–Regional Innovation Partnerships' Summary Reports Reveals, and Our Self-Assessment of the Relevant Monitoring and Evaluation Strategy discusses the results of the self-assessment. This section anticipates some conclusions regarding the four criteria of transdisciplinary quality adopted in the reporting system, reflecting, in particular, on how this could be improved in future applications. The section Conclusive Remarks: Transdisciplinary Research as the Art of "Bringing Order to Creative Chaos" provides

our concluding remarks. These regard improving the efficacy of systematic reporting by using explicit criteria of transdisciplinarity in the framework of large international projects during their entire development. The conclusions also stress the importance of communicating the scope of reporting on transdisciplinary quality criteria clearly to all project participants. These final recommendations are directed also at the research funding agencies that promote transdisciplinary research.

THE CHALLENGE OF BUILDING TRANSDISCIPLINARY CAPACITIES IN LARGE EUROPEAN UNION PROJECTS: NATURE-BASED URBAN INNOVATION METHODOLOGICAL APPROACH, AND THE PERSPECTIVE OF THIS STUDY

NATURVATION is a European research and innovation project that aimed at advancing innovative knowledge on nature-based solutions (NBS) to urban sustainability challenges. These included climate adaptation, air quality, and the related social questions of equity and inclusiveness. NBS (for example, green urban roofs) are solutions inspired or delivered by nature that constitute sustainable alternatives to their technological counterparts (for example, air conditioning systems) (Bulkeley, 2016). Identifying cost-effective NBS that could contribute to advance the sustainable development goals and promoting their implementation in urban and regional plans constituted the main objectives of the project.

For identifying and assessing the multiple benefits and potential uses of NBS, the project relied on an iterative program of activities conducted in six Urban–Regional Innovation Partnerships (URIPs) based in Utrecht (The Netherlands), Gyor (Hungary), Newcastle (UK), Leipzig (Germany), Barcelona (Spain), and Malmö (Sweden). Each URIP acted as "transdisciplinary unit" by being co-convened by researchers from local universities or research centers, local government representatives, and stakeholders relevant to the implementation of NBS in the respective urban region. As such, the URIPs constituted the "operational units" of the research consortium.

The methodological approach that framed the collaboration among their participants is the transdisciplinary approach. In NATURVATION's project plan, the transdisciplinary approach was qualified as "on-going and collective process of learning, where different knowledge communities are brought together" (Bulkeley, 2016, p. 27). Moreover, "the project emphasizes the importance of collaboration, co-production of knowledge, and the maximum outreach of its results" (Bulkeley, 2016, p. 31).

The concept of knowledge co-production was particularly relevant to the URIPs program of activities. Indeed, knowledge co-production "occurs" in context-based, pluralistic, goal-oriented, and interactive settings (Norström et al., 2020). The establishment of the six local partnerships, and the definition of their program of activities, was therefore meant to create the most favorable conditions for harvesting and channeling multiple local knowledge toward innovative learnings on NBS.

The URIPs' relevant activities were coordinated by ICLEI, the global network of local governments for sustainability, a boundary organization that supports local governments' sustainable development capacities (Frantzeskaki et al., 2019). The most important among these activities consisted of a set of thematic events on NBS focused on their assessment and implementation in local urban plans. Other events, like the Stakeholders Dialogues held in Utrecht and Malmö, were dedicated to advance specific NATURVATION's deliverables like the NBS integrated assessment framework. All events shared the goal of facilitating co-production of knowledge by bringing together multiple knowledge communities. Each URIP organized them autonomously on the basis of the common agenda coordinated by ICLEI. In parallel, ICLEI led an iterative program of knowledge exchange among the URIPs on the outcomes of all events in such a way to secure the accessibility of the relevant progresses to all project's participants.

As part of NATURVATION's transdisciplinary capacity-building objectives, the Netherlands Environmental Assessment Agency (PBL), one of the project's partner institutes, conducted a research on the operationalization of the transdisciplinary approach from an observant position. This article is one of the deliverables of this research trajectory. This study therefore combines the perspective of researchers not directly involved in the coordination of the transdisciplinary process with the perspective of its coordinators and participants. In it, we also jointly reflect on how the role of observers of the PBL researchers influenced the way in which the URIPs members experienced the task of reporting on the transdisciplinary quality criteria. Before doing so, in the following section, we describe the theoretical premises and methodological challenges that have informed NATURVATION's transdisciplinary research design.

Fostering Transdisciplinary Co-Production of Knowledge: Epistemological Premises, Methodological Questions, and Nature-Based Urban Innovation's Relevant Challenges

At the early stage of NATURVATION, the first step taken to identify workable strategies for operationalizing the transdisciplinary approach in the research practices of URIPs and evaluating their quality consisted of executing a literature review on different conceptions of transdisciplinary research (TDR) (Basta and Kunseler, 2018). The review, described in more detail in the section Literature Review: Transdisciplinary Quality Principles, Operational Criteria, and How "Putting Them to Work", explored different literatures, among which research methodology and sustainability literatures. This enabled to distill the "common denominators" among different conceptions of TDR. The review also revealed how, in approaching questions of transdisciplinary research quality, research methodology, and sustainability literatures

draw on the same underlying epistemological debate on the role of science in society (Owen et al., 2012; Osborne, 2015)[1].

From the prevention of natural and technological hazards (De Marchi and Ravetz, 1999; Culwick and Patel, 2016) to climate change adaptation (Gaziulusoy et al., 2016; Turnhout et al., 2016; Howarth and Monasterolo, 2017) up to nature-based solutions to sustainability challenges (Nesshöver et al., 2017; Steger et al., 2018; Hanson et al., 2020), the fields of study that have embraced this integrative conception of knowledge have steadily increased. In the field of urban sustainability studies, the most relevant to NATURVATION's objectives, such conception of integrated knowledge overlapped with the established theoretical tradition that sees the participation of different actors in knowledge production and decisional processes as instrumental to pursue urban goals more effectively (e.g., Forester, 1999; Maiello et al., 2010) and legitimately (Healey, 2003; Muller et al., 2005).

The interrelation of this wide range of sources with the idea of transdisciplinarity as "process of mutual learning" adopted in NATURVATION provided solid theoretical foundations for approaching the research design of the activities of the URIPs. However, at the beginning of the project, several operational questions had to be solved still. A particularly important question consisted of how monitoring such activities against transparent transdisciplinary quality principles at a two-fold scope of securing their methodological consistency and informing their progresses accordingly[2]. The relevant challenge was relative not only to conceptual questions like the identification of transdisciplinary quality criteria adapt to the operational context of the URIPs but also to pragmatic barriers like the multiple countries in which the URIPs were due to develop their works simultaneously.

To tackle these issues, the PBL researchers who author this article tailored the research strategy described in the following section, dedicated to the materials and methods that inform this study.

MATERIALS AND METHODS: LITERATURE REVIEW, URBAN–REGIONAL INNOVATION PARTNERSHIPS' SUMMARY REPORTS, AND OUR COLLABORATIVE SELF-ASSESSMENT

This section reconstructs the development of the monitoring and evaluation strategy adopted for documenting the adherence of the thematic events of the URIPs to the four transdisciplinary research quality principles adopted in NATURVATION. It also describes the methods used for elaborating the following self-assessment. Some of the steps described in the following subsections constitute the background work also for other studies conducted in the framework of our research on the TD approach (e.g., Basta, 2021, *forthcoming*). Some others instead are relative to this study only. These steps consist of:

1) A literature review on the transdisciplinary research methodology and on its implementation in research projects in the broad field of the sustainability sciences (section Literature Review: Transdisciplinary Quality Principles, Operational Criteria, and How "Putting Them to Work");
2) The identification of criteria suitable to operationalize the transdisciplinary guiding principles of relevance, credibility, legitimacy, and effectiveness in key knowledge co-production events (this study, section From transdisciplinary guiding principles to operational criteria: contextualizing transdisciplinary practices);
3) The establishment of a consistent practice of reporting on such events by the URIPs by means of the provision of template Summary Reports (this study, section From Operational Criteria to Information Gathering: Establishing a Consistent Reporting System);
4) The analysis of the reporting gathered over time by means of document analysis (this study, section The Urban–Regional Innovation Partnerships Summary Reports: A Document Analysis); and
5) A self-assessment of the efficacy of the reporting system to gather information and stimulate reflection on the transdisciplinary quality of each event (this study, section Looking Back: Shaping a Collaborative Self-Assessment Exercise).

We elaborate on each step separately in the following subsections.

[1]Initiated in the second half of the 20th century, such debate rooted in the academic rivalry between the theoretical and the applied sciences and in the "gulf of mutual incomprehension" between the two respective academic cultures (Snow, 1959). The following epistemological debate, progressed also under the influence of the French structuralist movement, developed up to envision "a superior order of knowledge" that integrates different disciplinary outlooks in the process of scientific inquiry. Such 'superior order' is what the French linguist and epistemologist Jean Piaget called transdisciplinary knowledge (Nicolescu, 2014).

[2]For the PBL researchers who author this study, besides a question of research *quality*, this operational question was also a matter of research *ethics*. Such matter was touched upon in the paper "Transdisciplinarity in Urban Studies: From 'preaching it' to doing it" presented at the yearly congress of the European Association of Schools of Planning in the summer of 2017 (Basta, 2017) and in a follow-up study (Basta, 2021, *in progress*). The ethical question regards the accountability of researchers involved in transdisciplinary projects funded by the EU structural research programs for the consistency between the methodological approach described in the respective project plans, and its concrete implementation. The relative concern originates from the observation that the involvement of multiple stakeholders in a project's consortium, and the labeling of such involvement as "participatory" and "collaborative" research, does not guarantee that their knowledge will be integrated in the project's deliverables. Research projects funded with EU structural funds that apply participatory and collaborative approaches to the production of knowledge should therefore include transparent monitoring and evaluation mechanism able to document the integration of the knowledges of different actors in the project's deliverables. However, as documented in the study that followed-up on the cited congress paper, in the H2020 program this has rarely been the case. The study includes the review of more than 40 Final Reports of H2020 projects in the social and in the environmental sciences that adopted the transdisciplinary approach. Of them, none included robust monitoring and evaluation mechanisms dedicate to document the integration of different knowledges in the project's deliverables. In the view of the author, this striking finding suggests the desirability of rendering these monitoring and evaluation mechanisms pre-requisites for obtaining structural research funds.

Literature Review: Transdisciplinary Quality Principles, Operational Criteria, and How "Putting Them to Work"

The first step taken to operationalize the transdisciplinary approach in NATURVATION and in the URIPs thematic events consisted of scoping relevant literature. The question that guided the literature review was how to operationalize the notion of transdisciplinarity as co-production of knowledge in a large international project of the scope and complexity of NATURVATION, with a focus on the methods for transdisciplinary knowledge co-production.

Standard scientific repositories and search tools like SCOPUS and Google Scholar were employed in the search of sources. Keywords like "transdisciplinary methodology," "knowledge co-production," and "transdisciplinary operationalization," among others, were used to detect relevant studies. From an initial set of several hundreds of titles, 100 sources on the theory and practice of transdisciplinary research were selected. These included both primary sources and grey literature. The selection was executed by quick-scanning abstracts and executive summaries. A second reading of the sources resulted into two subsets. One subset grouped the studies dedicated to the historical and epistemological development of the concept of transdisciplinarity from its origins to date. The other subset grouped the studies on the operationalization, monitoring, and evaluation of the practice of TD research in project-based researches[3]. This study is informed mostly by this latter subset.

From it, the clear prominence of the principles of relevance, credibility, legitimacy, and effectiveness as guiding principles for designing transdisciplinary investigations emerged (Belcher et al., 2016). These principles were therefore adopted as guiding principles for the research design of NATURVATION. At the same time, the review revealed the scarcity of studies on how operationalizing such principles in large projects that build-up upon different activities in multiple countries over several years (Hoffmann et al., 2017). Thus, rather than providing definite answers, the literature review supported the formulation of the following questions:

a) *what* criteria can facilitate the monitoring of the URIPs' knowledge co-production activities in such a way to assess their adherence to the principles of relevance, credibility, legitimacy, and effectiveness?
b) *how* can these criteria be operationalized in such activities in such a way to generate robust and consistent information and, at the same time, promote relevant reflections from the side of URIPs' members?

These questions are briefly discussed in the two following subsections.

[3]The full literature review is discussed in NATURVATION's milestone n.7.5, Basta and Kunseler (2018), *Working Paper on Transdisciplinary capacity building: Review of concepts to develop guiding-ideas for NATURVATION's transdisciplinary research design*.

From Transdisciplinary Guiding Principles to Operational Criteria: Contextualizing Transdisciplinary Practices

The literature review recalled in the previous section had made clear that the greatest challenge for monitoring and evaluating situated processes of knowledge co-production like those led by the six URIPs consists of identifying transdisciplinary quality criteria adapt to their unique research contexts. At this scope, between March and June 2017 the research team of PBL held several brainstorming sessions. Parts of these sessions were extended to ICLEI and to the coordinators of the project.

The PBL researchers advanced multiple proposals for operationalizing the transdisciplinary guiding principles of relevance, credibility, legitimacy, and effectiveness by means of suitable criteria. The initial proposal centered on the notion of mutual learning as key to transdisciplinary work. It consisted of inviting the members of the URIPs to set individual learning goals. Such goals should have covered the entire duration of the project and should have been the object of reporting regarding their achievement on a regular basis. This approach—inspired among others by the work of Roux et al. (2017)—was meant to generate information, from the perspective of the participants in the URIPs, regarding their achieved learnings. The idea was then to evaluate such learnings against the TD guiding principles of the project. If, for example, learning new ways to minimize heat island effects in the city would have been an explicit learning goal for one or more participants in the URIPs, whether or not such goal would have been achieved during the respective works would have enabled the evaluation of their relevance to the desired learnings of participants. The PBL team would have then been in a position to produce robust observations on the adherence of the project's outcomes to the principle of relevance and, by replicating the approach for all principles, to those of credibility, legitimacy, and effectiveness.

In the light of the task load that this otherwise promising monitoring and evaluation method could have implied for the participants in the URIPs, the proposal of its implementation was discarded. Indeed, due to the intensive project plan, at the time several URIP participants had already flagged the risk of suffering from "stakeholders' fatigue" (Baró, 2017): a risk that was not explicitly anticipated in the project proposal (**Table 1**), and that this approach may have exacerbated further. A subsequent proposal then consisted of identifying a set of quality criteria relevant to the four transdisciplinary guiding principles and proposing them to the participants of the URIPs as "reflexive devices" on the dynamics and results of the thematic events already on their agenda. The observations gathered would have enabled to reflect on the factors that had enhanced or undermined the quality of the TD collaboration among the members of the URIPs during each event. In the light of the simpler implementation of this method, the relevant proposal was endorsed by ICLEI and by the coordinators of the project.

The following steps consisted of identifying the most adapt criteria for reporting on the thematic events of the URIPs in such a way to capture their relevance, credibility, legitimacy, and effectiveness reported in **Table 2**. Based on inputs from the

TABLE 1 | Risks of the transdisciplinary approach in Nature-Based Urban Innovation (NATURVATION) and mitigating actions (adapted from Bulkeley, 2016).

Risk	Risk/impact	Description	Mitigating action	Responsible party
Developing and maintaining a transdisciplinary approach throughout the work program	Low/high	The project is grounded in a transdisciplinary approach which requires ways of working that are open to different perspectives, languages, and methods, and is able to accommodate diversity while also seeking to build consensus and delivering the work program effectively.	Transdisciplinary working built into all WPs and through URIPs. Maintaining the URIPs over time is central to mitigating this risk through the role of ICLEI facilitating the URIPs and six research partners will dedicate time to this role. We will also build on the extensive experience of Ecologic and PBL as transdisciplinary organizations that have dedicated resources to understanding and learning from this process in real time.	Project Coordinating Group WP7 Leaders WP7.1 Task Leaders and participants.

URIPs, Urban–Regional Innovation Partnerships; PBL, the Netherlands Environmental Assessment Agency.

literature review and on following brainstorming sessions, these criteria were identified in the criteria of inclusiveness, equity, flexibility, and consistency. From the side of the brainstorming sessions, one important input for arriving to identify these criteria consisted of articulating questions like, "what makes the questions discussed during a URIP thematic event relevant for those participating in it?"; or, "what makes participation in the event effective for individuals?" The writing of short answers to these questions—e.g., "one's professional goals"; "one's ability to voice her opinion," etc.,—provided the basis for reasoning around the criteria most adapt for capturing the guiding principles of transdisciplinarity as these would have "worked" in the specific context of the URIP events. From the side of the literature, an important role for their identification was played by the relevant study of Belcher et al. (2016), where questions of inclusiveness and equity of participation of stakeholders in collaborative forms of knowledge production are explicitly addressed. The Bracken et al. (2015) study on the perspective of stakeholders involved in large transdisciplinary projects provided additional arguments for including the criterion of flexibility. The fourth criterion of consistency was added with the intent of stimulating reflection regarding the overall adherence of thematic events with the inclusive, equitable, and flexible spirit that should have permeated their organization and management. Finally, comparable experiences of transdisciplinary research design of the authors of this study led to endorse the final set of four criteria (Kunseler et al., 2015; Wamsler, 2017). These are reported in **Table 3**.

How the criteria were "administered" to the URIP coordinators in such a way to gather relevant information is described below.

From Operational Criteria to Information Gathering: Establishing a Consistent Reporting System

Having identified workable criteria for generating information on the URIP thematic events relevant to the adopted guiding principles of transdisciplinary quality, the next question consisted of how "putting them to work." A particularly sensitive dilemma for the PBL researchers consisted of whether opting for "intrusive" information-gathering approaches, like interviewing the members of the URIPs regarding the dynamics and outcomes of thematic events by revolving around the four criteria, or opting for approaches that would have minimized their direct involvement in the gathering of information. This latter concern was corroborated by inputs provided by some URIP coordinators regarding the risk, for stakeholders, to feel like "guinea pigs" (Baró, 2017).

By virtue of this and other practical difficulties, including multiple language barriers, the most effective strategy seemed that of promoting systematic reporting on the four criteria from the side of URIP coordinators by incorporating them into the template Summary Report already used by them for reporting on the thematic events on their agenda. By filling in the template, URIP coordinators were required to report on "quantitative" aspects of each thematic event—like the number of participants—as well as on content-related aspects like the thematic sessions held, the information exchanged, the agreements reached, and so on. With the introduction of the four quality criteria of inclusiveness, equity, flexibility, and consistency as explicit points of reflection in the Summary Reports, starting from June 2017 the coordinators of the URIPs were put in condition to generate also this information on each event.

Table 4 reports a copy of the template used for facilitating the systemic reporting of the URIPs. In the following section, we present the method of analysis of the Summary Reports that was used for informing the self-assessment exercise discussed in the section Discussion: What the Analysis of the Urban–Regional Innovation Partnerships' Summary Reports Reveals, and Our Self-Assessment of the Relevant Monitoring and Evaluation Strategy.

The Urban–Regional Innovation Partnerships Summary Reports: A Document Analysis

To prevent any confusion, it is newly emphasized that the primary scope of this study does not consist of reflecting on the examined thematic events in relation to the criteria discussed in

TABLE 2 | Transdisciplinary research quality criteria (adapted from Belcher et al., 2016; in Basta and Kunseler, 2018).

Quality principles	Research evaluation criteria
Relevance Relevance is the importance, significance, and usefulness of the research project's objectives, process, and findings to the problem context and to society.	• The appropriateness of the timing of the research, the questions being asked, the outputs, and the scale of the research in relation to the societal problem being addressed; • Researchers must demonstrate an in-depth knowledge of and ongoing engagement with the problem context in which their research takes place; • From the early steps of problem formulation and research design through to the appropriate and effective communication of research findings, the applicability, and relevance of the research to the societal problem must be explicitly stated and incorporated.
Credibility Credibility refers to whether or not the research findings are robust and the knowledge produced is scientifically trustworthy.	• Clear demonstration that the data are adequate, with well-presented methods and logical interpretations of findings; • High-quality research is authoritative, transparent, defensible, believable, and rigorous; traditional disciplinary criteria can be applied in TDR evaluation to an extent; • Additional and modified criteria are set that address the integration of epistemologies and methodologies and the development of novel methods through collaboration, the broad preparation, and competencies required to carry out the research, and the need for reflection and adaptation when operating in complex systems; • Researchers are actively engaged in the problem context, which includes extra-scientific actors as part of the research process so that the relevance and legitimacy of the research are facilitated; • Heightened requirements of transparency, reflection, and reflexivity to ensure objective are carried out; • Transdisciplinary researchers must ensure they maintain a high level of objectivity and transparency while actively engaging in the problem context.
Legitimacy Legitimacy refers to whether the research process is perceived as fair and ethical by end-users. Whereas credibility refers to technical aspects of sound research, legitimacy deals with socio-political aspects of the knowledge production process and products of research.	• Genuine and appropriate inclusion and consideration of diverse values, interests, and the ethical, and fair representation of all involved; regardless of the depth of participation, processes for effective and fair collaboration are present; • Societal actors are involved along a continuum of participation from consultation to co-creation of knowledge; • Researchers explicitly reflect on and account for their own position, potential sources of bias, and limitations throughout the process, and make the process transparent to those external to the research group who can then judge the legitimacy based on their perspective of fairness.
Effectiveness The research contributes to positive change in the social, economic, and/or environmental problem context. Transdisciplinary inquiry must have the potential to (ex-ante) or actually (ex-post) make a difference if it is to be considered of high quality.	• Potential research effectiveness can be indicated and assessed at the proposal stage and during the research process through a clear and stated intention to address and contribute to a societal problem, the establishment of the research process and objectives in relation to the problem context, and the continuous reflection on the usefulness of the research findings and products to the problem; • *Ex post* research effectiveness can be measured "conventionally" (outputs such as e.g., journal articles) but require additional indicators, for example: • The contribution of the project to social learning and change (through e.g., capacity-building events); • The contributions of the project to changes in policy and practice resulting in social, economic, and environmental benefits.

TDR, transdisciplinary research.

the previous section. Our scope is rather self-assessing whether the identification and "administration" of the four criteria of transdisciplinary quality for reporting on such events was experienced as effective monitoring and evaluation strategy by the members of the URIPs who were involved in the reporting. That is why, for reasons of practicality, only a limited number of Summary Reports produced between June 2017 and December 2019 were included in the analysis. The URIPs of reference were reduced to three, namely, to Barcelona, Malmö, and Utrecht. For reasons of comparability, three reports per URIP were selected. The Summary Reports analyzed are, thus, nine in total[4]. All refer to events held in the same period of the year in the three respective cities. Overall, their level of elaboration and density of information is consistent. To corroborate the statements and narratives extracted from these Summary Reports, additional materials were included in the analysis, among which Barcelona's URIP Yearly Report (Baró, 2017) and two narrative reports relevant to the Stakeholders Dialogues held in Utrecht and Malmö (2018 and 2019, respectively).

The method used for analyzing this material is document analysis (e.g., Bowen, 2009). The main advantage of this method consists of the verifiability of the sources included in the analysis; something that other methods of information gathering like, e.g., participant observations methods, do not enable in full. One of the main disadvantages consists of the limitations intrinsic in the generation of information from the side of the document's writer, who filters it according to her subjectivity and contextual circumstances. This limitation is particularly relevant to the type of material analyzed here. A further limitation consists of the mutual subjectivity of the analyst in detecting significant statements.

For these reasons, rather than limiting the document analysis to the sections of text explicitly dedicated to comment on the four criteria of transdisciplinary quality, the analysis included all the text and illustrations in each Summary Report. Significant and/or recurrent statements from each report were extracted

[4]A more comprehensive analysis the URIPs Summary Reports is under completion and will be collected in the Final Report on the Transdisciplinary Practice in NATURVATION (Basta and Kunseler, 2018, *in progress*).

TABLE 3 | Overview of the quality criteria chosen for operationalizing the transdisciplinary research quality principles of relevance, credibility, and legitimacy.

Quality criteria	Indicators
Inclusiveness	How heterogeneous and representative in terms of interests, stake, and perspectives on NBS were the participants in the meeting? Were any disciplines, positions, interests, and/or cultural groups over or underrepresented? Was the overall age and/or gender diversity of participants noticeable?
Equity	Besides being present at the meeting, did all participants have equal opportunities to voice their opinions, interests, needs, and objectives? Could you give some examples? In case not all participants could be "heard" (e.g., because of lack of time, or because of the "predominance" of one or more participants' on others) what changes and/or improvements could be considered for organizing future events and ensuring all can participate equally?
Flexibility	Allowing for changes, remaining open to feedback, and facilitating learning helps engage participants in the co-creation of knowledge on NBS. Was flexibility evident in the organization of the event? Can you describe how this was the case?
Consistency	Reflecting on the three criteria of inclusiveness, equity, and flexibility—and reporting on them critically and with integrity—is essential for securing consistency among and distilling "lessons learnt" from the URIP's work. What practical measures have made the process and/or event consistent with a view on the criteria inclusiveness, equity, and flexibility? What new measures and/or criteria would you recommend considering and implement in the future?

NBS, nature-based solutions.

without clustering them by attribute (e.g., positive/negative) or category (factual or causal statement). Data and observations, whether explicit or implicit, regarding the four quality criteria of inclusiveness, equity, flexibility, and consistency of the activities object of reporting were also extracted. The extraction included both quantitative (i.e., data) and qualitative statements (i.e., observations, reflections).

To validate their relevance to the scope of this study, the extraction of statements was executed by one researcher and subsequently reviewed by a second researcher. Extracted statements were then submitted to the URIP members who participate in this study for further validation. Without the pretense of having executed a rigorous triangulation, the reliability of the statements extracted can be therefore considered high. Their overview is reported in **Table 5**. **Table 6** collects further significant statements extracted from the mentioned additional sources.

In the sections Discussion: What the Analysis of the Urban–Regional Innovation Partnerships' Summary Reports Reveals, and Our Self-Assessment of the Relevant Monitoring and Evaluation Strategy and Urban–Regional Innovation Partnerships' Summary Reports: A Closer Look, insights from these statements are briefly discussed. In the following subsection, a short description of the methods used for performing the self-assessment discussed in section The Integration of Transdisciplinary Quality Criteria in the Practice of Reporting: A Self-Assessment is reported.

Looking Back: Shaping a Collaborative Self-Assessment Exercise

The extraction of statements from the URIP Summary Reports relevant to the criteria of transdisciplinary quality of the examined events was meant to provide the basis for further discussion with the participants in this study regarding how the practice of reporting on the criteria was experienced in the course of the project. In essence, the self-assessment "looked back" at whether the four criteria were relevant to the thematic events, have influenced the relevant organization and management effectively, and enhanced the transdisciplinary quality of the URIP process.

To stimulate the discussion regarding these points, after the collection of statements reported in **Table 5** was shared with the URIPs members and the ICLEI coordinators who participate in this study, some informal questions were proposed, namely:

1. Was the setup of the transdisciplinary coordination effective? Was good and sufficient guidance provided?
2. Were the four criteria proposed for capturing the adherence of the process to explicit guiding principles useful for reflecting on relevant aspects of the URIPs meetings?
3. Would you, also just "in your mind," reflect on them again in future projects?
4. What are the key learnings—positive and critical—you can derive from the transdisciplinary process that you have led/in which you have participated?

The answers to these questions were summarized in a form suitable for further discussion. Then, a first summary of the outcomes of the self-assessment was circulated by the author leading this study. All participants in it have had an opportunity to integrate and modify its content. Its definitive version is reported in the section The integration of transdisciplinary quality criteria in the practice of reporting: a self-assessment.

DISCUSSION: WHAT THE ANALYSIS OF THE URBAN–REGIONAL INNOVATION PARTNERSHIPS' SUMMARY REPORTS REVEALS, AND OUR SELF-ASSESSMENT OF THE RELEVANT MONITORING AND EVALUATION STRATEGY

This section discusses the two questions introduced at the beginning of the article, namely, the criteria chosen for operationalizing transdisciplinary quality principles in the thematic events led by the URIPs, and the reporting system in which they were incorporated at the two-fold scope of gathering

TABLE 4 | The template of the summary report provided to URIPs coordinators in June 2017.

Meeting number and theme:
This report is authored by (name(s) and affiliation):
Host of meeting: Place/venue of event Date and time of event
(1) Description of the event
Objective(s)
Participants *(please list the names and affiliation of each participant)*
Agenda
Key points discussed *(e.g., identified priorities, difficulties, knowledge-gaps, findings on NBS)*
Main outcomes *(e.g., agreements, decisions taken, solutions found; please add timeline if applicable)*
(2) Reflection on the event
General observations
*Were the **objective(s)** set for the meeting achieved? What were the main **challenges** faced during the event (e.g., engaging participants, coordinating the discussion, agreeing on main points, keeping track of all contributions)? What general **"lessons learnt"** could be taken into consideration for organizing future events?*
Which follow-up actions (e.g., responsibilities/roles assigned, next meetings, events) have you identified? And by when should these actions be implemented, if applicable? Which issues/aspects/actions will you take into the next meeting?
What kind of inputs/support does the URIP need from NATURVATION in the near future (e.g., in terms of research work or content provided, organizational support, input during workshop, update, communication)?
Observations on the transdisciplinary practice
The four criteria listed below, which make transdisciplinarity possible, are illustrated in the URIPs guidance document. Please share your observations from the meeting.
1. Inclusiveness
How heterogeneous and representative in terms of interests, stake, and perspectives on NBS were the participants in the meeting? Were any disciplines, positions, interests, and/or cultural groups over or underrepresented? Was the overall age and/or gender diversity of participants noticeable?
2. Equity
Besides being present at the meeting, did all participants have equal opportunities to voice their opinions, interests, needs, and objectives? Could you give some examples? In case not all participants could be 'heard' (e.g., because of lack of time, or because of the "predominance" of one or more participants' on others) what changes and or points of improvements could be considered for organizing future events and ensuring all can participate equally?
3. Flexibility
*Allowing for **changes**, remaining open to **feedback** and facilitating **learning** helps engage participants in the co-creation of knowledge on NBS—and acts as a motivational factor. Was flexibility evident in the organization of the event? Can you describe how this was the case?*
4. Consistency
Reflecting on the three criteria of inclusiveness, equity, and flexibility—and reporting on them critically and with integrity—is essential for securing consistency among and distilling "lessons learnt" from the URIP.
What practical measures have made the process and/or event consistent with a view on the criteria inclusiveness, equity, and flexibility? What new measures and or criteria would you recommend to consider and implement in the future?

NATURVATION, Nature-Based Urban Innovation.

information and generating reflections on the quality of the transdisciplinary collaboration in the URIPs.

To do so, the section Urban–Regional Innovation Partnerships' Summary Reports: A Closer Look discusses what the statements reported in **Table 5** reveal regarding the dynamics of the thematic events of the URIPs, and what relevant information the four criteria were able to generate. Section The Integration of Transdisciplinary Quality Criteria in the Practice of Reporting: A Self-Assessment shares the outcomes of our self-assessment exercise, which looks back at the overall monitoring and evaluation method to which the criteria have contributed.

Urban–Regional Innovation Partnerships' Summary Reports: A Closer Look

Our document analysis and the following discussion of its outcomes with the participants in this study reveal a consistent demand of flexibility regarding the organization and content of the thematic events of the URIPs examined. Other similarities among the respective dynamics have emerged. For example, more scientists and public authorities have participated in such events than business representatives. This seems to show a consistent (under)representation of different parties in the URIP events examined. Another similarity that emerged from the reports is the demand of *relevance* and *applicability* of the scope and outcomes of the thematic meetings to the daily practices of stakeholders. Such demand seemed particularly strong in relation to one of the most important deliverables of the project, namely, the NBS assessment framework whose co-design involved the URIPs in Utrecht and Malmö in particular.

From the perspective of this study, what is important to note is that the narratives that can be extracted from the materials examined suggest a strong interrelation between the criterion of *flexibility* and the principle of *relevance*: at times, they both conveyed the demand of aligning the URIPs thematic events to the goals of stakeholders. In fact, the connotation of *flexibility* in large part of the text extracted is both organizational and thematic: in other words, it conveys a demand of "adaptivity" of thematic events to the stakeholders' goals. This two-fold meaning of *flexibility* as both organizational and thematic that emerged from the document analysis suggests, therefore, to consider the "synthetic" criterion of *adaptivity* of knowledge co-production events as possible criterion of transdisciplinary quality in future similar exercises.

TABLE 5 | An extraction of significant statements from the Summary Reports of URIPs.

URIP	Quality criteria	2017	2018	2019
Barcelona	Inclusiveness	*We could reach a fair variety of stakeholders (from public authorities to community-based organizations), including representatives of four levels of public administrations (regional, provincial, metropolitan, and municipal). [However] SME and community or non-governmental organizations were clearly a minority.*	*Our group is overrepresented by public authority and academia. The main reason for this is the scheduled time for the meetings. In terms of age and gender diversity we think there is an acceptable balance*	*(…) sessions in breakout groups are clearly valuable because they facilitate the involvement of all participants in the discussions and allow to focus on specific topics or case studies in accordance to stakeholders' interests or expertise We plan to invite other stakeholders to present their initiatives, plans, or policies in relation to NBS in future meetings since the online questionnaire results showed that many URIP members are ready and happy to do that.*
	Equity	*The unbalanced mix of stakeholders in the meeting had a direct impact on the prioritization or "voting" process*	*All participants had equal opportunities to voice their opinions and interests Small workshops foster the involvement of all participants*	*All participants had equal opportunities to voice their opinions and interests*
	Flexibility	*Flexibility measures in the organization of next URIP sessions [are welcome/desirable]*	*A flexible approach is adopted in the organization*	*(…) we try to engage with ongoing local policy processes or key topics (e.g., urban resilience in this case) related to NBS in order to raise interest and involvement among key participants.*
	Consistency	*(…) maintaining the engagement of some stakeholders during the whole URIP process will be challenging because of stakeholders' fatigue due to participation in other research or policy processes; critical view of NBS concept; feeling of "being used" by research projects but not getting any useful output in exchange. (…) to ensure that forthcoming meetings are also successful, we really need to keep fostering a transdisciplinary/co-creation process in which stakeholders feel that their interests and priorities are considered*	*Reaching full consistency is very challenging …especially (for) the lack of policy mandate (stakeholders' participation is only based on their own interest and willingness) New criteria/measures should be clearly orientated toward mitigating stakeholders' fatigue*	*(…) the presentation of ongoing initiatives related to NBS and UGI by the stakeholders themselves (in this case the Barcelona Resilience Strategy) is clearly positive because: (1) it provides an opportunity to stakeholders to actively contribute to the URIP meetings; (2) it links the URIP process with policy or social initiatives that have a clear mandate or support; and (3) it has a beneficial effect in terms of mutual learning and knowledge exchange.*
Utrecht	Inclusiveness	*Some sectors may have been underrepresented There was no noticeable underrepresentation in terms of age*	*All five Dutch partners were represented There was a reasonable gender and age distribution among the external partners who were represented*	*To improve inclusiveness, URIP Utrecht prepared posters announcing the event together with GroenMoetJeDoen!*
	Equity	*All participants seemed to be able to voice their concern and opinions, perhaps aided by the informal setting*	*There was limited time for discussion A small number of people did not actively participate in the discussion. This could have been prevented with small-group discussions*	*There were plenty of opportunities to ask questions following the symposium and during the informal bicycle tour*
	Flexibility	*There was scope for questions Speakers were flexible, open to questions, provided ample explanations*	*The program was changed during the event to allow time for presentations The format for the discussion was very open*	*Different ideas for the event were discussed, leading to e.g., the decision to include a mini-symposium, to invite the alderman, and to visit examples of initiatives in disadvantaged parts of the city*
	Consistency	*The interactive and active mode of the meeting worked well in drawing in and engaging stakeholders*	*There was little time for discussion and little representation of external partners.*	*Planning the event with representatives of three different organizations, visiting disadvantaged areas during the bicycle tour, inviting citizens, not only professionals, organizing it during the weekend to make it easier for citizens to participate, keeping the talks relatively short and at 'introductory' level.*
Malmö	Inclusiveness	*Need to increase the representatives from construction companies and business-oriented activities A female bias is in the group*	*The possible commercial developer was represented by one actor, the public (actors) of the two cases were not represented Many more women attended the meeting than men Mainly consultants, authorities, and scientists were present at the event*	*The meeting lacked the perspective of the property developer Seven women and four men attended the meeting*

(Continued)

TABLE 5 | Continued

URIP	Quality criteria	2017	2018	2019
	Equity	*No problems with equity in the group, open climate*	*The moderator made sure all participants who wanted to contribute had a chance to do so*	*The mini workshops provided all participants the opportunity to actively reflect and discuss from the perspective of their roles and competencies*
	Flexibility	*Flexible agenda, no real time slots*	*All presentations allowed for discussion. This was very positive for knowledge exchange* *We experienced the meeting environment as equal and flexible—no problem for anyone to ask questions, share their thoughts/ideas*	*The meeting always allowed for open comments and/or questions which is positive from a learning and exchange perspective*
	Consistency			*We experienced the meeting environment as inclusive, equal, and flexible*

TABLE 6 | An extraction of significant statements from additional narrative reports.

URIP	Qualitative statements
Barcelona	*Some outputs are difficult to be communicated to URIPs members because they are perceived as "too academic" or irrelevant for practice* *Inviting a wide range of stakeholders is an important aspect of the URIPs process* *[There is a] difficulty to engage grassroots/civil organizations in the process* *Flexibility measures introduced to adapt URIPs sessions to stakeholders' interest avoid stakeholders' fatigue (clearly perceived as a risk)*
Utrecht	*Participants found it difficult to understand the challenges "inclusive and equitable governance" and "social justice and cohesion"* *The participants also made some critical remarks (…). In their view, the [assessment] method has no added value for practical purposes*
Malmö	*Relevance and legitimacy are very important for the stakeholders.* *To ensure its legitimacy it is essential that [the tool] is made to fit into existing processes* *The developed tool has to fit existing and upcoming assessment needs, if not, there is a risk that it will not be used*

The document analysis revealed also several "local specificities." For example, the criteria of *inclusiveness* and *equity* led to signal the predominance of participation of women in the events held in Malmö. Less effective seems to have been the criterion of *consistency*, which was meant to capture the "*practical measures [that] have made the process and/or event consistent with a view on the criteria of inclusiveness, equity, and flexibility*" (**Table 4**). The criterion generated very different contents in the Summary Reports analyzed and was difficultly associable to any contents other than the content shared in the specifically dedicated section. Meant as a sort of "overarching criterion" for reflecting on the factors that had facilitated the satisfaction of the other three criteria, in fact, the observations generated by the criterion of *consistency* failed to convey original content in comparison with those generated by the other three criteria. This suggests to reconsider the suitability of the criterion of *consistency* as productive "reflexive device" in the framework of the systematic reporting on the transdisciplinary quality of knowledge co-production events of the type examined here.

In sum, the criteria of inclusiveness, equity, and flexibility concurred in generating valuable reflections on the thematic events examined. They were also sufficiently descriptive and comprehensive, in the sense that they did not seem to require further criteria to generate original information on the events' dynamics.

The real novelty though is the considerations engendered by the criterion of *equity*. Its scope was stimulating the coordinators of the URIPs to observe whether gender, age, cultural, and professional diversities among the attendants of knowledge co-production events were corresponded by equal opportunities to participate in the respective works. In other words, the criterion of equity was meant to generate considerations on whether the diversity of contributors to each event was only "formal," or also substantive. While a consistent climate of equity seems to have characterized the events examined, several Summary Reports reported on situations in which such equity of involvement was not fully achieved. The criterion of equity was therefore effective in generating observations on whether all participants in the events were concretely involved in their development. That is precisely what this criterion of equity was "meant to do." The rationale of its inclusion in the systematic reporting consisted of preventing what we may call a "bureaucratic" approach to the inclusion of multiple stakeholders in the works of the URIPs. In other words, the criterion intended to capture whether relevant organizational choices were limited to invite stakeholders to knowledge co-production events by virtue of their "representation" of different interest groups without, at the

same time, empowering them to contribute to their development in concrete.

Such intent was grounded on the experiential knowledge of the researchers of the PBL. Such knowledge suggests that, when limited to secure the "representation" of different parties and stakes in collaborative knowledge production events, the criterion of inclusiveness may well secure the invitation of a heterogeneous group of participants: but not their *actual* participation in the generation and mediation of contents. Some, for example, may find themselves in a position of minority and not feeling relevant enough to voice their viewpoints; others may be predominant in the discussion of contents and prevent others from participating in it actively. The criterion of equity was therefore meant to draw the attention of the coordinators and moderators of the URIPs' events not only on whether their participants would be representative of different disciplinary perspectives, professions, and social stakes, but also on the fair chance that each individual would have to contribute to the objectives of the event in concrete.

From the perspective of this study, having facilitated the emergence of observations relevant to the equity of participation of individuals in the events of the URIPs is one of the positive outcomes of the monitoring and evaluation strategy here described. Among the criteria of transdisciplinary quality for which there exists ample literature of reference, the criterion of equity is the least represented: thus, besides "productive," it is the most original criterion among those that were chosen as quality criteria of one of the most significant knowledge co-production activities of NATURVATION. This latter observation introduces our final reflections regarding how the four criteria for monitoring and evaluating the quality of transdisciplinary collaboration in the framework of the events of the URIPs, and the method through the criteria were "put to work," were experienced by the members of the URIP who participated in this study. This is discussed in the following section, after which we present our conclusive remarks.

The Integration of Transdisciplinary Quality Criteria in the Practice of Reporting: A Self-Assessment

Providing a thorough overview of all the remarks that the questions that were shared among the participants in this study in such a way to self-assess the criteria chosen for monitoring the transdisciplinary quality of the thematic events of the URIPs would conflict with the limited space of this article. This section is therefore limited to the clear points of agreements and shared reflections that have emerged from the analysis and discussion of the examined Summary Reports.

The first agreement regards the quality of the coordination of the URIP transdisciplinary process provided by the staff of the ICLEI. Besides the thematic events discussed here and the periodic plenary sessions of knowledge exchange, the devised iterative program included regular webinars. These provided an easily accessible platform for exchanging thoughts on the transdisciplinary process under development and sharing relevant experiences despite some participants experienced the iterative program as rather rigid ("*There was too much top-down steering on the agenda and a much more open-ended reflexive approach could have been taken in which the URIPs were invited to respond more strongly to local ambitions and processes*"), generally "*the thorough guidance, structure and documentation of the URIP activities, which was very well coordinated by ICLEI, helped the URIPs' staff to not get lost in such a huge project.*"

A second important point that emerged from the self-assessment regards the four criteria. All the participants in this study experienced them as rather useful for stimulating reflection on aspects deeper than the mere heterogeneity of the participants in the URIPs events. From this viewpoint, it can be concluded that the criteria were effective in stimulating reflections on the dynamics of participation of the events. However, most of the participants revealed limited knowledge of the background work that motivated the introduction of these criteria in the reporting system. The brainstorming sessions that led to their identification, and the several proposals advanced by the PBL team for operationalizing them in the activities of the URIPs, were from unfamiliar to unknown to the very members of the URIPs who co-author this study.

Retrospectively, this unfamiliarity can be explained as due to the combination of different factors. The first factor is the different timing of the activities of different teams in the indeed "huge project" that NATURVATION has certainly been. For example, the selection of criteria for operationalizing the guiding-principles of transdisciplinary quality in the operational context of the URIPs took place in the early months of 2017; at the time, however, several URIPs had not yet started to organize and communicate about their works on regular basis. A second factor that may explain the unfamiliarity of URIPs members with the selection of the four criteria and with the scope of their "administration" by means of the reporting system is the rigid separation of functions between the coordinators and the observants of the transdisciplinary process in NATURVATION: a separation explained in section The Challenge of Building Transdisciplinary Capacities in Large European Union Projects: Nature-Based Urban Innovation Methodological Approach, and the Perspective of this Study, and on which we will return in the conclusions of the article.

What our self-assessment certainly shows is that the lack of deeper "background knowledge" regarding the use and scope of the four criteria in the reporting system led several participants in the URIPs to approach the relevant sections of the template Summary Report as a bureaucratic task of unclear added value to their learning experience. One remark captures this feeling of unclarity well: "*The systematic reporting on URIP meetings was a good initiative to show the evaluation of the knowledge exchange process over time, although it has never been completely clear to me whether this was simply to fulfil our bureaucratic duties or whether that would serve a broader learning purpose.*" Moreover, "*These four criteria were useful to critically reflect on aspects of the process but rather broad, and therefore could easily be interpreted in a selective way.*" As recommended by another study's participant, "*My recommendation would be that the criteria should not only become a reporting task but actually something that gets explicitly discussed in the activities themselves.*"

While these and other similar remarks mirror a general feeling of unclarity regarding the rationale of selection and utilization of the four criteria of inclusiveness, equity, flexibility, and consistency in the reporting system, a general consensus regarding the perspective of using some of them as guiding-criteria in future collaborative projects emerged. For example, "*The URIP process made me appreciate the dimension of flexibility a bit more, because [by] taking a flexible approach we managed to engage many stakeholders and (hopefully) influence decision-making processes in the city relevant to urban nature.*" In the words of another participant, "*The criteria we used are relevant and good for operationalizing the overarching criteria…I would definitively use these criteria for future projects. I think that it is a relevant exercise to do this*." What is needed though is "(…) *to make people understand what is only an academic exercise, and what is actually relevant for practice*."

This latter advice anticipates our conclusive remarks, which conclude our reflection on our experience of transdisciplinary collaboration in NATURVATION.

CONCLUSIVE REMARKS: TRANSDISCIPLINARY RESEARCH AS THE ART OF "BRINGING ORDER TO CREATIVE CHAOS"

At the end of this account of our experience of transdisciplinary collaboration in the framework of a large EU research and innovation project, we share some reflections on the relevant challenges, distill lessons relevant to the two research questions that motivated this study, and formulate recommendations for the monitoring and evaluation of future transdisciplinary research. With respect to the latter, we address also the research funding agencies that encourage the adoption of transdisciplinary approaches in large international projects.

A first reflection regards the overall experience of maintaining a transdisciplinary research design in NATURVATION. What started as an apparently simple method for gathering information on given aspects of a set of knowledge co-production events held in six European cities over 4 years proved to be anything but a straightforward solution to an uncomplicated problem. Indeed, the identification of transdisciplinary quality criteria that would be applicable to the work of the URIPs, and the incorporation of these criteria in the systematic reporting system, responded to the need for generating a robust evidence-base on the building of transdisciplinarity capacities in a project involving hundreds of participants with diverse disciplinary backgrounds, work cultures, and objectives. What may appear as a basic information-gathering method stems from what we experienced as the effort of "bringing order to creative chaos": an expression that captures the research context in which our monitoring and evaluation strategy had to be devised. The very task of reconstructing the rationales and contexts that led to certain methodological choices and materials required a considerable collaborative effort by the very same authors of this study, all of whom were heavily involved in the project, but represent only a fraction of its core participants.

A second general observation is that participants in such large transdisciplinary projects tend to remain divided along the lines of academic vs. non-academic participants, that is between *research*-driven and *practice*-driven participants. In our experience, this divide tends to be collectively experienced as the boundaries within which individuals operate as "scientists" vs. "non-scientists," "researchers" vs. "stakeholders," and so on. In our view, the resulting clustering is not only simplistic, but unfounded. It is simplistic because it rests on the false assumption that "non-scientists" do not approach complex innovation questions scientifically, while scientists do not approach them practically. It is unfounded because, in large transdisciplinary projects, individuals assuming roles as researchers, policymakers, stakeholders, and professionals may have highly hybrid backgrounds, which may include having spent parts of their career in academia, public service, the private sector, or civil society. NATURVATION offered a clear example of such hybridity, and of the consequent inadequacy of dividing project participants along the lines of science, policy, and practice.

We now address the two questions that motivated this study, namely, the adoption of four transdisciplinary quality criteria for generating information regarding the collaboration within the URIPs, and their administration by means of a systematic reporting system. Regarding the former, our self-assessment showed that the criteria of inclusiveness, equity, and flexibility were able to generate sufficiently descriptive information about the dynamics of collaboration in URIP events. At the same time, they could also be used to generate insights from coordinators regarding the organization and management of these events. Not all coordinators shared an equal understanding of, and hence commitment to, the scope of reporting, however. An important lesson in this regard is the crucial importance of sharing the scope of future reporting systems and engaging participants from the very beginning. In future transdisciplinary projects, we are therefore likely to promote periodic exchanges on the reporting system with those involved in it; this should facilitate its "adaptivity" to their feedback with the connotation of this term that emerged from the document analysis that was executed at the scope of our self-assessment.

Positioning the PBL researchers as observers of the transdisciplinary process rather than as active participants in its coordination constituted a clear limitation for such an "adaptive" use of the monitoring and evaluation method described here. However, to come to our final remarks, the relevant choice mirrors the plurality of roles and objectives that characterize any transdisciplinary research endeavors. In our view, such plurality is the principal added value of research and innovation projects like NATURVATION: by bringing together diverse individuals, these projects create disciplinary conflicts, their subsequent mediation and solution, and thus facilitate the birth of novel cross-disciplinary collaboration. Through constant interaction and comparison with others, these projects enrich and widen perspectives of those taking part in them. In other words, by elevating the quality of the process of research to one of the explicit research objectives, these projects enable learning.

In our experience, the quality of this latter process is proportional to the commitment to create the conditions that allow all participants to reach their common, but also individual, objectives. Indeed, in the words of one

participant, "*transdisciplinarity should not be confounded with many-many-many being always involved in everything.*" We have found that working transdisciplinarily means heeding all such objectives equally—whether scientific, professional or social; theoretical or practical; individual or collective—and encouraging collaboration among project participants without clustering them into simplistic categories: an important lesson for project coordinators, we think.

In the same vein, transdisciplinary research should not be experienced as a fluid and somehow "spontaneous" form of knowledge co-creation for which traditional research methods and rigorous monitoring and evaluation mechanisms can be abandoned. On the contrary, "bringing order to chaos" in the framework of transdisciplinary research and with respect to the necessary teamwork renders the robustness, replicability, and verifiability of the ways in which knowledge is co-produced and synthetized only more relevant. Such relevance will often imply adopting traditional monitoring and evaluation approaches that will require, to some, to acquire data and information from others. While NATURVATION showed that the risk of letting these "others" feel like "guinea pigs" instead of participants on an equal footing in the process of research is present, loosening the methodological rigor by which information relevant to given project's objectives is gathered and analyzed is not a desirable risk-mitigation strategy. A more effective strategy consists of recognizing the importance of accurate and continuous internal communication on research methods from an early stage in the project. This will help foster a climate of goodwill among project participants at all levels.

Our self-assessment enabled us to recognize that the early recognition of such importance was not followed up by an entirely effective internal communication. As a result, some opportunities were missed. On the one hand, besides generating valuable observations, increased involvement of URIP members in reporting would have generated more actions on the proposed criteria, for example, by creating an even more flexible agenda or empowering all stakeholders to voice their opinions during each meeting. On the other hand, a stronger engagement of URIP participants in the reasons behind the use of the criteria of inclusiveness, equity, flexibility, and consistency for reporting on their events may have strengthened those "new capacities" that should be part of the ambitions of any knowledge co-production endeavor (Norström et al., 2020). Ambitions that, due to our discontinuous communication on the URIP reporting the scope of the system, were only partly met. Finally, more effective communication would have made the research goals of the PBL team, who designed the transdisciplinary monitoring and evaluation strategy, more accessible to the participants who were instrumental to their achievement.

These conclusions raise again the inherent difficulties of monitoring and assessing the process and outcomes of large international projects that have to contend with different cultures, multiple ambitions, and goals. Rather than having reduced such complexity, our monitoring and evaluation strategy struck a balance between the need of gathering and documenting the relevant process in a robust and accessible away, and allowing for the "creative chaos" of NATURVATION to generate innovation by means of unforeseeable and unconventional forms of collaboration. The importance of constant mediation is therefore the main lesson we will take forward into future transdisciplinary research.

Finally, our final recommendation addresses the research funding agencies that support the adoption of transdisciplinary approaches. In our view, requiring the adoption of transdisciplinary monitoring and evaluation methods already at the project proposal stage may be beneficial for national and international policies on research fund acquisition. Besides enhancing the methodological quality of future TD projects of future transdisciplinary projects regarding their scientific credibility and social relevance, the requirement of adequate transdisciplinary monitoring and evaluation methods at an early stage would help build a knowledge-base on the different interpretations and applications of the TD approach in the context of structural research. This would facilitate would facilitate parallel methodological research aimed at raising those methods to the highest standards of robustness and replicability. We hope that the experience documented in this article and other desirable developments of the practice of transdisciplinary research in the sustainability sciences.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

CB has designed and led the execution of the study documented in the article as well as all background-studies cited in it. EK has acted as internal peer-reviewer of the study, including the executed document-analysis. As member of the PBL's team responsible for the respective research, she has been involved in the study from its conception up to delivery. CW has thoroughly reviewed multiple versions of the article and partaken in the self-assessment exercise discussed in it. AJ and FB have contributed to the exercise of self-assessment. They have also provided valuable comments on the latest versions of the manuscript. IB and MB from the ICLEI Secretariat have contributed to the exercise of self-assessment. MB has also reviewed the last version of the manuscript prior to its re-submission, providing valuable inputs on the research-practice interface enabled by TD teams. BW has actively partaken in the online discussions that have informed the execution of the self-assessment discussed in the study. All authors contributed to the article and approved the submitted version.

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Knowledge and Its Legitimacy, an Exploratory (Meta)Ethical Framework-Based Analysis of Narratives on Coastal Flooding Risks in a Changing Climate

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Knowledge quality assessment (KQA) has been developed in order to analyze the role of knowledge in situations of high stakes and urgency when characterized by deep uncertainty and ignorance. Governing coastal flood risk in the face of climate change is typical of such situations. These are situations which limit the ability to establish objective, reliable, and valid facts. This paper aims to identify the moral frameworks that stakeholders use to judge flood risk situations under climate change, and infer from these knowledge legitimacy criteria. Knowledge legitimacy, defined as being respectful of stakeholders' divergent values and beliefs, is one of the three broad quality criteria that have been proposed in order to assess knowledge quality in such situations; credibility (as scientific adequacy) and salience (relevance to the needs of decision makers) being the two others. Knowledge legitimacy is essentially the subject of a literature analyzing, *ex-post* (once knowledge has been deployed), how stakeholders' participation is a factor contributing to knowledge legitimacy. Very little is known about *ex-ante* characteristics (i.e.: that can be observed, determined, before knowledge is deployed) that would make some types of knowledge more legitimate (i.e., respectful of stakeholders' divergent values and beliefs) than others. We see this as a significant blind spot in the analysis of knowledge and its role under deep uncertainty. In this paper we posit that this blind spot may be addressed, in part. In order to achieve this we first identify the ethical frameworks that stakeholders use to judge a situation of risk under rapidly changing conditions. We then associate these ethical frameworks to characteristics of knowledge. We tested this conceptualization through a case study approach centered on flood risk on the French Atlantic coast. We have adopted a narrative approach to the analysis of two diachronic corpora consisting of interviews conducted in 2010–2012 (33 interviews) and 2020 (15 interviews). These were approached as narratives of a risk situation. We thematically coded these along themes considered as metanarratives. These metanarratives are associated with predefined (deontology, consequentialism, virtue ethics) and emerging (discourse ethics, connection ethics, and a naturalistic ethic) ethical theories. Our results show that, when faced with flood risks, stakeholders tell stories that mobilizes

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several metaethical frameworks as guiding principles in the form of both procedural and substantive injunctions. In order to respect what we interpret as manifestations of the moral stances of stakeholders, our results indicate that knowledge legitimacy may be assessed against the following criteria: lability, debatability and adaptability; degree of co-production invested; place-based approach; ability to include lessons that would be given by nature. The operationalization of these criteria is promising in a time when the knowledge that is used for decision making under certainty is increasingly contested on the ground of its legitimacy.

Keywords: knowledge quality assessment, ethics, knowledge legitimacy, French Atlantic coast, flood risk

INTRODUCTION

When confronted to flooding risk under a changing climate, decision makers are confronted to a situation where the stakes may be high—including potentially displacing human settlements—while facing uncertainties that can't be easily reduced. Such high stake decision making under uncertainty raises specific challenges in terms of knowledge production and use: "hard" decisions are to be made, yet Science can't provide information endowed with the high degree of certainty that such decisions would call for (Funtowicz and Ravetz, 1990). When decisions are urgent and stakes high, facts and values may become intertwined (Funtowicz and Ravetz, 1993). In these situations, "knowledge quality criteria become unbounded, highly unstable, and contentious" (Bremer et al., 2019, p. 2). In order to face such situations, knowledge quality assessment (KQA) has emerged as an approach to disentangle facts and values: knowledge quality criteria include a reflection on the fitness for function of the knowledge. KQA entails an analysis and critical reflection on uncertainty, underlying assumptions, and associated dissent (van der Sluijs et al., 2008). KQA recognizes that decision makers are not only confronted with epistemic uncertainties (which the present paper does not deal with), they are confronted with moral and normative uncertainties (which is the focus of the present paper) associated to the context in which knowledge is being produced and used. In that vein, in order to tackle issues of sustainability, Cash et al. (2003) propose to qualify knowledge systems in terms of credibility (scientific adequacy), salience (relevance to the needs of decision maker), and legitimacy (being respectful of stakeholders' divergent values and beliefs). The latter criterion has been approached through the *ex-post* analysis of case studies demonstrating that stakeholder engagement in knowledge production and evaluation increases its legitimacy. Yet the *ex-ante* working of this increased legitimacy of knowledge is somehow left in the dark. Contributing to the empirical understanding of knowledge legitimacy, in terms of *ex-ante* conditions, as opposed to *ex-post* observations, is precisely the contribution of this paper. By using a metaethical lens we are able to develop empirically criteria showing whether knowledge coproduction and use is compatible with the ethical theories that stakeholders, in their diversity, seem to favor.

In this paper, we thus propose to revisit the knowledge legitimacy criterion of KQA in order to contribute to an increased understanding of the mechanism through which knowledge may be considered as legitimate. We use descriptive metaethics as an entry point. Descriptive ethics is the study of moral behaviors of individuals and groups as they are observed. Metaethics is the field of knowledge that seeks to understand the metaphysical, epistemological, semantic, and psychological, presuppositions and commitments of moral thought, talk, and practice (Sayre-McCord, 2014).

We therefore depart from the now well-documented empirical demonstration of the connections between broad stakeholders engagement and knowledge legitimacy. Rather than observing *ex-post* that stakeholder engagement increases knowledge legitimacy, we propose its assessment by (a) systemically exploring the ethical theories that are mobilized by stakeholders when conversing on risk issues and, (b) analyzing how these ethical frameworks relate to characteristics of knowledge production and/or use. This approach enables access to parts of the central determinants of the diversity of moral stances stakeholders may adopt—moral stances being understood as utterances where stakeholders express a judgement that appears to mobilize their values. We access these within stories of flood risk situations. We explore such a risk situation through the case of coastal and estuarine flooding risks on the French Atlantic coast under a changing climate. Our result contributes to the field of knowledge quality assessment, focusing on knowledge legitimacy and its determinants.

In order to pursue this goal, we acknowledge that adaptation to climate change entails increasing epistemic uncertainties (that we do not address here) that are accompanied by increasing moral uncertainties (that we wish to partially address here). From these results, we infer conditions for knowledge legitimacy in procedural and substantive terms. We thus share the results of an exploratory research which aims at proposing, developing, and testing an approach to decipher the interplay between moral uncertainties, ethical frameworks, and knowledge.

We begin this paper with a condensed state of the art of (a) the knowledge on the interplay between knowledge and associated uncertainties (section Knowledge Quality Assessment and the Legitimacy of Knowledge), (b) moral uncertainty (section Moral Uncertainties), and (c) metaethical frameworks as ideal types (section Defining and Using Ethical Framework Ideal Types as a Metaethical Approach). Building on this theoretical bricolage (Denzin and Lincoln, 2018, p. 45–46), we propose

to analyze a risk situation using a narrative lens (see section Case Study Description below). We conduct this analysis on diachronic corpora consisting of two series of interviews dealing with the risk of coastal flooding in a changing climate (see section Methodological Stance). This analysis identifies the metaethical theories mobilized when stakeholders express stories of risk situations (see section Data Collection Procedures). Our results show how various metaethical frameworks are mobilized by stakeholders (see section Results). We show how these metaethical frameworks connect with knowledge, both substantively and procedurally (section Discussion).

KNOWLEDGE QUALITY ASSESSMENT AND KNOWLEDGE LEGITIMACY, MORAL UNCERTAINTIES, AND METAETHICAL THEORIES

Knowledge Quality Assessment and the Legitimacy of Knowledge

Decision making situations entailing high stakes and high uncertainties, call for a practice of knowledge production that strays away from what Kuhn (1970) has coined as normal science: i.e., the practice of science within a settled paradigm, or explanatory framework, progressing through the progressive accumulation of stabilized knowledge, while not calling for the questioning of underlying assumptions. When high stakes decisions are urgent, these may be taken before conclusive evidence are available (van der Sluijs, 2005). In such cases the criteria for knowledge assessment need to be expanded, which is the crux of KQA. KQA has been defined as the task of exploring the relevance of knowledge in the face of deep uncertainty and ignorance that limit our ability to establish objective, reliable, and valid facts (Bremer and van der Sluijs, 2019). The KQA literature demonstrates the importance of stakeholder engagement and proactive uncertainty communication. Modes of participatory science making are seen as a mean to nurture, procedurally credibility, salience and legitimacy. More recently knowledge for climate change adaptation has been the subject of various enquiries (Haque et al., 2017; Bremer et al., 2021). In this paper we focus solely on the legitimacy criterion.

In their seminal paper, Cash et al. (2003) define knowledge legitimacy in the following way: "[knowledge] legitimacy reflects the perception that the production of information and technology has been **respectful of stakeholders' divergent values** and beliefs, unbiased in its conduct, and fair in its treatment of opposing views and interests." (Cash et al., 2003, p. 8086, our emphasis in bold). Under such a definition, knowledge legitimacy relates essentially to the perception, by stakeholders, of the knowledge production and use processes: "[knowledge] legitimacy involves the belief that S&T systems are "fair" and consider appropriate values, interests, concerns, and specific circumstances from multiple perspectives." (Cash et al., 2002, p. 5).

Our working hypothesis in this paper is that in order to nurture knowledge legitimacy one has to identify, and take stock, not only of divergent values, but of how these values are underpinned by metaethical theories. We consider that the metaethical justifications of stakeholders judgements on various states of affairs inform us on the nature of the knowledge that they judge as respectful of their understanding of what deserves to be judged and how. We propose to approach moral uncertainties, through the narrow, yet fundamental, lens of metaethical theories.

Moral Uncertainties

In a foundational paper, De Marchi (1995) positions moral uncertainties within other sources of uncertainty in situations of risks management. De Marchi presents moral uncertainties as "linked to the ethical traditions of a given country [...], as well as the psychological characteristics of the persons in charge, their social status and professional roles." De Marchi sees moral uncertainties as the consequences of actors taking decisions in light of likely future legal liability, moral guilt and/or possible ostracism by his or her community.

Similarly, and with increasing precision, Lockhart (2000) associates moral uncertainties with situations where one is uncertain what the morally right thing to do is. Conducting a systematic enquiry into moral uncertainties, Lockhart shows the centrality of moral uncertainties in decision-making when combined with decision criteria not related to ethics.

More recently, in a groundbreaking contribution, Taebi et al. (2020) have further developed the associated concepts in the context of climate change. They develop a broad category of normative uncertainties: "that is, when there is not one unequivocal right or wrong answer to an ethical question regarding risk" (p. 2). They further classify normative uncertainties into four categories: evolutionary (uncertainty about the moral norms that will be applicable in the future for a future risk situation), theoretical (when different [meta (our addition)]ethical theories lead to different recommended courses of actions), conceptual (situations when different ethical concepts or values are mobilized, prioritized or interpreted differently), and epistemic (those associated with ignorance).

In this paper we see the deciphering of the metaethical ethical sources of moral uncertainties as central to the challenge of achieving knowledge legitimacy. We focus on the analysis of theoretical normative uncertainties as identified by Taebi et al. (2020).

Defining and Using Ethical Framework Ideal Types as a Metaethical Approach

Metaethics is not about the content of moral claims, but it is about their status—it is about the justifications used to reach a judgement, rather than about the content of the judgement itself, "it asks about the status of ethical claims, rather than about their content" (Shafer-Landau, 2012, p. 2). Metaethical frameworks set the stage for identifying a source for moral judgement. Metaethical frameworks are not so much about what people ought to do. They are about what they are doing when they talk about what they ought to do (Hudson, 1970, p. 1, in Miller, 2013). Our working hypothesis in the course of this research, is that it is possible to capture, describe and analyze, partially, yet productively, the diversity of stakeholders' moral

stance through the identification of a limited number of ethical framework ideal types. Conditional to this working hypothesis we are in a position to associate utterance expressing judgement with specific ethical theories.

We have identified and defined, metaethically, a series of ethical frameworks that we had observed, rather informally and conversationally, in the course of past fieldwork. We observed that moral issues lay at the center of the concerns expressed by coastal flooding stakeholders on flood risk and its mitigation. While not being engaged into research on ethics and metaethics *per se* at the time, we observed a tension between various expressions of what we identified as consequentialist statements and deontological statements, that were somehow intertwined with expressions of virtue ethics. This observation led us to the work that we present here. We are metaethically analyzing our corpora through the lens of these three dominant ethical frameworks: consequentialism, deontology and virtue ethics. Many other frameworks exist, yet we collectively considered that these three fundamental categories should be used as a starting point because of their importance in the literature.

For this paper we consider that consequentialist ethical frameworks are frameworks that guide moral claims according to some sort of end results (for a more formal presentation see for instance Frankena, 1973, p. 14–16). Within flood risk management assessing options in terms of their end-results amounts to consequentialism. For instance cost-benefit analysis, which focus on the difference of the total costs and benefits of a risk mitigation approach does not take into account the associated process.

Deontological ethical theories, on the other hand, focus on formal and non-formal rules to be respected regardless of the outcome (see Frankena, 1973, p. 16–17). Considering that existing regulatory frameworks must always be respected corresponds to a deontological ethical stance. In such a context formal regulations are seen as non-negotiable regardless of their outcome.

Finally, for the purpose that we are pursuing, virtue ethics focus on the moral character of decision-makers, e.g.: generosity, self-discipline, fairness, compassion. For instance expressing that a decision-maker is fair or unfair for considering a specific flood risk mitigation option corresponds to a stance that we associate to virtue ethics.

It must be noted that these categories are by no means categories that exist in a pure form: ≪ any plausible normative ethical theory will have something to say about all three ≫ (Hursthouse and Pettigrove, 2018). We use these as ideal types and use interpretation in order to identify which ethical theory is central to specific utterances that are made by stakeholders.

MATERIALS AND METHODS

Case Study Description

Flood risk management on the French Atlantic coast has gone through several phases. A first phase, relying mostly on structural mitigation options (mainly dikes and levees) and a state-guaranteed post-catastrophe reinsurance scheme, lasted up to the mid to late 1980s. A second phase followed, characterized by a maze of structural and non-structural measures, none fully implemented (Gilbert and Gouy, 1998; Barraqué and Gressent, 2004). A critical turning point occurred following the Xynthia storm in 2010 (Touili and Vanderlinden, 2017). Since then, non-structural measures have been refined in a third ongoing phase including land-use planning, emergency planning, risk perception analysis and warning systems. These have been more thoroughly implemented than before (for a more detailed description of flood risk management on the French Atlantic coast and its post-Xynthia evolution, see Hissel et al., 2015).

Considering our research objectives, flood risk management on the French Atlantic coast is a particularly relevant case study. First, flood risk has been identified as a major challenge in terms of public research. Flood risk has also been identified as a priority area for public education campaigns targeted at the communities that are exposed. Issues around knowledge and its articulation with decision-making are always present in stakeholder discourses—an abiding part of the technocratic French culture that somehow seems under siege in these highly uncertain times. Second, and more importantly, the Xynthia storm and its impacts is seen as a turning point in the discourse around climate change adaptation. Storm Xynthia has been framed by many as a window into what the future has in store (e.g., Galliot, 2012; Jouzel, 2012). Ten years after the Xynthia storm, one outcome is that stakeholders are willing and in a position to express themselves on coastal adaptation in a changing climate.

Finally, the co-authors collectively have access to uniquely diachronic corpora. This gave us access to two types of narratives. A first series of narratives, collected between 2010 and 2012, dwell on Xynthia, its aftermath and provide a window into the discourse on the future that ensued. A second series of narratives, collected in 2019–2020, is more reflexive on the side of the interviewee, and focuses on "now that 10 years have passed, what did we achieve in terms of adaptation?" Such a pair of corpus allows for the joint capture of both prospective (relating to future, potential events) and retrospective (relating to past events) stances.

Methodological Stance

For this analysis, we adopted a narrative methodological approach. It is based on the assumption that people understand their lives in storied forms, connecting events in the manner of a plot that has beginning, middle, and end points (Sarbin, 1986; Josselson, 2011). Narratives are dynamic, dialogical, often contested, and reveal values and meanings (Krauß, 2020; Krauß and Bremer, 2020). Narratives grant us access to lay ethics, the value system of narrators that are not professional ethicists (see Nordmann and Macnaghten, 2010). In addition to their important capacity to encapsulate human experience in its diversity, narratives also inform us through metanarratives. Metanarratives exist as collective shared visions of the world, of its governing forces or of what should govern it. Metanarratives are: "larger explanations of our reality that guide us through our smaller narratives. Metanarratives explain in big-picture fashion why we do what we do and thus define our view of the world or a portion of it" (Badke, 2012, p. 104). In our

analysis here, we recognize that narratives are carried by one or more metanarratives. We consider that these metanarratives summon the lay ethics of the utterers. We posit that these metanarratives may, when judgement is being expressed, be organized thematically in order to conduct a metaethical analysis of the ethical theories that we are observing.

Data Collection Procedures

Our corpora consist of two sets of interviews. These interviews were collected in the course of various research projects and archived for further use—provided that these were in line with the ethical guidelines that our research center adheres to (see section Research Ethics Protocol). These corpora are presented in this section.

The first series of interviews from the 2010 corpus is made up of 33 semi-directed interviews conducted between 2010 and 2012 with stakeholders in flood risk management and the general population in the Gironde area. This sample was constituted from a first series of interviews with nine key respondents that were identified in order to capture a diversity of experience in terms of flood risk. We then proceeded with a snowball sampling procedure—i.e. interviewed people identified as "important, yet different" by the interviewee belonging to the initial core sample. The sampling was designed in order to capture a high variety of differing experiences in relation with flood risk in the Gironde estuary (see **Table 1**). The sample size has been defined by saturation: constant comparisons were made between a broad initial thematic coding and the raw data until no new findings or views emerged regarding central flood risk governance concepts. The interview framework focused on coastal risks and the management of them. In the immediate aftermath of Xynthia, this was the subject of a dynamic debate and respondents express themselves willingly, sometimes in heated fashion. This corpus has been used in the past to analyze qualitatively the stakeholders' social representation of risk mitigation, in a comparative setting with several other European sites (Touili et al., 2014; Touili and Vanderlinden, 2017; Vanderlinden et al., 2017). The analysis conducted for the present paper is original and has not been published as part of these papers.

A second series of interviews constitutes the "2020 corpus." It is made up of 15 semi-structured interviews conducted between mid-2019 and mid-2020 with coastal risk management stakeholders. These interviewees were selected using a stratified, informed selection process (selection criteria based on geography and type of responsibilities). This selection was associated with a limited snowball sampling. The interviews were centered on how risk management has evolved since the Xynthia storm. The sample representativeness was ascertained through saturation and further checking with local stakeholders through the snowball procedure. The results associated to this corpus are about to be published. It has been used for an analysis of the evolution of the regulatory environment and the learning process associated to the Xynthia storm.

TABLE 1 | Categories of interviewees.

	2010 corpus	2020 corpus
River basin authority/erosion manager	X	X
Land use planner	X	X
City council employee		X
Regional level employee of the Ministry for Environment	X	X
Flood risk manager	X	X
Harbor administrator	X	
Coastal manager at the local or regional level	X	X
Representative of the local Chamber of Commerce and Industry	X	
Scientist	X	X
Employee from an NGO dealing with environmental protection	X	
Citizen living in flood prone area	X	X

Some categories were represented by more than one interviewee, some interviewees self-identified as belonging to more than one category. These sample were geared at capturing the diversity of possible relations that stakeholder may have with flood risk and its governance. Both sample showed features indicating that the information had saturated.

Research Ethics Protocol

These interviews followed a research ethics protocol—which while being quite standard, is specific to our research team. There were, and still are, no formal requirements neither institutionally nor legally. The interview process has been collegially identified as a minimal risk process—i.e., a process for which the, discursively assessed, probability and magnitude, in lay persons terms, of possible harms implied by participation in the research is no greater than those encountered by participants in those aspects of their everyday life that relate to the research. Informed consent was obtained orally and recorded.

Data Analysis

Our corpora were analyzed using thematic analysis. Thematic analysis consists of identifying sections of a corpus that are deemed relevant to the issue under scrutiny, in our case, phrases expressing judgments. These sections are then (re)-organized along thematic lines—here, predefined or emerging ethical theories. **Table 2** presents the various predefined coding categories or themes (see section Defining and Using Ethical Framework Ideal Types as a Metaethical Approach for the rationale for these choices). These themes were used to analyze utterances that express a normative judgment either explicitly (use of verbs such as "ought to," "must," "should," and adjectives such as "good," "bad," "preferred," "desirable") or implicitly (narration expressing positive or negative judgment, yet without explicit and clear direct normatively loaded vocabulary). Throughout the analysis we refined these categories by identifying subcategories (see Results, section On the Three Initially Identified Ethical Frameworks to 4.3). Along the way we identified ethical theories that we had not preidentified and that are described in the results section (see **Table 3**; Section 4.4)

RESULTS

Through the analysis we coded and grouped thematically utterance that we identified as manifestation of consequentialism,

TABLE 2 | Predefined thematic coding categories.

Ethical theory serving as a coding theme	Instance of utterance coded under this theme
Deontology: groups ethical theories that define courses of action regardless of their consequences or of the ends being pursued. These rely on shared norms and values. This broad family is also identified as Kantian deontology or Kantian categorical imperatives. It is not used here in the narrower meaning of "professional deontology."	"*What should be achieved, as a public service, is to ferociously prohibit. We should not be "forbidding, while authorizing"* [at the same time]" (County-level civil servant and risk manager, speaking on the links between climate change and the regulatory context, 2010).
Virtue ethics: groups ethical theories that consider that there are some fundamental characteristics within decision-makers that are seen as virtuous, it is the decision-maker and his or her intention that are evaluated, not their actions in context	"*[disapprovingly] Elected officials today are saying, we are here now, in the future they will see what they will do*" (Local authority manager reflecting on climate change uncertainty and how to integrate it into planning, 2020)
Consequentialism: groups ethical theories that define desired courses of action in terms of their consequences, for the ends being pursued. In Kantian terms, these are identified as hypothetical or conditional imperatives.	"*I don't see that it's impossible to live in risk zones as long as the building is adapted and there is the possibility of making people safe and the dwelling easily resilient.*" (Local authority manager talking about long-term impacts and the possibility of living with these, 2020).

deontology, and virtue ethics. While coding we identified utterance that we associated to other ethical theories—some existing and being well-defined in the literature (discourse ethics, some being generic (naturalistic ethics) and one that we named ourselves (connection ethics). We thus enriched our coding themes with that of discourse ethics, connection ethics and naturalistic ethics. These are described in **Table 3** below and further discussed as part of the results.

On the Three Initially Identified Ethical Frameworks

Consequentialism, i.e. the assessment of a decision or an action in terms of its consequences, manifests itself in the 2010 corpus in several forms. First, there are regular utterances stressing the fact that flooding and flood risk management is purely a pragmatic issue: it is about water not damaging things of value: "*If we want to preserve inhabited areas [. . .] then it is into the empty spaces that we must send water. It's somehow a practical reality.*" (Executive at county level, speaking about the potential for transforming the territory under the pressure of evolving risks, 2010) Second, consequences are called upon to assess the seemingly unforeseen distributive consequences of decisions taken. "*We have farmers who don't understand the rationale for increases in risk with the disappearance of dikes [. . .] to protect the Bordeaux conurbation, a conurbation that has happily spread over flood-prone areas*" (Engineer and researcher in a public research center, talking about land use planning issues in relation to risk management, 2010). In the 2020 corpus, consequentialism manifests itself in the concerns associated with adaptation to climate change. Some interviewees believe that *ex-post* assessment of risk management should be based on whether the area has remained "habitable" and losses were actually reduced.

In terms of deontology, legal rules and associated regulations are frequently referred to in the 2010 interviewee narratives. In the aftermath of Storm Xynthia some interviewees would like them to be strictly enforced: Others criticize these legal rules and regulations for their inability to efficiently address flood risk while taking into account local specificities: "*It is working in the opposite direction that makes more sense, there is no need to only look at the regulatory document, [... it is preferable to] think about the safety aspect, the economic damage that a flood could generate.*" (Local government civil servant, responsible for environmental risk management, speaking about the stakes for land use planning in relation to risk management, our emphasis, 2010) Legal rules and associated regulations are also contested because of their impacts on specific categories of stakeholders: "*We don't know how to strike a middle ground or be balanced: we either do almost nothing or too much. Typical example: you have a farmer who wants to build a shed to protect his equipment, he can't, it's forbidden to build—an industrialist who needs to enlarge, he can't. We have managed to do too much and too badly.*" (Member of a citizen association speaking on its behalf, talking about the interactions between land use planning and flood risk management, 2010). Legal rules and regulations are mentioned in the 2020 corpus to show how they have evolved. They are presented in a less clear-cut way than in the 2010 corpus. Acceptance through learning are central to the narrative we identified: "*In the past, the mayor fought with the director of the DDTM [national authorities] to get some building permits accepted. After the storm [Xynthia], [. . .] Bylaws forbidding any real estate developments are [now] accepted.*" (Local authority manager, talking about urban restrictions immediately after Storm Xynthia and today, 2020).

Fine-tuning of the deployment of rules and regulations is often stressed with an emphasis on the fundamental importance of spatial and historical variability when it comes to flood risk management: "*It would be a mistake to try to contrast the approaches by saying that there are good approaches and there are bad ones, [. . .].*" (Public-service manager for coastal land management, sharing his view on the options and approaches for coastal risk management, 2020). More importantly for our purpose, in the 2020 corpus, narratives are centered on the interplay, or potential future interplay, between rules and regulations, on the one hand, and a changing climate and necessary adaptation, on the other hand: "*We must also learn to live with these events, it is not because we are in a risk zone that we can no longer live there.*" (National authority manager talking about adaptation in flood-prone areas, 2020) These results point to the need for rules and regulations to evolve in a way that is attuned to the evolution of the climate.

Virtue ethics appears in the 2010 corpus in two forms. First, as an injunction, not to envision degrading the situation of some stakeholders by implementing risk management measures intended to protect others—an injunction at being fair, seen as a virtue. Virtue ethics is about who one is, as seen through one's intention: "*you don't want to protect us, you want to flood us to protect Bordeaux*" (County-level risk manager, presenting the challenges facing his department, 2010). Second, virtue ethics manifests itself as an injunction of solidarity to correct a sense of injustice, in this case, in support of the victims of hazards in order to correct a differential in exposure, taking the form of a state-guaranteed insurance fund: "*solidarity measures* [will have to] *ensure that all the rest* [of the population] *takes care of that fraction*." (Harbor manager, listing the issues he observes along the Gironde, 2010). The focus in 2020 is also on distributional issues. These are raised in terms of both territorial and intergenerational justice that must be motivating key decision makers—they are judged, their virtue is assessed.

On Ethical Frameworks Emerging in the 2010 Corpus and Increasingly Present in the 2020 Corpus

When analyzing the 2010 corpus, a series of ethical theories appeared from the narratives that we coded. We grouped these under the general category of "emerging ethical theories." These belong to three broad domains: discourse ethics, connection ethics and naturalistic ethics.

First, most interviewees referred to concepts in discourse ethics (i.e., norms are to be established on the basis of rational argumentation in practical discourse, see Habermas, 1991). Deliberation are seen as either as a way of reaching more acceptable decisions, or as a way of providing awareness of multiple perspectives for better informed decision-making. This was confirmed in the 2020 corpus where we found clear signs that discourse ethics were progressively being transferred into practice. The following quotes illustrates the situation in 2010, contrasting the 2020 sample quote provided in **Table 3**: "*Land use planning decisions are imposed on us by the state, without any consultation. [. . .]* [disapprovingly] *they put us in front of a ≪ fait accompli ≫*" (Engineer in charge of research, research center, talking about the stakes of land use planning in relation to risk management, 2010).

Secondly, interviewees identify that spatial and temporal connections are central to risk situations: history matters, as well as do future generations. Neighbors and larger territorial units, must be taken into account. We considered that these utterances were sufficiently normative to deserve a separate category, not necessarily associated with any

TABLE 3 | Emerging thematic coding categories.

Emerging themes	Theme descriptive content	Sample quote
Discourse ethics: under this category we grouped utterances associated with discourse ethics. In our corpora, these utterances are expressing the benefits of deliberative decision-making either in terms of acceptance of decisions or in terms of the substantive quality of the decision that is taken.	Utterances expressing the importance of a deliberative process in order to reach compromises that are beneficial to all involved Utterances connecting the acceptance of a decision by a party to his or her participation in deliberations regarding this decision. Utterances stating that the substantive performance of a decision is associated with many perspectives being considered in a deliberative process	"It [the SLGRI—a recent, post-Xynthia implemented, regulatory tool named 'local strategy for flood risk management'] has the merit of increasing cooperation in the territories and making people, users, elected officials, consular chambers, etc., talk better to each other. It has been a place for exchange and discussion." (Public service manager for the estuary basin reflecting on the local strategy for flood risk management in place in the area, 2020)
Connection ethics: under this category we group utterances associated with either spatial connections (between places, spaces, and scales) or temporal connections (through historicity, foresight, or intergenerational consideration).	Utterances judging the importance of taking the historical dimension into account in a current process Utterances judging the importance of taking the future into account today. Utterances judging the importance of taking multiple scales and their interactions into account.	"The geographical scale of the SCoT [land use planning regulatory tools] needs to be changed, of course. A coastal SCoT should be made on the scale of the department [county] of Charente Maritime. The inter SCoT between us and the Rochefort and Royan [neighboring communities whose risk governance has influence] has been latent for a very long time" (public service manager for land management, speaking about land use plans in their interactions with coastal risk management, 2020)
Naturalistic ethics: Under this category we group utterances referring to nature as a normative frame in a general sense.	Utterances expressing that nature always wins and that it is better to be respectful of its strength. Utterances indicating that nature should serve as a model for human action. Utterances questioning the nature/culture divide.	"*Why not give back the natural character to these dikes, let nature finally take back its rights, and manage the bays, colonize them either with plants, and let the animals, the small beasts, come and settle on this territory*?" (R&D manager, State service, risk management, envisaging the paths for the future, 2010)

These themes emerged from the analysis of the 2010 corpus. We then included them in the analysis of the 2020 corpus and in further iterations of analysis of both corpora.

currently clearly identifiable ethical theory, and that we named connection ethics.

Finally, we identified utterances that refer to nature as either a model to be followed or as a force to be respected. In these utterances nature, and its functioning, has metaethical properties: *"we have to work with nature and perhaps accept to retreat"* (public service manager for coastal land management explaining the context for people's lack of understanding of depolderisation, 2020). We named the associated ethical theory "naturalistic ethics" as the source of moral judgement lies externally to humans.

DISCUSSION—ARTICULATING ETHICAL FRAMEWORKS WITH ASSESSMENT OF KNOWLEDGE LEGITIMACY

As pointed out in the introduction, and in section Knowledge Quality Assessment and the Legitimacy of Knowledge, knowledge legitimacy entails that the divergent values of stakeholders be respected (Cash et al., 2002, 2003; Cash and Belloy, 2020). Our approach posits that such a respectful stance may be guided in part through analysis of the ethical theories identified as metanarratives in stakeholders' stories, and in our case study of risk situations. Such an approach entails connecting, adopting the posture of metaethics, ethical theories with knowledge production and use.

Connecting ethical theories with knowledge production and use is thus the purpose of this discussion which is organized around four threads: (a) knowledge lability in connection with the manifestations of deontology and consequentialism that we observe in our corpus; (b) knowledge co-production in connection with the manifestations of discourse ethics that we identify in our corpus; (c) place baseness in connection with connection ethics; and (d) reliance and the nature-culture divide in relation with naturalistic ethics as it manifests itself in our corpus.

We do not address here issues relating to the legitimacy of decision and decision making. Our goal lies strictly in connecting ethical theories as a source of value diversity when envisioning knowledge legitimacy. We thus consider that knowledge legitimacy relies, in part, on a convergence of knowledge's characteristics with the ethical frameworks that appears to underpin the stakeholders' utterances. We see this as a novel way to ascertain knowledge legitimacy. Rather than assessing *ex-post* how stakeholders assess the legitimacy of knowledge, we are in a position to qualify knowledge substantively *ex-ante*. We see this as the central contribution of this paper, within the field of KQA.

The deontological and consequentialist underpinning that we have observed in our results points to knowledge that is labile, debatable in the face of local specificities and revisable. In the case of flood risk in the Gironde, such a knowledge would allow for respecting the diversity of judgements that are expressed. Knowledge legitimacy would in part rely on a convergence of knowledge's characteristics with the ethical framework that appears to underpin the stakeholders utterances.

Sections On the Three Initially Identified Ethical Frameworks of the results indicate a longing for a constant *ad hoc* tuning of rules and regulations. Yet there is a need for predictability when it comes to rule systems. This tension is an important characteristic of our corpora. The central issue for this paper is to ascertain how such a tension translates into issues of knowledge production and use. Flood risk is unevenly allocated spatially. It is currently changing because of climate change. The knowledge that is mobilized needs to be attuned to local specificities while being adapted to changing risk envelopes.

These characteristics, spatial and temporal variability, do relate to knowledge. With these results we observe that we live in a "rapidly shifting world of knowledge and action" (Cash and Belloy, 2020, p. 1) and this has consequences for knowledge production (Cash and Belloy, 2020). Our interviewees stress, through their partial rejection of rule-centered deontology, that rules and regulations must be attuned to the dynamic nature of the temporally and spatially changing environment. In this context, knowledge is seen as labile and debatable in the face of local specificities. Furthermore, the uncertainties surrounding the future climate are consubstantial to knowledge that conveys the possibility for change. The production of knowledge has to connect in real-time with the way that climate evolves. These results resonate with the concept of "iterativity" as presented by Sarkki et al. (2015, p. 507): "a continuous multi-directional interaction that goes beyond simple repetition, building on previous practices, learning from success and failure, and fostering evolution of constructive relationships and knowledge itself among all participants at the interface, and between SPIs and external audiences." While we see lability, debatability, and flexibility as substantive features of the knowledge that is called upon by our results, the concept of Sarkki et al. points to the fact that such characteristics have a procedural origin as well.

Secondly, the desire for deliberative decision-making and the associated discourse ethics points to the need for procedures in the continuous co-production of knowledge. We see this as a second essential feature in the revision of the knowledge legitimacy principle. Such a revision needs to be procedural. When analyzing the 2010 corpus, the presence of discourse ethics initially surprised us (see section On Ethical Frameworks Emerging in the 2010 Corpus and Increasingly Present in the 2020 Corpus). The importance of this ethical metanarrative is confirmed by the analysis of the 2020 corpus—with a focus on the need for institutional stakeholder to engage into deliberations—not necessarily with the general population. These results indicate that, beyond their effects, decisions are assessed in terms of procedure so that the risk management process matters. Our interviewees request that a voice be given to those affected by the decisions that are envisioned. This points to the need that the knowledge used to take such decisions be co-coproduced. Co-production is understood here as a normative practice that consists of "the deliberate collaboration of different people to achieve a common goal" (Bremer and Meisch, 2017, p. 2). Knowledge co-production is now widely accepted as a central feature of knowledge production for climate change adaptation (see Bremer et al., 2019). Within the context of adaptation to climate change, the acceptance of knowledge

co-production reconciles the desire for discourse ethics in decision-making with the need for new knowledge. Furthermore, the co-production of knowledge finds a new justification: the management of knowledge lability, iterability, and debatability attuned to local specificities.

Thirdly, place and time are key sources of concern within our corpora. Ignoring the past, or making abstraction of the future, is judged negatively by our interviewees who express views that flood risk management should be clearly situated within a timeline that has explanatory power, and that has moral weight as well. Not acknowledging where one comes from, and one's place in history is seen as wrong. Not preparing the path ahead for those to come is seen as wrong. Spatially, the central issue is that various territorial units are connected, sometimes distantly, by hydrology, sedimentary basin, etc. Our interviewees stress that places are not isolated entities and correct management of risk necessarily entails taking both local and distant interactions into account. The importance given to space and place indicates that risk narratives find one of their sources in the metaphysics of place. Malpas's "Proustian principle" applies. "People are who and what they are through their inhabiting of particular places and their situation within particular locations" (Malpas, 2004, p. 176). Such a stance entails that knowledge be place-based (Groulx et al., 2014)—i.e. be intimately connectable in space and time to specific places, their history and future, their intra- and inter-connections. Place-based approaches to climate change adaptation knowledge production have been experimented with promising substantive results (e.g., Schweizer et al., 2013; Krauß, 2020; Marschütz et al., 2020). Our results show that the degree of place-based approach (maybe place-basedness) may be proposed as an additional third area for revision of the knowledge legitimacy criterion.

Finally, the emergence of naturalistic ethics in our corpus may call for a radical move in the assessment of knowledge legitimacy. Naturalistic ethics call into question the ethical autonomy of decision-makers that is foundational in current scientific practices. Knowledge legitimacy could be assessed in terms of the ability of knowledge to accept a broader order, that of nature. Such an assessment criterion is both procedural: it is about how, and under what assumptions, we conduct science—and substantive: it is about the place that nature occupies in scientific narratives, about the very essence of scientific results as cultural artifacts.

CONCLUSION

In this paper, we used an empirical approach to revisit the concept of knowledge legitimacy through the metaethical lens of identifying ethical theories appearing as metanarratives shared by narratives of risk situations. We focused on a risk situation closely associated with climate change: risk management of coastal flooding on the French Atlantic coast.

Such a case study approach raises the question of the generalization of our results to other settings—other case studies and, or, risk situations other than flood risks. It seems that flood risk at the coast, under a changed, and still changing climate, captures many of the characteristics of high stake, high uncertainty situations, that are calling for urgent decisions. Generalizing the *applicability* of the method seems in such a light fairly safe. Nevertheless, generalizing the results themselves should not be envisioned lightly. Such a generalization would betray the very contextual, and culture-specific nature of situation of risks. It would also betray the very contextual, and culture-specific nature of situations where stakeholders mobilize the ethical underpinning of the judgement that they express over various state of affairs. Yet, our results open what we see as windows of opportunity into furthering the understanding of knowledge legitimacy. For instance our results raise the following questions. Are there other situations where connection-ethics would make sense when assessing the legitimacy of knowledge? How far, in operational terms, would the mobilization of a naturalistic ethics make sense when assessing knowledge—could we judge knowledge using nature as an ethical benchmark? This last question may deserve extra care. Many current risk situations are driven by the inability for some human to see themselves as an integral part of the natural world. The nature-culture divide is consubstantial to environmental degradation and to modern science as inherited from the Age of enlightenment. Yet this science is the central reference knowledge when managing risks. Further work is thus needed to go beyond the *Catch 22* situation that seems to be at hand—this work is beyond the scope of the present paper.

Considering the exploratory nature of the work that we are presenting here, we are not in a position to propose an operational framework as of now. Such an operational framework would allow for a systematic analysis of knowledge legitimacy before starting to use knowledge in applied settings. It seems that such an operationalization would entail working on ethical frameworks, transparently, with stakeholders. Rather than identifying ethical frameworks indirectly through narratives and metanarratives, as we did, one could envision engaging a conversation with stakeholders on these subjects. Such a conversation, connecting, through metaethics, in explicit terms ethical frameworks and knowledge legitimacy, would allow for the adoption of a reflexive conversation as to what counts as legitimate knowledge and why. We see the setting up of such an experimental action research design as a potential first step toward a more operational framework where lay ethics would be at the center of the conversations on knowledge legitimacy.

Finally, we started our paper by presenting KQA as an exercise analyzing the fitness for function of knowledge. We then engaged an empirical conversation connecting ethical frameworks with precise characteristics of knowledge that could be identified as nurturing its fitness. This seems to open a potential enquiry into the analysis of fitness for function in ethical terms—something we are tempted to name the ethical fitness of knowledge. Such an avenue seems promising in a time when knowledge is increasingly contested on grounds that seem to go way beyond its credibility, or its fitness for function in a narrow sense—knowledge legitimacy needs to be further enquired and we believe that this paper opens a promising avenue in that direction.

DATA AVAILABILITY STATEMENT

The data analyzed in this study is subject to the following licenses/restrictions: Commitment was made to the interviewees that the data would not be shared beyond the research team without their authorization. Requests to access these datasets should be directed to Jean-Paul Vanderlinden, jean-paul.vanderlinden@uvsq.fr.

ETHICS STATEMENT

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. Written informed consent for participation was not required for this study in accordance with the national legislation and the institutional requirements.

AUTHOR CONTRIBUTIONS

J-PV designed, led and contributed to the study, contributed to the data analysis and discussion and was responsible for writing up. ER and NT designed the data collection process and contributed to the writing up, the data analysis, presentation of results and discussion. All authors contributed to the article and approved the submitted version.

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