HELPING SCIENTISTS TO COMMUNICATE WELL FOR ALL CONSIDERED: STRATEGIC SCIENCE COMMUNICATION IN AN AGE OF ENVIRONMENTAL AND HEALTH CRISES

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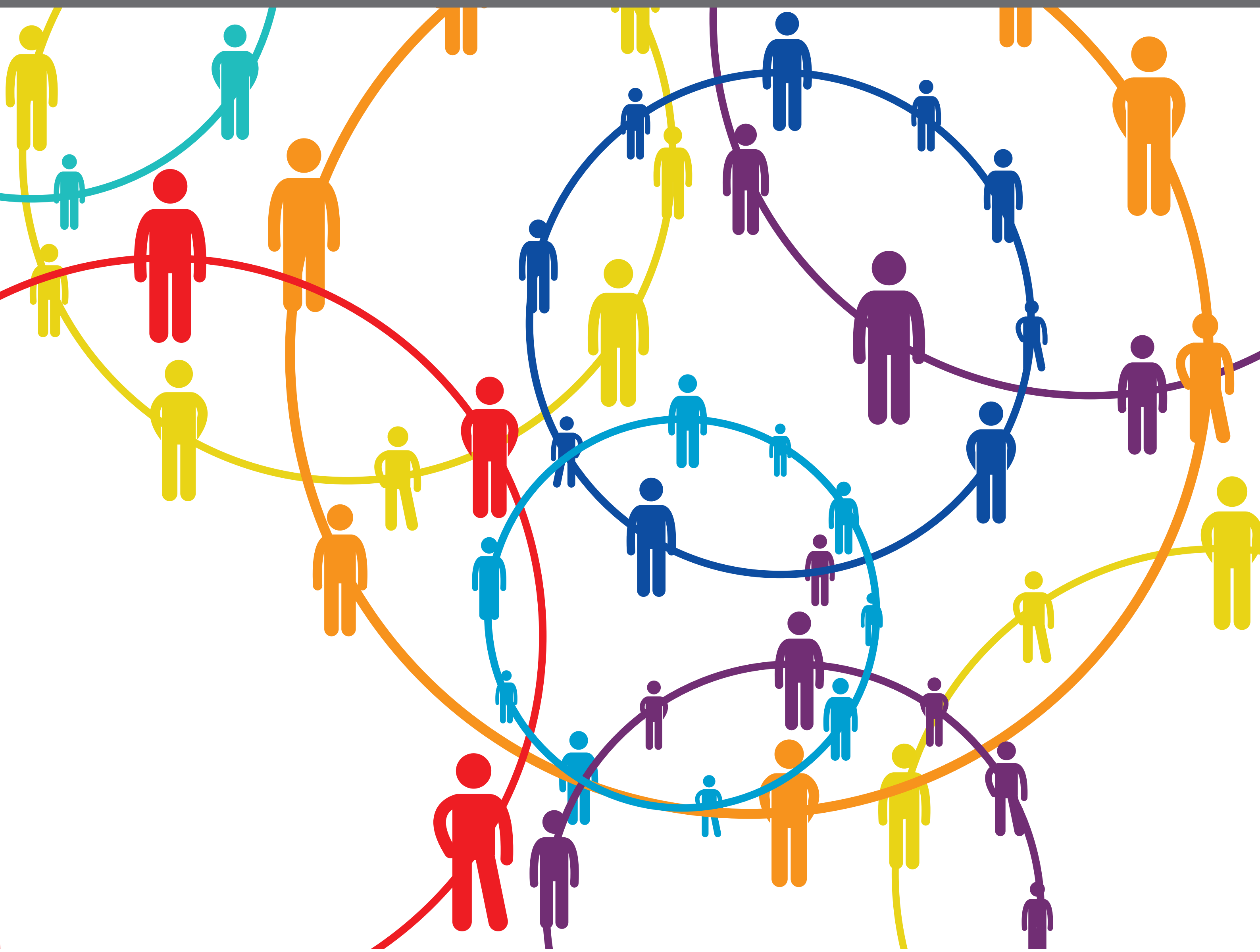

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HELPING SCIENTISTS TO COMMUNICATE WELL FOR ALL CONSIDERED: STRATEGIC SCIENCE COMMUNICATION IN AN AGE OF ENVIRONMENTAL AND HEALTH CRISES

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Editorial: Helping scientists to communicate well for all considered: Strategic science communication in an age of environmental and health crises

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Editorial on the Research Topic
Helping scientists to communicate well for all considered: Strategic science communication in an age of environmental and health crises

As the scale and scope of environmental and health crises increase, it is essential that scientists communicate with a diversity of stakeholders and audiences (National Academies of Sciences, 2017). Inclusive science communication is exceptionally critical for engaging diverse audiences in scientific research and ensuring equitable applications of scientific research to meet societal needs (Polk and Diver, 2020).

Despite the clear need for inclusive science communication, many practicing scientists have no formal public engagement training (Brownell et al., 2013) and there is no uniform, comprehensive approach for effective public engagement (Scheufele et al., 2021; Weingart et al., 2021). There is also a considerable gap between science communication practitioners and researchers (Han and Stenhouse, 2015). As a result, scientists' public engagement efforts risk being more reactive than strategic, and may result in unintended consequences (e.g., Ma and Hmielowski, 2022).

This special issue includes 12 articles that examine inclusivity in science communication and public engagement. These articles explore inclusivity within the context of science communication training programs and practices and exemplify how social scientific and rhetorical approaches can be used to increase inclusivity in public engagement practice.

Training for inclusivity

King-Kostelac et al. (2022) outline a Science, Technology, Engineering, and Medicine (STEM) graduate student training program at the University of Texas San Antonio that was designed to enhance the public engagement component of student thesis research with direct training in inclusive science communication. Their case study demonstrates the effectiveness of designing thesis research with inclusive science communication in mind, and the importance, especially for minoritized students, of a facilitated peer-to-peer model for such training.

Kimbrell et al. advocate for inclusive public engagement strategies and offer The American Association for the Advancement of Science (AAAS)'s Center for Public Engagement with Science and Technology as a model for other institutions. Their article details how the Center facilitates inclusive and accessible dialogue between scientists and publics through public engagement training informed by AAAS's Public Engagement Framework.

Fähnrich et al. propose a new "competence model" for science communication training programs, with a specific focus on the skills that are required to communicate with a diversity of audiences in an increasingly digitized science communication ecosystem. Their research draws on the experiences of science communication professionals who participated in the EU-funded RETHINK project, as well as the curricula of 13 science communication degree programs in Europe.

In their Perspective, Callwood et al. describe how science communication operates within and normalizes a White supremacy culture, and how science communication training can perpetuate this culture. They argue that science communication trainers are well-situated to dismantle White supremacy in science communication, STEM, and society, and aid in systemic change. They provide four core themes for action that build on the Key Traits of Inclusive Science Communication, and provide a concept map for co-creating Inclusive Science Communication that is authentic and culturally competent.

Kago and Cissé focus on how language barriers function as key obstacles in making public science communication and engagement more equitable and inclusive. They reflect on how public understanding and confidence can be enhanced by using local languages in a variety of African settings, ranging from courtrooms to classrooms. They call for a much wider adoption of African indigenous languages in settings where science and its publics meet, with a focus on using regionally relevant languages.

Social scientific approaches

Capers et al. experimentally examine the effects of science communication training courses taken by STEM graduate students. Among other things, the results suggest trainees' jargon use declined, and their movement of hands and hesitancy during talks was correlated negatively with audience ratings of credibility and clarity, and smiling was correlated with improvement in credibility, clarity and engagement. Overall, they show how objective tools can be used to measure training program success through audience feedback, multiple textual analysis tools, and body language analysis.

Osman and Ogbunugafor provide a framework for science communicators to combat the start and spread of misinformation when it comes to public health and other scientific issues. Based on an epidemiology analogy, they argue that this framework is especially applicable for historically underrepresented communities who may not trust scientific institutions and where there may be indirect means of misinformation.

Nogueira et al. explore the challenges of relying on the diverse worldviews, expertise, and interests of scientists and stakeholders as they co-produce knowledge. The authors reflect upon their experiences with the practical and methodological challenges stemming from knowledge co-production research projects. They discuss the role social scientists can perform in such projects, providing a critical, reflexive lens, and a safeguarding role of the process they engage in while working with scientists and stakeholders in the co-production of knowledge.

Rhetorical approaches

Grady et al. examine how STEM communication initiatives can be improved from rhetorically-informed approaches to writing. The authors develop, implement, and assess 2 context-dependent science communication writing rubrics, which they argue function as rhetorical boundary objects. They identify four specific facets of "good" STEM writing—(1) connecting to the big picture; (2) explaining science; (3) adhering to genre conventions; and, (4) choosing context-appropriate language—the authors thus offer a cross-disciplinary analysis for STEM administrators and funders.

Harrington et al. test a rhetorically-informed model of science communication training, "SciWrite," which focuses on encouraging habitual writing for multiple genres and audiences, and continuous peer-review of written science communication. Using the interdisciplinary SciWrite rubric, the authors find that science graduate students who are trained in SciWrite score higher across all assessment categories, suggesting that writing quality is best explained by a critical understanding of higher-order writing skills.

Patenaude and Bloomfield conducted a rhetorical analysis of 12 semi-structured interviews with nuclear scientists and engineers to better understand their perspective on nuclear energy and public engagement. Among other things, they demonstrate how the deficit and dialogue models function within the context of nuclear experts' perspectives on risk and safety, government regulation and public policy, and public education and engagement surrounding nuclear energy. They argue for increased dialogue and collaborative engagement between public stakeholders and nuclear experts.

Finally, McGreavy et al. explore how interdisciplinary and rhetorical approaches to communication can help illuminate the ways in which communication shapes transdisciplinary collaboration and knowledge co-production. Based on an ethnographic research project in Maine that focuses on the development of environmental DNA science for coastal resilience, they find that definitions of eDNA, perspectives on communication, and constructions of audience and expertise work together to shape the knowledge co-production process.

Summary

From documenting evidence-based science communication training programs to examining issues of intersectionality and inclusivity in science communication, each of the 12 articles in this special issue offers a unique perspective on science communication, public engagement, and inclusivity. The case studies of training programs provide helpful lessons learned that have broad applicability. The descriptions of how social scientific and rhetorical approaches have been used to enhance inclusive science communication offer new insights into more effective science communication practices. Our hope is that, taken together, these articles will inspire improvements in our collective ability to more effectively and equitably apply scientific research to meet societal needs.

Author contributions

BS led the creation of the editorial. MA, MJ, IL, and SM wrote initial drafts of multiple article summaries, edited the editorial draft, and conducted a final review of the editorial before submission. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Conducting Research in a Post-normal Paradigm: Practical Guidance for Applying Co-production of Knowledge

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Meaningful engagement between scientists and stakeholders has been extensively promoted as a tool for increasing public participation in science, as well as for increasing the relevance and impact of scientific research. Yet, co-production of knowledge entails practical challenges, since participants with diverse worldviews, expertise and interests are expected to collaborate. These obstacles have not received enough attention, as current debate has focused more on the merits and principles of this approach. We address this gap by reflecting upon our experiences with both practical and methodological challenges stemming from research projects based on co-production of knowledge, thereby exposing what we see as common but under-discussed obstacles, as well as guidance for tackling them. We highlight the role of social scientists in the process not merely as facilitators but also as agents that promote critical reflection and safeguard the salience, credibility, and legitimacy of both the process and its outputs.

Keywords: co-production of knowledge, post-normal science, experience-based knowledge, science–practice interface, transdisciplinary research projects, science technology and innovation

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INTRODUCTION

Science and technology have long been promoted as central tools for addressing all sorts of challenges, from the threats of climate change and overconsumption to the perils of food scarcity (European Commission, 2013; Üzelgün and Pereira, 2020). More ambitiously, science and technology are often placed prominently in our conceptions of a good society (e.g., Brey, 2018), despite growing recognition that there can be a dark side to innovation (Nogueira and Nogueira, 2015; Coad et al., 2020). Hence, enthusiasm for science and optimism for innovation currently coexist with misinformation and skepticism towards experts. To counteract the effects of this polarization, civil society and policymakers expect scientists not only to justify the relevance and usefulness of their pursuits, but also to anticipate the impacts of their work (Rau et al., 2018). Arguing for impact also grounds the scientific enterprise in a broader set of stakeholder interests (Rodríguez et al., 2013), and legitimizes the public value of research (McNie et al., 2016). These shifts in the social contract between science and society have demanded that collaborative methods are adopted more widely (Chopyak and Levesque, 2002; Wildschut, 2017).

As a result, co-production of knowledge has emerged from the recognition that science and society are intertwined (Jasanoff, 2004), and hence the process of research and its resulting scientific knowledge do not merely depict and describe the world "as is" (Williams and Edge, 1996). Instead, the communion between the physical and the social worlds is an inherent characteristic of knowledge production (Funtowicz and Ravetz, 1993; Ravetz, 1999; Jasanoff, 2004). Science (i.e., "fact") cannot be neatly separated from the influence of the socio-political world (i.e., "values"), and the "*post-normal problems*" of our time increasingly challenge the notion of scientific purity (Jasanoff et al., 1995; Farrell, 2011). The social world shapes decisions concerning which problems are investigated and how they are researched, i.e., the angles from which phenomena are observed, the premises that are adopted, and the processes of allocating funds. We can identify a problem as "post-normal" when it is characterized by high complexity and uncertainty, is riddled with conflict of values, and, at the same time, challenges established legitimacy. The process of solving such problems rarely yields single answers, if any at all (Funtowicz and Ravetz, 1993; Ravetz and Funtowicz, 1999). In fact, living in the post-normal world increasingly requires living with—and planning through—contingencies (Foucault, 2008). Arguably, recognizing the ways in which science, technology, and society interface "*is one of the most pressing issues of the 21st century*" (Chopyak and Levesque, 2002). Co-production of knowledge is a fitting approach in such landscape.

In line with Norström et al., we define co-production of knowledge as "*iterative and collaborative processes involving diverse types of expertise, knowledge and actors to produce context-specific knowledge*" (Norström et al., 2020, p. 5). Although there is abundant and long-standing literature on the topic, particularly stemming from Science and Technology Studies (which is in turn heavily influenced by a century of anthropological research), collaborative processes require practical skills about the challenges that arise in such transdisciplinary and collaborative contexts (Polk, 2015; Dankel et al., 2017). The current landscape of policy and funding for science and technology mean that knowledge is often produced on demand and with the intent to address a specific problem of immediate consequence (Boswell and Smith, 2017). As such, scientific advancement as a purely intellectual pursuit motivated mainly by curiosity all but ceases to exist. The implication for scientists—the majority of whom are trained to overlook the social embeddedness of their activities—is that they strive to balance what they perceive as the nobility of the scientific enterprise ("the ideal") with utilitarian interests and practical concerns ("the real"). Addressing gaps concerning how to operationalize co-production research is of utmost importance as this approach becomes institutionalized (Lemos et al., 2018). It is not sufficient to merely put people together in a room. Constructive results depend on researchers addressing colliding worldviews, worries, vocabularies and interests. Yet, there is little knowledge and even less guidance on how to go about this task.

Hence, the purpose of this paper is to address this need for guidance for co-production of knowledge. In putting forth our recommendations, we rely upon our applied experiences examining a broad array of themes, industries, and sectors. These range from the management of fish resources, marine plastics, and petroleum exploration in the Arctic to the overarching challenge of climate change (Kristoffersen and Dale, 2014; Dale, 2016; Rybråten et al., 2018; Johnsen et al., 2019a; Johnsen et al., 2019b; Bjørkan and Veland, 2019; Dale et al., 2019; Röhrs et al., 2020; Strand et al., 2021). Our ambition is to reflect upon these experiences and illuminate what we view as typical challenges that come about when implementing "*principles for knowledge co-production*" (Norström et al., 2020). We focus predominantly on the dynamic that emerges when science embraces diverse types of experts[1], who then become present in spaces that had been restricted to them until post-normal problems began to challenge traditional boundaries between experts and lay-people.

The following section discusses co-production of knowledge as a hands-on method that is relevant to different schools of thought on why co-production matters. Additionally, it situates co-production of knowledge in relation to other types of stakeholder participation. We will offer our suggestions for executing research projects based on this approach, and subsequently discuss what role the social sciences can play in such processes.

CONTEXTUALIZING CO-PRODUCTION OF KNOWLEDGE

Co-Production Within the Post-normal Paradigm

The dynamics of post-normal times entail that facts are uncertain, legitimacy and credibility are disputed, and solutions might be ambiguous (Funtowicz and Ravetz, 1993; Ravetz, 1999; Jasanoff and Simmet, 2017). Technology is, in this context, both a concrete and politicized tool for human agency and an abstract and exogenous force that shapes social relations (Üzelgün and Pereira, 2020). Such context is, at once, an emergent empirical phenomenon, and a normative prescription on how science should be carried out. We explore below the differences between these two perspectives.

Portraying post-normality as an emergent empirical phenomenon requires recognizing that the conflation of facts and values does happen in research, whether or not people are cognizant of it, and despite their best intentions to keep these separate (Williams and Edge, 1996). In particular, as knowledge production has become more industrialized and disciplines more specialized, there have been dramatic changes in the relationships between scientists, their peers, and the actors who judge and use the output of scientific work (e.g., funders and policymakers). These changes have driven the merging of facts and values further (Ravetz, 1971; Skolnikoff, 2001; McNie et al., 2016). Moreover, lay-people are becoming ever more knowledgeable and trained in scientific methods and now have unprecedented access to resources for data collection and small-scale experiments (Chopyak and Levesque, 2002; Wildschut, 2017). In

[1]We note a nuanced distinction between science-driven and context-driven initiatives. In the first, which is our focus, the driving force is the long-standing scientific ambition to advance knowledge; in the latter, more tangible and immediate interventions are the central drivers. Context-driven initiatives have some overlap with the field of user-driven innovation (Hippel, 2006), which is in itself a large body of literature and falls outside the scope of this paper.

Scandinavia, for example, anyone can register their observations of bears, wolves, and other predators in an app (i.e., Rovdata and Naturvårdsverket, 2021), which is used for monitoring and research purposes; likewise, fishers in Norway are routinely involved in the gathering of scientific data for assessment of fish stocks (Bjørkan, 2011). This competence is also spreading through the developing world, as internet connection and smartphones become ubiquitous (e.g., Liebenberg et al., 2017).

Some challenges arise under this expanding empirical reality, such as how decision-makers design policies (and how scientists carry out their work) when hard facts become "soft", and "fluffy" values become solid (Funtowicz and Ravetz, 1993; Jasanoff, 2004). Such questions do carry normative implications, but these are based on acknowledging that attempts to neatly categorize findings into the domains of either value or fact are dissonant with the reality of science in practice (Latour, 1987; Farrell, 2011; Rau et al., 2018).

Another perspective portrays post-normal science in normative terms—that is, it prescribes that science is supposed to be carried out in close connection with diverse social actors (Saltelli and Funtowicz, 2017). Such perspective can be traced to the 1990s, when political theorists began to consider that there was a wider role for citizens in a democracy, beyond that of expressing preferences through votes; that is, public deliberation should precede the vote and inform decision-making (Poblet et al., 2019). This became known as the deliberative turn in democracy theory of the 1990s (Dryzek and Braithwaite, 2000; Lövbrand et al., 2011), and it builds upon the notion of social justice. As such, the deliberative turn advocates for the democratization of knowledge and expertise, not only regarding who consumes it, but also who produces it. Research is then seen as a space for presenting evidence and for mutual learning in which various types of knowledge and ways of knowing are accepted (Turnpenny et al., 2011). A normative viewpoint on post-normal science extends the boundaries of traditional science, and places greater emphasis on relevance than on truth (Funtowicz and Ravetz, 1993).

Because of its strong foothold in public engagement, science under the post-normal perspective tends to be more issue-driven than curiosity-driven. This shift has been embraced by large funders of scientific research, such as the European Framework Program for Research and Innovation, and made apparent by the growing demands for projects to adopt a multi-actor approach and adhere to the principles of Responsible Research and Innovation (European Commission, 2014), as well as to co-design activities with stakeholders (European Commission, 2021). One crucial concern in this regard is the potential for normative standards to become merely bureaucratic requirements (Lemos et al., 2018) or performative discourses (Owen et al., 2021). Or worse, that public engagement becomes a rhetorical device for legitimacy, and means to further prevalent worldviews and practices. Ideally, normalization of engaged scholarship (Van de Ven, 2007) would promote substantial exchanges across various types of stakeholders with diverse interests and expertise in the pursuit of knowledge.

While there are differences between post-normal science as an empirical phenomenon and as a normative prescription, both perspectives give rise to the need for a hands-on method—whether the point is to deal with the way the relationship between science and politics is, or to facilitate how society would like it to be (Turnpenny et al., 2011; Kønig et al., 2017). Such method must address the blurred lines between the social world as it is lived and the natural world as it is observed. This method must not obscure the constructed nature of scientific knowledge, rather, it should maintain, or even strengthen, scientific integrity. Moreover, such method can serve the purpose of expanding and increasing public participation in science (Latour, 2004; Lövbrand, 2011; Scherhaufer, 2021), while recognizing science as culture (Latour, 1987), as well as encouraging a broadened and deepened understanding of what constitutes knowledge. Thus, co-production of knowledge (Jasanoff, 2004), aided by the concept of extended peer-community (Funtowicz and Ravetz, 1993; Ravetz, 1999), emerges as a methodological approach that is fit for descriptive/empirical and ethical/normative ambitions.

As a method, co-production of knowledge aims to escape the confines of tradition and linearity, in which complexity is reduced to problems that are researchable through usual methods, within traditional disciplinary domains and communicated to policymakers in a value-free language. Indeed, in many instances, statistical and quantitative methods and models are useful tools for controlling uncertainty. Other issues, however, are exceptionally complex, and uncertainty in these instances may become uncontrollable (Funtowicz and Ravetz, 1993; Strand and Oughton, 2009; Bjørkan and Hiis Hauge, 2019). The latter instances are the situations of interest in this paper, which we exemplify next, before discussing different forms of obtaining knowledge.

Marine Litter as an Exemplary Post-normal Problem

The case of marine litter embodies the type of systemically intricate circumstances that characterize post-normality. Plastic pollution is of particular concern, since plastic not only takes several hundred years to decompose, but its presence is now also ubiquitous and irreversible (Villarrubia-Gómez et al., 2018). Besides the visually offending plastic litter on shorelines and in the sea itself, micro-plastics have also been documented in ecosystems as remote as the Alps and the ice-covered Arctic (Bergmann et al., 2019). An empty water bottle collected on an Arctic beach could have been discharged into the sea elsewhere in the world and brought there by ocean currents. Thus, as plastic litter travels long distances and respects no socio-political boundaries, it defies our organizational arrangements in ways that also challenge how we produce knowledge to combat it (Haward, 2018). Likewise, the impacts of pollution are manifold. In addition to the noticeable disruptions to marine life and ecosystems, marine plastic pollution also impacts human health, the quality and availability of fish biomass, as well as economic activities such as fisheries (e.g., ghost fishing from fish nets abandoned at sea), shipping (e.g., propeller fouling) and tourism (e.g., littered beaches) (Derraik, 2002; Bonanno and Orlando-Bonaca, 2018). As a result, addressing the problem of marine litter is a shared responsibility across distinct levels of government from local to international bodies, and any isolated policy or measure will reverberate across jurisdictions concerning the environment, society, health, and the economy.

To add to this complexity, there are numerous knowledge gaps concerning not only the amount, trajectory, and fate of plastic particles, but also the effects and toxicity of plastics on humans and ecosystems (Bonanno and Orlando-Bonaca, 2018). In short, marine litter is a problem plagued with uncertainty and high-stakes decisions, and it is futile to try to neatly separate which elements reside in fact, and which represent values. When viewed as the ambition to advance knowledge on problems of this nature (as well as advance meaningful action), reductionist approaches and silo thinking are, at best, inadequate. Any measure that fails to account for the problem's systemic nature will fall short of a substantial solution.

Different Forms of Obtaining Knowledge

Science and Technology Studies illuminate that science is cultural and embedded in social practices. This culture is distinct from others, such as that of policy actors (McNie et al., 2016). Although science aims to produce "a view from nowhere", it is made "somewhere", and in this respect science is like experience-based knowledge (Latour, 1987). However, the processes through which experience-based knowledge are produced typically lack systematic, formalizing methodologies that are required in the production of scientific knowledge (Holm, 2003; Bjørkan, 2011). Consequently, this knowledge does not fit the frame of formal, authorized knowledge upon which policy management is founded.

In science, there are institutionalized mechanisms for testing, certifying, or dismissing knowledge claims, thereby transforming technical knowledge (*technê*) into academic knowledge (*epistêmê*). There are no comparable mechanisms readily available for transforming applied doing/making (*praxis and poiêsis*) into experience-based knowledge (*phronêsis*) (Parry, 2020). Hence—while potentially relevant, reliable, and valid—experience-based knowledge is seldom organized in a way that makes the knowledge directly transferable for policy and management purposes (Harrison et al., 2018).

It is important to address that the institutionalized trust in science and its mechanisms typically excludes experience-based knowledge, despite the latter's potential relevance and helpfulness towards the production of knowledge for political or managerial advice, especially in the context of post-normal problems (Saltelli and Giampietro, 2017). Co-production addresses this, since it opens the knowledge production process and brings in various types of knowledge, including that of practice-experts/lay-experts (i.e., non-scientist experts)[2]. Accordingly, co-production should accelerate the diffusion and uptake of the outcome knowledge (Boswell and Smith, 2017), while also adding to the more traditional mechanisms of quality control (Funtowicz and Ravetz, 1990) and institutionalizing more democratic participation (Aminpour et al., 2020).

Co-production requires adjustments in the way alternative courses of action are included or excluded in decision-making processes, with the aim of embracing discrepancies, numerous possibilities, and multiple tangible futures (Poli, 2014; Alvial-Palavicino, 2016; Granjou et al., 2017). From historic tragedies like Chernobyl to the COVID-19 pandemic, we have seen time and again that the future is highly uncertain and full of potential events that can never be completely predicted by models or forecasts. The need to ensure future resilience and adaptive capacity might just as well be "*secured through contingency*" (Dale, 2011, p. 60–61) rather than through the familiar process of establishing truth through the "*rationalization of chance and probabilities*" of scientific assessments (Foucault, 2007, p. 59). To that end, opening up the knowledge production process is particularly relevant. We illustrate this below with an example of the first-hand knowledge of practice-experts.

An Example of Practice-Experts' Knowledge in Early Identification of Post-normal Research Problems

Practice-experts are in a privileged position to identify research problems and the need for regulation or intervention by governance systems, as well as possible hypotheses and appropriate measures to address those problems. They can also facilitate data collection or be trained to collect data themselves.

One example is a case involving shrimp fishers in Norway, who were the first to observe a decline in shrimp stock and shrimp health around aquaculture sites (Bjørkan and Rybråten, 2019). Their early hypothesis (though not formulated in scientific terminology) was that the shrimp population was harmed by the use of sea lice chemicals in fish farming.

Post-normal dynamics were present at the junction of knowledge gaps, different understandings of the uncertainties involved, and substantial conflicts of interest between shrimp fishers, fish farmers, coastal authorities, and others. Moreover, the problem is related to several wider public debates: the use of common pool resources (in this case, disputes over the use of coastal zones), sustainable food production, the sustainability of fish farming, etc. The issue quickly became polarized.

At first, the hypothesis put forth by the shrimp fishers was dismissed and climate change became one alternative explanation for changes in shrimp health and stocks. Yet notably, this particular case came after a study linked the chemicals in question with shrimp mortality (Busch, 2015). If advisory bodies had adopted precautionary principles, then the use of sea lice agents would have been stopped.

This example (explored in depth in Bjørkan and Rybråten, 2019) also depicts how difficult it is in such cases to separate facts and values in research and decision-making. Thus, it becomes difficult to assess how the socio-political and the natural-scientific are intertwined. It also shows the importance of meaningful interactions between practice-experts, scientists, and advisory bodies, and how co-production of knowledge can support these relationships.

[2]According to Turner, expertise and scientific knowledge differ in that the first "*represents the state of knowledge at a particular time, and is not limited to fully developed or tested theories or facts accepted as textbook knowledge by the academic community*" (Turner, 2015).

Degrees of Stakeholder Involvement

Involving stakeholders in knowledge production entails participation, which is a notion more complex than the everyday use of the term might suggest. A large body of literature highlights that, despite the apparent, generally positive acceptance associated with participation, there is an open debate concerning what it really entails (Rowe and Frewer, 2004; Silver and Campbell, 2005; Bjørkan, 2011). Participation can mean many things, from differing levels of communication with no input on decision-making (i.e., receiving information or voicing opinions), to directly impacting how a research process unfolds or what the outcomes are (Arnstein, 1969; Green and Hunton-Clarke, 2003; Rowe and Frewer, 2004). Arnstein's "*ladder of citizen participation*", for instance, describes three general levels of engagement: non-participation, tokenism (i.e., symbolic participation or lip service) and citizen power (Arnstein, 1969).

In principle, it is possible for stakeholders to participate in knowledge production through a variety of functions—from designing a project proposal to contributing to a scientific article, for example (Polk, 2015; Hickey et al., 2018). In all stages of the process then, possibilities for stakeholder involvement range from exclusion, cooperation, responsibility for the relevant function or question at hand, all the way to ownership. While the depth of stakeholder involvement can be represented as three steps on a ladder like Arnstein's, there is significant room for variation between these steps. Arnstein's typology helps pinpoint both the level of responsibility and the location of stakeholder inclusion in the process. Note that stakeholder involvement does not necessarily mean that the stakeholder performs any given task, as they can also hire others (such as scientists) to perform a task on their behalf. This conceptualization can be read in a normative sense—i.e., the more responsibility given to stakeholders, the better, but that is not the argument we make here. We contend that different approaches to stakeholder engagement will result in different levels of stakeholder participation, and that critical reflection on the purpose of participation in any given project is useful. In other words, for some issues, more superficial cooperation may be adequate, but other matters require deeper involvement, like co-production, where stakeholders are, to some degree, also made responsible for the process.

Take the issue of plastic litter, which is addressed by the EU Marine Framework Directive. Stakeholders like fishers might have relevant information depending on the project's aspects of interest. If visual plastic in fish stomachs is used as an indicator of marine litter, for example, this is something that is easily observed by fishers in their daily operations and, thus, their knowledge is relevant. But, if microscopic particles in fish stomachs are to be a primary metric of litter, then fishers will likely not be able to lend their knowledge to the project, as this metric does not allow for observation with the five perception senses, unaided by instruments. Hence, fishers' knowledge is not relevant in and of itself, yet one can argue that since fishers are well-positioned (while catching fish at sea) to provide relevant knowledge, it makes sense to train them in scientific methods that allow for the observation of microscopic particles. Since participation can mean many things to different people, this type of exercise is useful in ensuring legitimacy and avoiding disappointment, which can cause accusations of merely paying lip-service to their involvement.

A related issue concerns what it takes to be considered an expert. It is important to highlight that although practice-experts are stakeholders, not all stakeholders are experts. A stakeholder is someone with an interest in a project, or who stands to be affected by it. A practice-expert is someone who will contribute to the knowledge production process. We contend that co-production projects refrain from using the "expert" label if they cannot ensure that the participant in question will be able to engage with decision-making in the project.

One could ask how many knowledge functions must be met or how deep a level of participation must be in order for a stakeholder to be considered an expert. There are, however, no obvious metrics. The notion of expertise is a relative term and depends on the processes by which cognitive authority is granted (Bjørkan, 2011). Simply put, the concept of cognitive authority indicates that people rely on others to acquire knowledge that is outside their scope of experiences (Wilson, 1983). While reliable and relevant knowledge can be obtained through training or by practicing a skill, the delineation of "expert" is achieved through the social processes of allocating authority to some person or group. While there are exceptions, in most established management regimes (e.g., fisheries management, aquaculture management) the expert role is the exclusive privilege of institutions like the International Council for the Exploration of the Sea and the scientists working for them.

Identifying a project's relevant stakeholders and prominent practice-experts is like aiming at a moving target. What is most important is to reflect upon these questions of stakeholder knowledge and participation intently, honestly, and explicitly.

GUIDANCE FOR EXECUTING RESEARCH PROJECTS BASED ON CO-PRODUCTION OF KNOWLEDGE

In this section, we expose what we see as typical but under-discussed challenges that arise as project leaders go about operationalizing principles of co-production. These issues have been distilled from our concrete experiences with this approach, but the following list is not exhaustive or definitive. Possible solutions and further systematic empirical investigation are most welcome. As we use examples and relevant supporting literature to make cases for how to address common challenges, we primarily address the project leader or principal investigator, but all participants can find value in these insights. **Figure 1** summarizes our recommendations.

Unite Diverse Participants Through a Shared Objective and Manage Divergent Motivations

The notion of "co"-production hinges on the assumption that a bond is created across heterogeneous contributors. A project's purpose and objectives are the first components of bringing together participants and building community. However,

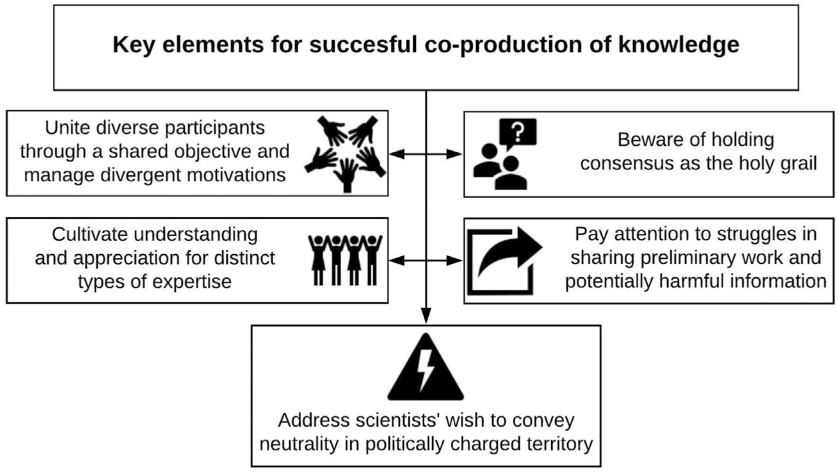

FIGURE 1 | Summary of recommendations.

uniting diverse contributors demands an awareness of what motivates each group, and how distinct motivations can align with a shared objective.

Misalignment between what motivates distinct stakeholders to participate and what they find they get out of the project brings about challenges in communication and execution. While individuals' own motivations may be clear, they often overlook what is at stake for other groups of collaborators. For instance, scientists' motivations to engage in a project may include a desire to understand a phenomenon or the need to publish and advance one's career. For them, a worthwhile output is knowledge in an abstract sense, and publications that are more concrete. In this fashion, scientists behave according to an ethics of conviction (Kim, 2019), i.e., they are committed to truth and to contributing to a "knowledge commons".

Arguably, the motivations of practice-experts are more sensitive to immediate problems at hand. That is, they often want to promote or inhibit a specific behavior or policy, and a worthwhile result for them is change. Practice-experts are guided by an ethics of responsibility, i.e., they are committed to consequences (Kim, 2019). This is not to say that scientists do not care about action or that practice-experts are oblivious to advancing knowledge. Rather, actors themselves are embedded in structures that seek to guide how they behave and what they prioritize, and thus what primarily drives scientists is often different from what motivates practice-experts. Especially relevant among these structural factors are performance metrics, which traditionally have not valued or rewarded co-production—although, with recent years' focus on signaling impact, this is changing (Durose et al., 2018; Lemos et al., 2018). Highly structured and quantitative performance metrics are saliently institutionalized in academia, but by no means absent in other professional contexts that can be of relevance in a project.

While some of these drivers are known beforehand, at least in principle, it is fundamentally important to go beyond these archetypes and assess drivers and expectations for specific contexts and project stakeholders. Creating a statement of purpose and goals is, therefore, no trivial matter. A project's objective needs to be as concrete as needed in order to be meaningful, and as comprehensive as possible for all participants to recognize it as aligned with their own goals.

One strength of science is that it affords access to knowledge that would otherwise be unreachable through experience alone. In science, one may choose from numerous technologies to help understand nature as a quantifiable, comparable, and subsequently controllable and manageable object for advisory bodies (Asdal, 2003). This should also be discussed in co-production of knowledge processes to ensure a realistic starting point.

Early negotiations of project objectives happen at the stage of project design, most often before the project has any funding. Still, it is an important stage, specifically because the project can be hampered when the broader set of stakeholders is not engaged with design and only comes onboard after the project descriptions and objectives are set. When this happens, stakeholders' interests and knowledge are bound to be subject to a pre-existing agenda, which influences the way science-experts and practice-experts interact. When this is the case, it becomes even more crucial to take the time to consider how each participant understands the stated goals, how distinct motivations can be aligned, or how unsolvable misalignments can be addressed. At the same time, it is vital to keep in mind that motivations and outcomes are distinct, as we discuss next.

Beware of Holding Consensus as the Holy Grail

While alignment of objectives is important, consensus of decisions is a different matter. Consensus is an elusive target. Insisting on not acknowledging dissensus, however, can lead to shallow or disappointing outcomes (Hillier, 2003; Barry and Ellis, 2011), especially in the post-normal context and when the end-result creates winners and losers (Bjørkan and Rybråten, 2019; Bjørkan and Veland, 2019).

Recognizing the problem of holding consensus as the "holy grail" of a project's success is of particular importance, since co-production of knowledge processes are often deliberative in nature. As such, arenas for co-creation should be organized in line with the ideals of deliberative democracy, i.e., that collective reasoning between actors is the most legitimate and superior means of making decisions (Meadowcroft, 2004; Lövbrand et al., 2011). The deliberation process should take place in a space free from manipulation and the exercise of power. In general, deliberative democracy has faith in consensus and that "*public reason-giving is the best way to uncover what is good and true*" (Lövbrand et al., 2011, p. 6).

The deliberative turn has been criticized by many (e.g., Mouffe, 2000; Pløger, 2004). Bäckstrand challenges the assumption that broad participation in decision-making will bring about more legitimate and effective policy outcomes (Bäckstrand, 2010). In the same vein, Johnson et al. underline that even if something is perceived as legitimate, it can be both inefficient and inequitable (Johnson et al., 2006). Yet, legitimacy is difficult to measure, since it is not directly observable, and consensus in deliberative democracy does not deal well with conflict. Consensus-based approaches seek to overcome conflict, but in practice they mask the fact that conflicted power relations become stabilized only temporarily and are often characterized by thin agreements at the lowest common denominator (Mouffe, 2000; Hillier, 2003; Porter, 2011).

This problem has been shown in action in the context of including stakeholders in the revision of the Norwegian management plan for the Barents and Lofoten seas (Dale, 2016). The initiative sought to include multiple voices and concerns while making a distinction between "knowledge contributions" and "public opinions". However, the decision on what constituted knowledge took place behind closed doors and resulted in a report that included input almost solely from physical/natural scientists, but which was presented as a consensus, as if everyone involved had produced this consensus. What passed for consensus then was, in fact, artificial and shallow, since a substantial portion of stakeholders (who were included in the process in a more symbolic than tangible way) had it imposed upon them. A focus on consensus also narrows the range of issues that gets to the table (Law, 2004; Scott, 2016). Actors who attended an open hearing reported that, after a number of scientists and Ministers from the government had explicitly talked about the need for solid, scientific knowledge as the foundation for decision-making, they found no room for their contributions in the process (Dale, 2016).

Aiming for consensus hides a foundational trait in modern politics: the desire to research oneself out of political and ethical decisions that are either controversial, contrary to ideological standpoints or challenging to electoral campaign promises. This is the flipside of knowledge-based decision-making. The construction of an imagined, definite barrier between science and politics (from both sides of the fence) shifts the responsibility of decision-making from politicians to scientists, who are portrayed as "objective truth tellers", as if scientific knowledge were stable and immutable. This also puts pressure on scientists, who insist on avoiding political preconditions and implications in their work—a notion that oversimplifies the relationship between science and political power (Bjørkan and Hiis Hauge, 2019; Douglas, 2005; Foucault, 2007; Latour, 1987, 2004).

While simple solutions to complex problems are hard to find, the issue of consensus likely cannot be solved. One way forward, then, is to come to terms with this realization and create a space in which there is high tolerance for respectful conflict. Such an approach involves making explicit the multiple values underlying the conflict, as well as generating an atmosphere of respectful disagreement. This can be challenging, because while one can expect the result to be less conflict, it can also generate suspicion and distrust, and hence more conflict (Johnson et al., 2019). We cannot propose a one-size fits all solution to this complexity. What is important is that scientists in charge of co-production approaches are aware of conflicts and give room for transparent negotiation and compromise based upon open discussions of incommensurate values and choices (Stoffle et al., 2020). We put forth the pragmatic position that the resolution of a conflict will likely not represent enthusiastic consensus (Hillier, 2003), but being involved in a discussion concerning tensions and controversies may actually facilitate the de-escalation of conflicts.

As a result, while decision making processes that explicitly address multiple values do not guarantee that the chosen way forward will account for all parties, they can tame the level of conflict to a manageable degree. This requires tolerance and the creation of spaces for the expression of conflict without abuse; it requires participants to be willing to look beyond their rights and righteousness, empathize with their adversaries, and be curious about uncovering what underlies the other side's position (Hillier, 2003). This, however, relies on an understanding—if not an appreciation—for others' values, knowledge, interests, and motivations in an empathetic manner.

Cultivate Understanding and Appreciation for Distinct Types of Expertise

Diversity of backgrounds and types of expertise is not a barrier to creating a cohesive project team, but overlooking differences can create problems. In addition to the question of what is at stake for each actor, it is imperative to create a shared understanding of why each participant has relevant knowledge that warrants their engagement in the project (i.e., their epistemological background and legitimacy), and what world views (ontologies) and values (axiologies) inform their attitudes and contributions to the project. Clarifying these aspects is important because practice-experts and experts from distinct scientific disciplines occupy different positions of status and power in society, and a genuinely co-produced approach requires that the worth of all participants stand on equal footing with mutual authority.

This appears to be a challenge for scientists, since many are inexperienced in evaluating and valuing knowledge from sources other than science. This is not only the case when scientists decide the direction of a project and where to look for data, but also in deciding why they should research, what they should look at, and how to conclude their research and subsequently advise. Yet, practice-experts can be valuable in a variety of research strategies.

In research projects that rely on deduction, practice-experts can take part not only in data collection, but also in the interpretation of findings and their implications. This is also the case, perhaps even more so, for projects that rely upon induction. That is, rather than starting with a hypothesis, such projects begin with a grounded observation of what is going on in the world, and very often a preliminary hunch of the causes for the event in question. Practice-experts can be invaluable in these early observations. Finally, projects that rely on abduction (i.e., from observations to inferences to the best explanation, Danermark et al., 2001) can benefit from practice-experts for the interpretation of phenomena and to construct rich, contextualized explanations.

It is the role of the project leader to consider how to promote these interactions and not succumb to downplaying knowledge from practice-experts or inputs from stakeholders, including when these inputs question the very rationale of the research. Accordingly, the project leader must also ensure that practice-expert and stakeholder information is communicated throughout the project. Information flow is fundamental for effectively including non-scientists in both the research process and the formation of a research agenda. In practice, this means that each participant (or group of stakeholders in large partnerships) needs to be aware of how other participants contribute to the overall project objective, and why that contribution is valuable. Inclusion also requires new conceptualizations of what knowledge is, which knowledge is relevant, which knowledge is not relevant and why (i.e., boundary work, Gieryn, 1999). As such, co-production as a method challenges the usual set of activities that scientists carry out with little consideration, precisely because they have become standard.

Therefore, co-production research can be demanding to the project leader, who is tasked with keeping collaborations running smoothly. The ability to manage people is a necessary skill in this context. The scope and resources of each project determines how thoroughly this analysis of stakeholders can and ought to be carried out. At a minimum, it is useful for the project leader to reflect on these questions of knowledge, introduce their concerns during the design phase of the project, and continue to voice their opinions as the project begins.

A widespread appreciation of others' knowledge and expertise is also helpful in dissociating people's identity from the knowledge they bring to a project. This is critical to securing a participant's legitimate position in a project, as well as confidence in their contribution even if their preconceived notions are shown to be mistaken—for instance, if an initial observation or hypothesis turns out to find no support in the data. Scientists know all too well how the peer-review process can be both unpleasant and necessary. Arguably, at the core of science is the inclination to judge all knowledge claims with organized skepticism. This is especially crucial if the issue at hand affects society at large: knowledge claims about issues such as food, health, ecosystems and so on cannot be considered truly independent from whomever makes the claims. The claims must go through some quality control—a tenet upheld by the co-production approach and extended peer-review processes. Hence, any knowledge claims must be scrutinized and questioned.

Practice-experts are more vulnerable to having their expertise questioned, but the opposite could also conceivably happen. That is, scientists run the risk of putting forth interpretations or hypotheses that do not hold up in a specific context, and thus lead to resistance from local communities when engaging with scientific projects, threatening the legitimacy and applicability of potential results. This matters in a world threatened by fake news and anti-science conspiracies. In any case, the purpose of co-production of knowledge is to increase the salience and robustness of the knowledge that is produced through the meaningful integration of diverse types of expertise. In a research project, no knowledge should be immune from scrutiny, and all assumptions must be open to respectful examination in a way that does not invalidate the identities of stakeholders.

We see the growing focus on inclusion and co-production as a reaction to the traditional power imbalances between science and other knowledge systems—including indigenous practices and experiences. Amidst this pushback, we contend that one can simultaneously: 1) hold the standpoints that no knowledge systems ought to be given epistemological privileges, 2) be aware that power differences do exist, 3) acknowledge that different forms of knowledge have different virtues and shortcomings, and 4) uphold the importance of science. Our recommendation is to address questions of knowledge and power explicitly and to ensure that inclusive methods are implemented in knowledge production processes that leave room for other types of knowledge, where science is not able to contribute (Bremer and Meisch, 2017). In the same vein, discussions on civic science have facilitated the inclusion of multiple knowledge traditions *de facto* in the science–policy interface, and thus ensures an understanding of the need for knowledge to be inclusive in order to maintain legitimacy (Bäckstrand, 2003).

Despite the effort required upfront, these precautions promote a fruitful work environment, improve the quality of exchanges, and also open the door for stakeholders to express their dissent when it arises. As previously discussed, by taking the time to engender understanding and appreciation for distinct types of expertise, heterogeneous project groups become better positioned to engage in debate when dissensus arises (Mouffe, 2000; Hillier, 2003). Failure to explicitly address these issues in the project can lead to miscommunication, misunderstandings, lack of rapport and the creation of dysfunctional hierarchies amongst project participants. This, in turn, leads to thin agreements that risk being little more than a front for incumbent interests and powers paying lip-service to stakeholder engagement. Genuine knowledge co-production depends on a shared appreciation for one another's backgrounds, roles, and contributions.

Pay Attention to Struggles in Sharing Preliminary Work and Potentially Harmful Information

In a (Kuhnian) normal scientific paradigm, knowledge production appears to take place in a linear fashion, beginning with the identification of research questions, and ending with the publication and dissemination of results. In a post-normal paradigm, this appearance of linearity is disrupted, processes that normally lie in the background are exposed to a broader audience, and information must be exchanged even if it has not been processed to its finished state. Whether this information concerns untested hypotheses, undecided premises or preliminary data, the reality of co-production projects is that scientists are pushed to be open about work with which they might be uncomfortable or unsure of.

This conflict is related to the cognitive authority of science in the public arena, which demands effort to generate and maintain (Wilson, 1983). Science and Technology Studies refer to frontstage performances (Hilgartner, 2000), purification (Latour, 1987) and boundary work (Gieryn, 1983; Gieryn, 1999) as processes that play a role in establishing cognitive authority. Most notably, Latour differentiates between "science-in-the-making" (when knowledge claims are still subject to revision and disagreements are seen as an integral part of the process) and "ready-made science" (the final, cleaned-up product put forth as scientific fact) (Latour, 1987). Co-production processes invite new actors to the backstage of science-in-the-making, and this can be new and uncomfortable to many scientists.

While scrutiny of preliminary work is common in academia—such as a conference presentation or peer-review—it usually happens between specialists that have the same background competence. The presence of practice-experts creates an uneven baseline for knowledge sharing. This gives rise to a fear that information could be misinterpreted or misused. Reluctance to share preliminary work is also associated with scientists' loss of control concerning the narratives that are derived from their work. When scientists disseminate work done in the intellectual safety of their labs, they have better command of what interpretations will come from their results and how those results will be communicated. Forfeiting control over these aspects also threatens a scientist's ability to convey impartiality.

The recommendations we have offered thus far (i.e., establishing shared goals, creating space for respectful debate and conflict, and promoting adequate understanding of partners' motivations and expertise) aim to create trust that mitigates the struggle of sharing preliminary work. Nonetheless, it is important that project leaders pay attention to this type of conflict so as to avoid hindering information exchange. Acknowledging these challenges beforehand also brings to mind the fact that scientists' degree of confidence in the information they share can be substantially diminished. It can then be useful to point to the positive aspects of sacrificing the intellectual comfort-zone. That is, in the true spirit of co-production, data, procedures, and assumptions will be scrutinized and debated early on, with the expectation that this will lead to better quality knowledge with high validity, contextual relevance and impact.

A similar problem can afflict practice-experts, who might be hesitant to share information if they perceive that doing so will affect them negatively. For instance, in the case of the Norwegian Reference Fleet, we see many instances in which fishers share information about illegal, unreported and unregulated fishing practices. This can affect them at a personal level, by incriminating them or affecting the size of the total allowable catch and, by extension, their income. In this particular arena, several measures have been put in place to ensure a trust-based information flow (Bjørkan, 2011).

Project leaders might also detect a kind of observer effect, in which participants modify their behavior or stage their performances in a group setting when they know they are being observed or evaluated (Monahan and Fisher, 2010). Experienced project leaders are aware of such performativity. They can then check for validity and triangulate information accordingly, and even potentially harness this display of rehearsed behavior to the benefit of the research project (Monahan and Fisher, 2010).

Pushing project participants, whether they are scientists or practice-experts, to share their work and knowledge without the necessary precautions and preparations can lead to problems that will ultimately damage the project. Participants may become selective and strategic in relation to what they put forth and what they hold back. By cherry-picking the most desirable or least controversial bits of information, the project misses worthwhile discussions and, in the worst cases, lacks integrity in research and damages validity of results.

Though well-intentioned, reminding project participants of the importance of sharing freely is insufficient. Project leaders need to build sufficient trust among stakeholders. Otherwise, if stakeholders perceive sharing to be a personal threat, it is reasonable to expect that they will omit or directly withhold information that could lead to a different research picture. Cherry-picking refers not just to pieces of data and results, but to all aspects that can be manipulated in a research process, including the research design, which may have implications for a specific industry or political actor, as the quote below illustrates.

"It is easy for us researchers to cherry-pick and influence results if one wants to. Luckily, this is not what motivates us".—Quote by a scientist in a co-production workshop.

In the above quote, the scientist was reflecting upon the process of establishing the assumptions that would inform a model designed in partnership with scientists and practice-experts. Depending on which premises were established, results could be used to assign or dismiss blame in a given industry for an environmental problem. The team was aware of their responsibility and of the political implications of engaging with a post-normal research problem. At the same time, they wanted to assert neutrality not only in relation to the results, but also in the very assumptions and premises adopted for the research, itself. This leads us to our final recommendation.

Address Scientists' Wish to Convey Neutrality in Politically Charged Territory

Whereas the previous point concerned participants' positions within the project, we turn now to their relationship with actors outside the project group. As we touched upon in the previous section, most scientists (though not all, in our experience) are used to caring for housekeeping behind the scenes (e.g., cleaning up datasets, fine-tuning methodological approaches, discarding negative results before publishing, trial-and-error testing of hypothesis) and only reach out to the public once there is consensus and they can speak with a stronger, unified voice. Scientists assert their authority precisely by means of their commitment to truth over convenience; taking any position in a disputed problem threatens this projection of neutrality (Skolnikoff, 2001). This tension is especially salient in times of fake news and public discrediting of scientific expertise, and scientists may fear taking a public position that can turn out to be disproven later (e.g., Oreskes and Conway, 2010). Thus, scientists may worry about damaging their reputation, credibility, and authority, which is already under threat in some circles.

However, science and scientists are becoming increasingly challenged in the public eye (Skolnikoff, 2001). Among several reasons for this, we highlight the prominence of evidence-based policy and management in which politicians push science to the fore of their decision-making, forcing science "on stage" to make statements about issues where research is preliminary or controversial (Saltelli and Giampietro, 2017). The general public, in turn, lacks an understanding of how science deals with uncertainty, which hinders honest and effective debate (Bjørkan and Hiis Hauge, 2019).

The Norwegian aquaculture sector is a good example of how scientists have been under pressure from both politicians and business representatives (Bjørkan and Hiis Hauge, 2019). They fear that uncertainty will be mishandled or misconstrued to push an agenda amidst a conflict of interest. Two quotes exemplify this concern:

> "When we talk about who is going to confront the sources (of pollution), I think it is important that it is not us researchers who are going to do it because we produce the knowledge that someone else is going to use. As a researcher, I should not be the one to say, "This cannot be allowed". Here, it is someone else who should make the decision in a democratic way. In the long term, this could eventually damage my reputation as a scientist who needs to tell the truth but not have too many opinions at the same time".
> —Quote by a scientist in a co-production workshop.
>
> "For an NGO, it would be catastrophic to form an alliance with scientists who have an agenda. It would undermine what we do".
> —Quote by the director of an NGO in a co-production workshop.

That is, not only do scientists prefer to adopt a posture of neutrality, but other stakeholders also expect this of them (Skolnikoff, 2001), even though there is an argument to be made for taking sides (i.e., Rosendahl et al., 2015). Scientists are presumed to make assertions backed by multiple qualifications, limiting conditions and caveats, while practice-experts (and the press) are more eager to dismiss these qualifications and work only with the substance of findings and arguments. If practice-experts need support from project leaders to assert their legitimacy towards the group, scientists need support to explore and document the limiting conditions of the knowledge they put forth. This support contributes to trust and prevents scientists from experiencing "*a dilution of the authority of science*" and being "*dragged into the world of politics*" (Ravetz, 1999). As a result, scientists will be more at ease to express ideas that may be preliminary, uncertain, or politically charged. Allowing scientists space to be cautious precludes them from evading or concealing the policy implications associated with their work.

SOCIAL SCIENTISTS' CONTRIBUTIONS TO CO-PRODUCTION OF KNOWLEDGE

Based on our experience—which the advice we put forth in this paper reflects—much of what can be challenging in co-production research is of a tacit and social nature. Stimulating exchanges between scientists and practice-experts is only the first step in successful co-production of knowledge. What comes next relies upon the kind of soft skills that can be (and often are) taken for granted. These kinds of contributions, which are more difficult to articulate and measure, are often at the very core of what social science and humanities experts can offer (Turner, 2015). Thus, the contributions from "hard-discipline" scientists and practice-experts are generally more applied than those of social scientists.

Different actors have different expectations for social scientists. Some practice-experts, such as indigenous or marginalized groups, are in a more vulnerable position in the configurations of power and might expect social scientists to assist them in making their voices heard and to voice concerns regarding social justice issues. Other practice-experts (e.g., NGOs with international reach) have no problem voicing their knowledge and perspectives. Often, employees in NGOs have academic degrees and enter partnerships with scientists active in academia. Moreover, with the decline in permanent positions in scientific careers, many doctoral graduates look for jobs outside academia after earning their degrees. Natural scientists often expect social scientists to build communication channels between themselves and practice-experts, and to ensure that people "get it". But natural scientists are also less open to critical social inquiry into, for instance, how scientific knowledge is produced as an expression of a particular knowledge culture (Latour, 1987) and less focused on their roles as gatekeepers of and contributors to large, powerful, and segregated communities of experts (Jasanoff and Kim, 2015).

One of the most common expectations put upon social scientists is that they should serve as brokers between other scientists and practice-experts, facilitating the implementation of research projects, enabling contact between stakeholders from diverse backgrounds, and solving logistical problems. While these are indeed tasks that social scientists can and often do take on in co-production projects, it would be unfortunate to limit the scope and ambitions of social scientists to mere facilitation. This is both an inefficient use of project resources (since other professionals can perform these tasks) and a devaluation of the contributions social scientists can offer. We therefore stress in our recommendations here that social scientists be allowed the space and resources needed for thorough and analytical social science research and reflection. Naturally, these contributions should aim at a better understanding not only of the practical

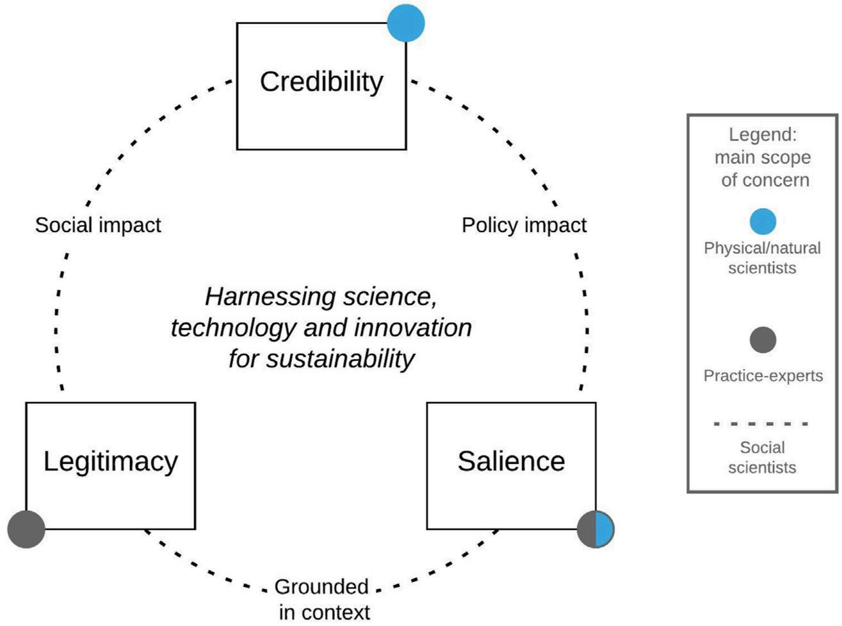

FIGURE 2 | Credibility, legitimacy and salience (inspired by Cash et al., 2003).

obstacles to solving a particular societal problem, but also of how project goals align with and/or contradict the rights, concerns, goals and ambitions of multiple actors and stakeholders.

We further assert that this narrow view of the social scientist's role more often reflects a lack of familiarity with what the social sciences do than a lack of valorization of the field as a systematic field of inquiry. That said, many expect social scientists to "handle" the social, the political and even the economic implications of a project, as if these were nuisances and hindrances instead of integral elements of knowledge production in a post-normal context. This tendency towards accepting the incomplete picture is unfortunately not often challenged by funding agencies, which assign social science contributors the role of ensuring society's readiness to accept a project's innovations and subsequent implementation of results through favorable policies. In our anecdotal experience, projects (and calls for projects) that center around hard technology development and technical solution-finding in pathways that are politically pre-decided are most often guilty of misusing co-production and the social sciences.

It is important that social scientists are more than the "icing on the cake" in transdisciplinary funding applications (a characterization that one of us has heard from a natural scientist). Social scientists can and should contribute as more than project advocates performing for social actors who influence and are influenced by the project and its results. However, if we are to acknowledge the ways in which social scientists can meaningfully contribute to transdisciplinary co-production in research projects, it is imperative to accept that the contribution of social scientists is often intangible. What is more, we should see and frame this intangibility as an asset. While some actors provide hard data measuring a phenomenon, create an innovative prototype, or produce a number of other material deliverables, social scientists' contributions are distinctive in that they can illuminate multiple potential outcomes, multiple assessments and understandings of the problem at hand, and the awareness that, no matter what contributions a project provides in the end, society will proceed not without arguments, disagreements, insecurities and contingencies, but through them (Foucault, 2008; Dean, 2010; Dale, 2011).

Earlier work on how to harness science, technology and innovation for sustainability transitions has shown that successful cases are those in which there is a balance between credibility, salience, and legitimacy of knowledge (Cash et al., 2003). The challenging task is to enhance these three dimensions simultaneously, as efforts in one area often impact the others (Cash et al., 2003). We consider social scientists' contributions to lie in promoting and maintaining ties between credibility, legitimacy, and salience, as illustrated by **Figure 2**.

Just as the social sciences are diverse, there are multiple ways in which different disciplines can contribute to a research project. What is shared across disciplines—from anthropology to economics—is that social scientists can ask unusual questions, visualize the bigger picture, analyze the complexities in which an issue is embedded, and form connections between a project and other relevant problems for mutual learning. Social scientists can map and document how different processes unfold and create analytical toolboxes for the social, political, and economic aspects relevant to a project. It is the job of social scientists to create space for critical reflection on a project's process and results, and to address the ways in which the process both influences and is influenced by society at large.

Social scientists can also play a role in consistently operationalizing methods that prevent the misuse of a research process by any given group, and thereby calibrate the scales of power in knowledge production (Turnpenny et al., 2011). Emphasizing and utilizing this ability would be beneficial not only to social scientists, but to all stakeholders and, not least, to the production of knowledge that measures up to the ideals of credibility, salience, and legitimacy.

CONCLUSION

In this paper, we sought to offer practical guidance to researchers interested in adopting co-production of knowledge in their work. Increasing demands for the adoption of co-production in scientific research is noticeable, whether through the EU's multi-actor approach, stakeholder engagement, citizen participation and other related notions. While there are nuances to these labels, what they have in common is the social justice premise that diverse stakeholders have not only the moral right to participate in knowledge production and decision making that affects them, but also that actors other than scientists have expertise that matters and should be better accounted for. More democratic processes of both production and consumption of knowledge also reframe knowledge and expertise as a commons, rather than privileged, exclusionary, and rival arenas.

While there is a rich literature in Science and Technology Studies that deals with science as process and culture, knowledge (co-) production, public engagement, and power, among other aspects, we observe that these insights are often unfamiliar to scientists leading research projects. Often, project leaders either learn through trial and error and lack deep understanding of these issues, or they remain oblivious to the socio-cultural dynamics that affect knowledge production. To address this pressing need, we have revisited key works and arguments from the STS tradition in light of our experiences and what we see are concrete challenges involved in co-production of knowledge. Our ambition has been to build upon this knowledge, extend it to a broader audience, and illustrate its intricacies with practical guidance.

Our main contribution is in putting forth five crucial elements that arise as project leaders go about operationalizing principles of co-production. Our core recommendations are: 1) unite diverse participants through a shared objective and manage divergent motivations; 2) beware of holding consensus as the holy grail; 3) cultivate understanding and appreciation for distinct types of expertise; 4) pay attention to struggles in sharing preliminary work and potentially harmful information; and 5) address scientists' wish to convey neutrality in politically charged territory. Binding these recommendations is the need for project leaders to develop soft skills for coordinating collaborative work in a way that foments trust and goodwill, despite possible conflicting values and interests.

We also call attention to the role of social scientists in transdisciplinary collaborations of this sort, which we see as crucial for promoting and maintaining ties between credibility, legitimacy, and salience of the research process. The contribution of social scientists is often less tangible than other types of experts, but their inherent value needs more recognition, both in the form of wider acknowledgement and as allocation of funds for these tasks in research projects. We believe this is fundamental to avoid that co-production becomes a bureaucratic box-checking, or worse, that it gets coopted as devices for granting the appearance of participation to processes that are in fact not in essence concerned with it.

This article was not conceived to be exhaustive or definitive, but to advance a dialogue on the challenges that come about when operationalizing co-production in practice. We hope to motivate others to share their experiences, and, in doing so, contribute to a toolbox equipped to realize collaboration and knowledge production across diverse values, disciplines and expertise.

AUTHOR CONTRIBUTIONS

LN was co-responsible for the conception of this manuscript, and the primary responsible for its framing, development, writing and editing. MB was co-responsible for the conception of this manuscript and contributed to the framing and co-writing of all sections of the manuscript. BD contributed to the framing of the article, contributed particularly to the Introduction, the section on consensus and the section on Social Scientists' Contribution to Co-Production Processes, and commented upon all other sections.

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Training Graduate Students in Multiple Genres of Public and Academic Science Writing: An Assessment Using an Adaptable, Interdisciplinary Rubric

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There is an urgent need for scientists to improve their communication skills with the public, especially for those involved in applying science to solve conservation or human health problems. However, little research has assessed the effectiveness of science communication training for applied scientists. We responded to this gap by developing a new, interdisciplinary training model, "SciWrite," based on three central tenets from scholarship in writing and rhetoric: 1) habitual writing, 2) multiple genres for multiple audiences, and 3) frequent review and created an interdisciplinary rubric based on these tenets to evaluate a variety of writing products across genres. We used this rubric to assess three different genres written by 12 SciWrite-trained graduate science students and 74 non-SciWrite-trained graduate science students at the same institution. We found that written work from SciWrite students scored higher than those from non-SciWrite students in all three genres, and most notably thesis/dissertation proposals were higher quality. The rubric results also suggest that the variation in writing quality was best explained by the ability of graduate students to grasp higher-order writing skills (e.g., thinking about audience needs and expectations, clearly describing research goals, and making an argument for the significance of their research). Future programs would benefit from adopting similar training activities and goals as well as assessment tools that take a rhetorically informed approach.

Keywords: science communication, STEM, graduate training, program assessment, SciWrite, rubric development, science writing, writing and rhetoric

INTRODUCTION

Institutions in the United States and Europe, such as the National Science Foundation, Council of Graduate Schools, and the European Commission, have recently called for Science, Technology, Engineering, and Mathematics (STEM) graduate programs to incorporate more communication training to better prepare future scientists to communicate to a variety of audiences (Linton, 2013; Kuehne et al., 2014; Druschke et al., 2018; Costa et al., 2019). Such calls for better science communication training for future scientists are driven by the realization that scientists should be involved in effectively conveying scientific information to a broad cross-section of society (Roux et al., 2006; Nisbet and Scheufele, 2009; Meyer et al., 2010; Smith et al., 2013; Taylor and Kedrowicz, 2013; Kuehne and Olden, 2015; National Research Council, 2008). Despite this expressed need for broader impacts and improved communication training for scientists, little research has been conducted on the most effective ways to implement and assess communication training programs for science graduate students (Kuehne et al., 2014; Skrip, 2015; Druschke et al., 2018; National Alliance for Broader Impacts, 2018). We responded to this gap by developing, implementing, and assessing a new, interdisciplinary model for developing more effective graduate science writers at the University of Rhode Island (URI) — the SciWrite@URI program (hereafter "SciWrite"). This program was designed to be adapted for a broad cross-section of science disciplines for a variety of scientists and communicators at institutions across the globe.

The goal of the SciWrite program was to better equip science graduate students with the tools necessary to be effective writers for any audience. What makes SciWrite unique from other programs with similar goals is its foundation in rhetoric-based theories and practices. Though the term rhetoric often circulates in common discourse as a term meaning "political spin," the discipline of rhetorical studies is a field of research, at least 2,000 years old, dedicated to better understanding the ways that humans communicate, in speaking, writing, and other modes, for a variety of audiences and a variety of ends. SciWrite adopted theoretical work from the field of writing and rhetoric in order to create tangible and practical learning outcomes for our SciWrite graduate students. We developed three primary learning outcomes for SciWrite students based on three central rhetorical tenets often taught in writing and rhetoric courses: habitual writing, multiple genres for multiple audiences, and frequent review (Bruffee, 1981; Porter, 1986; DiPardo and Freedman, 1988; Lunsford, 1991; Lundstrom and Baker, 2009; Crowley and Hawhee, 2012). Upon successful completion of the SciWrite program, we expected that students would meet the following primary learning outcomes associated with each rhetorical tenet:

1) Habitual writing–students will produce high quality writing earlier and more frequently in their graduate school tenure
2) Multiple genres for multiple audiences–students will demonstrate effective command of writing in multiple genres for multiple audiences
3) Frequent review–students will evaluate peer drafts in order to provide helpful writing feedback and to improve their own writing skills

In this article, we focus on assessment of student writing for Learning Outcome Two (related to Multiple genres for multiple audiences), which required the development of a flexible rubric for the assessment of written products of different genres. For the purposes of this article, we are defining genre as "a category of writing" (e.g., scientific manuscripts, proposals, and news articles). This rubric allowed us to evaluate whether students demonstrated effective command of writing in multiple genres for multiple audiences and also provided us an effective, holistic framework for feedback. Learning Outcomes One and Three (related to Habitual writing and Frequent review) were assessed using SciWrite Fellows' self-reported surveys and not the rubric. Because this assessment methodology was so different from our rubric assessment, we will report on that portion of the study in a different article.

Science communication training informed by rhetoric reorients the assessment and revision of writing, and this assessment and revision process is crucial for learning and improving academic and public writing. As a case in point, there is often disagreement among science faculty about the most helpful strategies for providing writing feedback, and many attribute this confusion to a lack of adequate instruction in the teaching of writing and/or inadequate support in developing their own writing skills (Pololi et al., 2004; Reynolds et al., 2009). Due to this lack of training in writing and rhetoric, common feedback approaches consist of either copious sentence-level edits or providing almost no feedback at all (Reynolds et al., 2009). However, decades of research in writing and rhetoric (Bruffee, 1981; Lunsford, 1991; Chinn and Hilgers, 2000; Bell, 2001; Lerner, 2009; Nordlof, 2014) tell us that to help students improve their writing over the long term there are a number of feedback strategies that are more important to focus on than merely directive, sentence-level editing (Neman, 1995; Straub, 1996). For example, a focus on "higher-order concerns" is much more effective than a focus on "lower-order concerns," and because of this, most assessment and feedback should place more emphasis on higher-order concerns (Elbow, 1981; North, 1984).

Higher-order concerns deal with matters such as thinking about audience needs and expectations, developing clear arguments, and adhering to genre conventions. Such writing practices are critical when science students must determine how best to convey their results in writing (Groffman et al., 2010; Druschke et al., 2018). For example, the general wisdom is that when science students write about their research for a scientific audience they should establish credibility by being explicit yet concise with their methodology and deliberate with citing previous studies relevant to their research. However, when writing about this same research for a public audience, methodology and citation of sources would not be relevant to their readers (Baron, 2010; Heath et al., 2014; Kuehne et al., 2014). Instead, they can best establish credibility with a public audience by making it clear why the results are important and how they may affect society at large—this is what writing and rhetoric scholars refer to as an awareness of the "rhetorical situation" (Bitzer, 1968; Fahnestock, 1986; Druschke and McGreavy, 2016). For the purposes of this article, rhetorical situation can be defined simply as the context within which scientists communicate their research to others. Important parts of this rhetorical situation are the audience they are communicating to, the expectations and needs of that audience, and the purpose for communicating their research. When writers can identify the purpose of their writing project and the needs and expectations of their audience, they have a strong awareness of their rhetorical situation. Writing and rhetoric studies stress the importance of writing feedback that takes a more holistic approach than simply proofreading; the most useful writing feedback for graduate science writers will focus on higher-order concerns and will help students better understand their rhetorical situation (North, 1984; Neman, 1995; Straub, 1996). Our study will help to evaluate the utility of such skills. Here we present and use an evaluation rubric that emphasizes this holistic approach, and that is applicable for assessing the written work of graduate students in the sciences writing for multiple audiences with a variety of needs and expectations.

The aim of this study was to determine whether SciWrite students were able to demonstrate effective command of writing in multiple genres for multiple audiences, and if so, what factors most contributed to their ability to meet this learning outcome. We also aimed to test whether there was a difference in rubric scores for SciWrite trained students versus non-SciWrite trained students. First, we developed and present here a rubric that assesses students' writing progress on both higher- and lower-order fronts, and helps science faculty members give their students more effective writing feedback. We then used this SciWrite rubric to assess two important types of writing products that many science graduate students at URI produce as part of their program requirements: 1) a thesis/dissertation proposal that outlines the rationale, study design, and planned outcomes of their graduate project, and 2) relevant written assignments from graduate-level science courses that included writing training. For all genres of writing, we compared the writing of SciWrite-trained graduate students to non-SciWrite trained science graduate students. This study design helps us to better determine how rhetorical tenets can contribute to other science writing programs, and also helped us evaluate the potential utility of the SciWrite program for other institutions with similar writing program goals.

MATERIALS AND METHODS

Below we describe the comparison groups of science graduate students in more detail, the training experienced by SciWrite-trained students, the SciWrite rubric used to assess the writing products, and the assessment process.

Recruitment

In 2016 and 2017, two cohorts of SciWrite fellows were recruited via departmental and university announcements, faculty and staff recommendations, and word of mouth. Only graduate students at URI who had at least 2 years remaining in their program and were enrolled in a graduate science program were eligible to participate. Candidates were chosen based on perceived level of dedication and ability to participate in the intensive 2-year writing program, rather than writing ability. This allowed us to avoid potential bias toward candidates who already had above average writing skills compared to the average science graduate student.

Study Design

The overall 2-year timeline of the SciWrite program for each cohort of students consisted of regularly scheduled workshops (4 over the 2 years), two writing-intensive courses, a summer science communication internship in the first year, followed by a multimedia journalism class, writing tutor training, and writing tutor work at the URI Graduate Writing Center in the second year (**Figure 1**). Two separate cohorts of six students completed this timeline from 2016 to 2019. All of these activities were designed with program learning outcomes in mind. We have outlined a more detailed description of the particular components of the SciWrite program and the ways in which SciWrite differs from other writing programs in Druschke et al. (2018). Therefore, the description we give here will be an abbreviated version that can be supplemented with additional details from Druschke et al. (2018).

In our courses and trainings, SciWrite fellows engaged in habitual writing, wrote in multiple genres for multiple audiences, and participated in frequent review. For example, assignments were scaffolded into simpler, shorter assignments (rather than entire drafts) (Druschke et al., 2018). Such an approach helped students to take on writing projects that were less daunting and lower stakes, and so made it easier for students to get into the habit of writing early and often for writing assignments (Coe 2011; Petersen et al., 2020). SciWrite fellows practiced writing in multiple genres (e.g., manuscripts, blog posts, news articles, editorials, White Papers, proposals) for academic and nonacademic audiences (e.g., lay readers, technicians, practitioners, and scientists). After working on assignments in their courses and workshops, SciWrite fellows entered a process of review and revision in one-on-one and small group tutorials in classrooms, online forums, and while working as writing tutors at the Graduate Science Writing Center that we opened in fall 2017. SciWrite fellows learned how to provide facilitative feedback rather than directive feedback and to focus their feedback on higher-order rather than lower-order concerns (Elbow 1981; North 1984; Neman 1995; Straub 1996). This allowed SciWrite fellows to practice giving and receiving peer feedback in a structured, holistic way. Three genres of writing that SciWrite students practiced during their tenure with SciWrite were used for assessment: 1) a thesis/dissertation proposal submitted to the graduate school, 2) one final "Writing in The Life Sciences" assignment, and 3) one final "Public Engagement in Science" assignment.

The three writing products (i.e., thesis/dissertation proposal, one assignment from each of two courses) produced by SciWrite fellows and other science graduate students were assessed over the course of the SciWrite program from 2016 to 2020. Proposals for non-SciWrite students were selected using a random-stratified process. Proposal samples were stratified by department in order to ensure a departmental composition roughly equivalent to that of the SciWrite fellows. Individual proposals were randomly selected from each stratum for the non-SciWrite group. Final course assignments for both SciWrite and non-SciWrite students were assessed at the end of each course.

Assessment of Three Genres of Writing

Trained assessors used the SciWrite rubric to assess three written products: the thesis/dissertation proposal, the public science writing piece, and the public engagement in science project

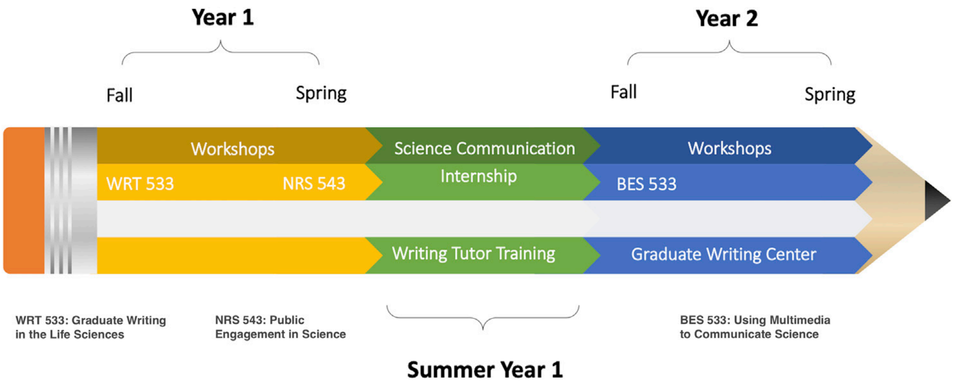

FIGURE 1 | Timeline of the 2-year SciWrite Program used to train each of the two cohorts of graduate students from 2016 to 2019: Progression through three courses (WRT 533 Graduate Writing in the Life Sciences, NRS 543 Public Engagement in Science, and BES 533 Using Multimedia to Communicate Science), simultaneous workshops, a summer internship and writing tutor training, and working as writing tutors at the Graduate Writing Center.

TABLE 1 | Rubric items used to assess SciWrite and non-SciWrite academic written products, arranged from "higher-order concerns" to "lower-order concerns." Rubric items in bold address higher-order concerns. Written products were assessed on a scoring scale from 1 to 3: "does not meet expectations," "approaches expectations," and "meets expectations."

1. Is the text appropriate for the target audience?
2. Does the text follow the conventions of the genre including tone, vocabulary, style, and delivery?
3. Is there an appropriate depth of content given genre and subject matter?
4. Does the text make a compelling argument for the significance of the student's research within the context of the current literature?
5. Does the text clearly articulate the student's research goals?
6. Is the text clearly organized?
7. Are the citations presented consistently and professionally throughout the text and in the list of references?
8. Is the text free of writing errors?

report. Assessors were seven graduate students in the Writing and Rhetoric graduate program, one graduate student in the Biological and Environmental Sciences graduate program, and one faculty member with a joint appointment in the Writing and Rhetoric program and Biological and Environmental Sciences program. All assessors were previously trained in writing program assessment best practices. Assessors convened for shared norming sessions and discussions of sample essays and baseline scores. Where necessary, norming sessions included defining key terms and reference guides to aid coders in scoring. In total, the norming process consisted of roughly 10 h of training in 2017, 2019, and 2020.

Proposal

Identifying information was removed from all thesis/dissertation proposals, so assessors were unaware of author identity or their participation in the SciWrite program. Each of the 49 graduate proposals ($n = 10$ for SciWrite and $n = 39$ for non-SciWrite) was randomly assigned to two different assessors, and assessor rubric scores were averaged. Assessors gave each of the eight rubric items a score between 1 and 3 (i.e., "does not meet expectations," "approaches expectations," and "meets expectations," **Table 1**). We compared assessors' scores of the proposals to assess inter-rater reliability of the rubric. In instances where one or more rubric items had a disagreement of more than one point between assessors, those written products were then assessed by a third assessor and scores were averaged. The maximum score for the proposal rubric was 24 points; the lowest possible score for the proposal rubric was eight points.

Public Science Writing Piece and Public Engagement Project Report

In the first year of the SciWrite program, course assignments were assessed by the course instructor. There were 14 Public science writing pieces ($n = 6$ for SciWrite and $n = 8$ for non-SciWrite) and 15 Public engagement project reports ($n = 5$ for SciWrite and $n = 10$ for non-SciWrite). For the second cohort of the SciWrite program, each of the 13 Public science writing pieces ($n = 5$ for SciWrite and $n = 8$ for non-SciWrite) and 15 Public engagement project reports ($n = 6$ for SciWrite and $n = 9$ for non-SciWrite) was randomly assigned to one assessor. All assessors gave each rubric item a score between 1 and 3 (**Table 2**). The maximum score for the Public engagement project report rubric was 24 points; the lowest possible score for the Public engagement project report rubric was eight points. The maximum score for the Public science writing rubric was 21

TABLE 2 | Rubric items used to assess SciWrite and non-SciWrite written products for public audiences, arranged from "higher-order concerns" to "lower-order concerns". Rubric items in bold address higher-order concerns. Written products were assessed on a scoring scale from 1 to 3: "does not meet expectations," "approaches expectations," and "meets expectations."

1. Is the text appropriate for the target audience?
2. Does the text follow the conventions of the genre including tone, vocabulary, style, and delivery?
3. Is there an appropriate depth of content given genre and subject matter?
4. Does the text delineate and accomplish a specific purpose within the conventions of the rhetorical situation?
5. Does the text demonstrate its significance in a wider context, and build on the existing knowledge base by using literary elements appropriate to the genre (e.g., analogies, metaphors, similes, visual examples, case studies, etc.) to support deeper levels of understanding of complex ideas and phenomena?
6. Is the text clearly organized?
7. Are the citations presented consistently and professionally throughout the text and in the list of references?
8. Is the text free of writing errors?

TABLE 3 | Component weights from the Principal Component Analysis after Varimax rotation with Kaiser normalization for all eight rubric items for both SciWrite and non-SciWrite proposals. Rubric items addressing higher-order concerns are in bold, and the order is determined by the first principal component (PC1) weights. The first two principal components are presented because only their eigenvalues were >1.

Rubric item	PC1	PC2
Significance of research	0.797	0.188
Appropriate for audience	0.746	–0.154
Organization	0.659	0.266
Research goals	0.601	0.406
Depth of content	0.588	0.525
Genre conventions	0.363	0.455
Free of errors	0.297	0.746
Citations and references	–0.128	0.840

points because in-text citations are inappropriate for public science writing, and so the citations and references rubric item was removed; the lowest possible score for the Public science writing rubric was eight points.

Given that we were most interested in differences between SciWrite and non-SciWrite students in both courses (rather than differences between years and assessors), we combined rubric scores between years for each course for this analysis which resulted in a comparison of 11 SciWrite and 16 non-SciWrite students for the Public science writing piece, and 10 SciWrite and 19 non-SciWrite students for the Public engagement project report. The final count for SciWrite Public science writing pieces was 11 because one student in the second cohort left the program after the first year. The final count for SciWrite Public engagement project reports was 10 because one student in the second cohort left the program after the first year and because an additional SciWrite student had already taken the Public Engagement in Science course the year before the SciWrite program began.

Intended Audiences and Genre Expectations of All Three Products

Because this rubric is deliberately adaptable for a variety of audiences, we used it in conjunction with the assignment guidelines of the written product being assessed. This assured the assessor could understand the genre conventions and specific expectations of each assignment. Therefore, we have listed the conventions and expectations of the written products below.

The thesis/dissertation proposal submitted to the graduate school was a research project proposal standard to most science graduate programs. The intended audience was an academic audience that did not necessarily have science training specific to that discipline (see **Supplementary Materials** for further description of genre expectations). This written product was assessed with these genre expectations and rhetorical situation in mind.

The Writing in The Life Sciences course assignment was a writing piece intended for a public audience, in which each student was required to write about a specific scientific study in an engaging and accessible way for an audience with no scientific background (see **Supplementary Materials** for further description of genre expectations). The Public Engagement in Science course assignment was a project report that each student had to compose that assessed and evaluated their own public engagement project which they had created for the course. The intended audience was a professional and/or academic audience that did not necessarily have a scientific background (see **Supplementary Materials** for further description of genre expectations). Each of these written products were assessed with these genre expectations and rhetorical situations in mind.

Rubric Background

During the first year of the project, the SciWrite team developed a rubric to assess all written products created by SciWrite program participants. This was one primary result of the SciWrite program, and the rubric is now being used in the URI Graduate Writing Center and in some URI graduate courses as a helpful feedback framework. The SciWrite rubric was adapted from Duke University's BioTAP rubric for scientific writing (Reynolds et al., 2009). The BioTAP rubric placed emphasis on creating a flexible and adaptable assessment tool for science students and faculty that could be used across a diversity of writing products, genres, audiences, and subjects. In addition, the BioTAP rubric encourages faculty to give holistic, "reader-based" feedback (Reynolds et al., 2009). This emphasis on adaptability and holistic feedback aligned closely with the goals of the SciWrite program.

The original BioTAP rubric was designed to evaluate success based on both the standards of writing and rhetoric, and the goals of the biology department at Duke University. To ensure the rubric language lent itself to accurate evaluation, the rubric was based on best practices from foundational academic writing courses, and researchers consulted with their Writing in the Disciplines department and

Office of Assessment program as well as collaborating with biology faculty (Reynolds et al., 2009). The authors designed the rubric with the goal of it serving as a model for other STEM departments. Furthermore, the rubric was tested on a large sample size (190 written products) and each writing product was evaluated by two separate assessors. Researchers found there was moderate to strong agreement between raters. Because this rubric was designed to serve as a model for other STEM departments, and because of the tested reliability of this rubric as an assessment tool, we chose to adopt it for our assessment process as well with only a few important additions (see "Development of rubric" section below).

Reynolds et al. (2009) highlighted the standards addressed in each section of the rubric, and we modelled our assessment off of these standards as well. The first section (questions 1–5 in our rubric) addresses higher-order concerns such as targeting the intended audience, contextualizing the research within the scientific literature, and communicating research aims (Reynolds et al., 2009). The second section (questions 6–8 in our rubric) addresses organization, mechanistic issues, and citations. To receive a score of "approaches expectations" for question 1, for example, the written product must include appropriate definitions or explanations of key terms and concepts with minor lapses that do not prevent the primary intended audience from accessing or engaging with the research/text (**Supplementary Materials**, SciWrite rubric). In comparison, to receive a score of "meets expectations" the written product must make the research not only accessible but also engaging for the intended audience. To adequately define the intended audience and genre conventions of the written product they were assessing, assessors always referred to the assignment sheet for that written product. (For further explanation of assessment standards, consult Reynolds et al. (2009) as well as our rubric in the **Supplementary Materials** section).

Development of Rubric

We collaborated with departments in the College of the Environment and Life Sciences, Writing and Rhetoric faculty, and program assessment experts to specifically tailor the rubric to the needs of the SciWrite program (**Tables 1, 2**). The rubric was slightly adapted to incorporate multiple criteria that assessed students' ability to meet our program learning outcomes. For example, items 1–3 and 9–10 addressed Learning Outcome Two, related to Multiple genres for multiple audiences (**Tables 1, 2**). To determine if students were demonstrating effective command of their writing in multiple genres for multiple audiences, the rubric evaluated whether the writing was audience appropriate, followed genre conventions, and used techniques appropriate to the genre and rhetorical situation. We added one additional item for the academic writing rubric, and two additional items for the public writing rubric, in order to more fully assess Learning Outcome Two. The additional items were: 1) Is there an appropriate depth of content given genre and subject matter? 2) Does the text delineate and accomplish a specific purpose within the conventions of the rhetorical situation? and 3) Does the text demonstrate its significance in a wider context, and build on the existing knowledge base by using literary elements appropriate to the genre (e.g., analogies, metaphors, similes, visual examples, case studies, etc.) to support deeper levels of understanding of complex ideas and phenomena? (See **Supplementary Materials**)

The final rubric consisted of 10 items that addressed both higher-order and lower-order concerns, and we created two different versions of the rubric for academic versus public audiences (**Tables 1, 2**). Items were arranged along a hierarchy of higher-order concerns to lower-order concerns.

Statistical Analysis

We examined rubric items for potential correlations using Spearman's correlation tests. We found no significant ($r \geq 0.70$) correlations between rubric items and thus retained all rubric items in our analyses, except as explained below. For the thesis/dissertation proposals, we used a parametric t-test to compare the total rubric scores for proposals written by SciWrite versus non-SciWrite students. Data conformed to normality assumptions and we detected no outliers. Given that we were comparing relatively few thesis/dissertation proposals written by SciWrite students to many more written by non-SciWrite students, we bootstrapped the data with 1,000 samples using the BCa method and created bias-corrected confidence intervals (Hall, 1988; Lehtonen and Pahkinen, 2004). In addition, we conducted a principal component analysis (PCA) to determine which of the eight rubric items contributed most to the variation in writing quality scores of thesis/dissertation proposals. We used a Varimax rotation with Kaiser normalization to simplify interpretation of the resulting PCA loadings for each rubric item (Abdi, 2003). For the two course assignments, we used separate Mann-Whitney tests to compare the writing quality between SciWrite and non-SciWrite students for the Public science writing piece (n = 11 and 16, respectively) and for the Public engagement project report (n = 10 and 19, respectively). We used this non-parametric test because the course data were not normally distributed. We used a paired t-test to detect potential improvement over time in course-based writing assignment scores for SciWrite students in their first course (Writing in The Life Sciences) versus second course (Public Engagement in Science). To make total possible points for the two course rubric datasets equivalent, we removed the citations and references score from the Public Engagement in Science data before conducting this paired t-test. All statistical analyses were performed using SPSS (IBM SPSS Statistics Version 26).

RESULTS

Writing Quality of Proposals

Writing quality of thesis/dissertation proposals differed significantly between SciWrite and non-SciWrite students. Total rubric score (mean ± SE) for SciWrite proposals was 2.4 points higher (21.55 ± 0.58) than that of non-SciWrite proposals (19.15 ± 0.38, $t_9 = -2.98$, $p = 0.005$), a mean difference that equates to an entire letter grade if the rubric was being used for grading purposes. All SciWrite proposals received scores between 18 and 24, whereas non-SciWrite proposals received scores between 13 and 23 (**Figure 2**). One SciWrite proposal received the maximum score, but no non-SciWrite proposals did.

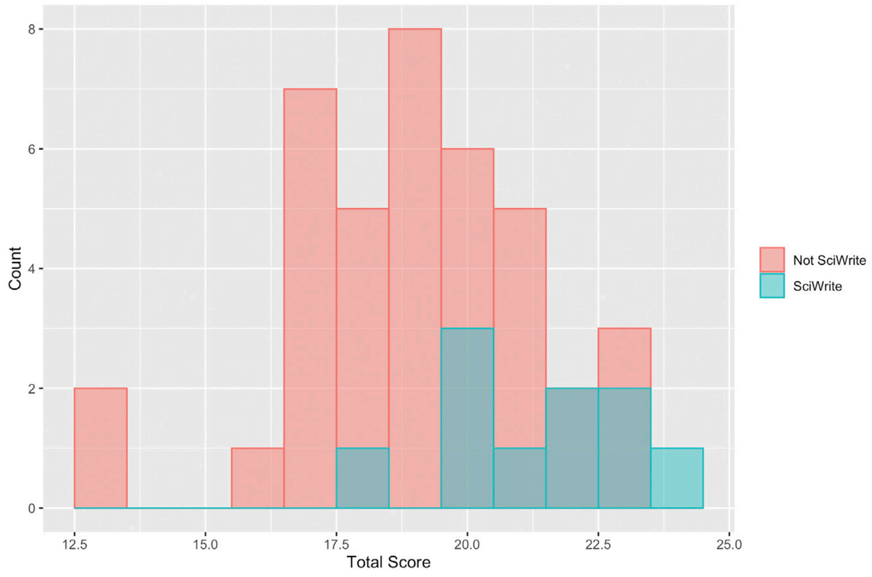

FIGURE 2 | Frequency distribution of total rubric scores for thesis/dissertation proposals written by graduate students trained in the SciWrite program vs. those not trained in this program ("Not SciWrite").

The mean score for each rubric item was consistently higher for thesis/dissertation proposals produced by SciWrite students compared to those produced by non-SciWrite graduate students, and the range of scores was always smaller for SciWrite participants (**Figure 3**). We found that two components were sufficient (i.e., eigenvalues >1) to explain variation in rubric scores and that higher-order concerns on the rubric were a better predictor of variation in writing quality of the proposal than lower-order concerns (**Figure 4**). PC1 explained 42.2% of the variation in rubric scores for the proposal (**Figure 4**). PC1 had relatively large positive associations with all the rubric items addressing higher-order concerns (e.g., *Appropriate for audience*, *Argument for significance of research*, *Research goals, etc.*) except for *Genre conventions* and the lowest loadings for the two lower-order concerns (i.e., *Citations and references*, *Free of errors*), suggesting that PC1 primarily indicates higher-order concerns (**Table 3**). PC2 explained 15.4% of the variation in rubric scores for the thesis/dissertation proposals (**Figure 4**) and had large positive associations with the rubric items addressing the lower-order concerns (i.e., *Free of errors* and *Citations and references*) suggesting this component primarily indicates lower-order concerns (**Table 3**). The PCA also indicates that if a proposal was free of errors and contained appropriate citations and references (lower-order concerns), it was not necessarily appropriate for the intended audience (**Figure 4**).

Writing Quality of Public Science Writing Pieces and Public Engagement Reports

For both genres, mean total rubric score was more than two points higher on average for SciWrite students compared to non-SciWrite students (**Figure 5**). For the Public science writing piece, the higher total rubric score (mean ± SE) for SciWrite students (18.82 ± 0.64, range: 15–21, n = 11) compared to non-SciWrite students (16.31 ± 1.09, range: 9–21, n = 16) was not significantly different (Mann-Whitney U = 114.5, p = 0.195). For the Public engagement project report, the higher total rubric score (mean ± SE) for the SciWrite students (21.6 ± 0.88, range: 15–24, n = 10) versus non-SciWrite students (18.79 ± 0.92, range: 12–24, n = 19) approached statistical significance (Mann-Whitney U = 136.0, p = 0.062).

Total rubric score (mean ± SE) for SciWrite students on the second of their two course-based writing assignments did not differ statistically from that of their first assignment (18.6 ± 0.67 vs. 18.9 ± 0.71, t_9 = −0.605, p = 0.560, n = 10).

Inter-Rater Reliability

Rubrics used to assess writing quality should ideally produce scores that are repeatable and consistent across trained assessors (Jonsson and Svingby, 2007; Rezaei and Lovorn, 2010; Cockett and Jackson, 2018). We compared assessors' scores of the proposals to assess inter-rater reliability of the rubric. There was disagreement between raters on only 14 out of 49 proposals for a total of 22 out of 392 rubric item scores (5.6%). After a third assessor scored the proposals for which there was disagreement, total rubric items with disagreement was reduced to 15 out of 392 total rubric item scores (3.8%). Two rubric items accounted for nearly half of the disagreements between assessors (44%) — the *Citation and references* and *Free of errors* rubric items. Thus, of the 3.8% disagreement in scores, assessors disagreed mostly on the evaluation of rubric items that addressed the two lower-order concerns.

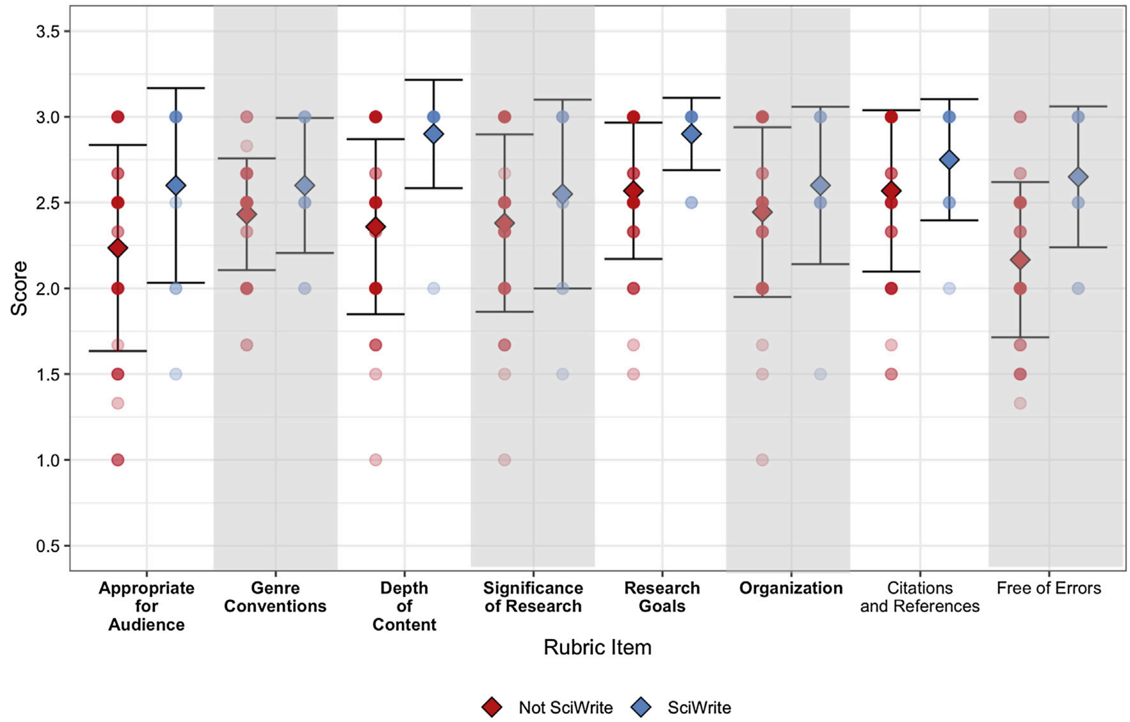

FIGURE 3 | Each of the eight rubric item scores (mean ± SD) for proposals written by SciWrite and non-SciWrite students. Mean scores are diamonds. Scores of individual students on each rubric item are the circular points with darker points for scores earned by at least five students and lighter points for scores earned by fewer than four students. Rubric items in bold address higher-order concerns.

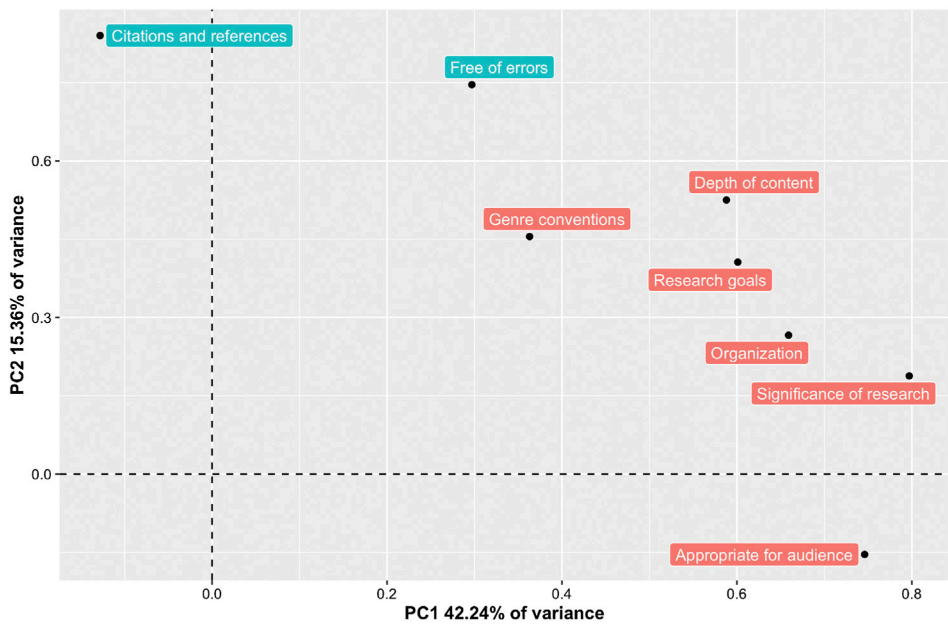

FIGURE 4 | Plot of principal component scores after Varimax rotation with Kaiser normalization for the eight rubric items used to evaluate thesis/dissertation proposals written by SciWrite and non-SciWrite students. Rubric items that addressed higher-order concerns are labeled in red, rubric items that addressed lower-order concerns are labeled in blue.

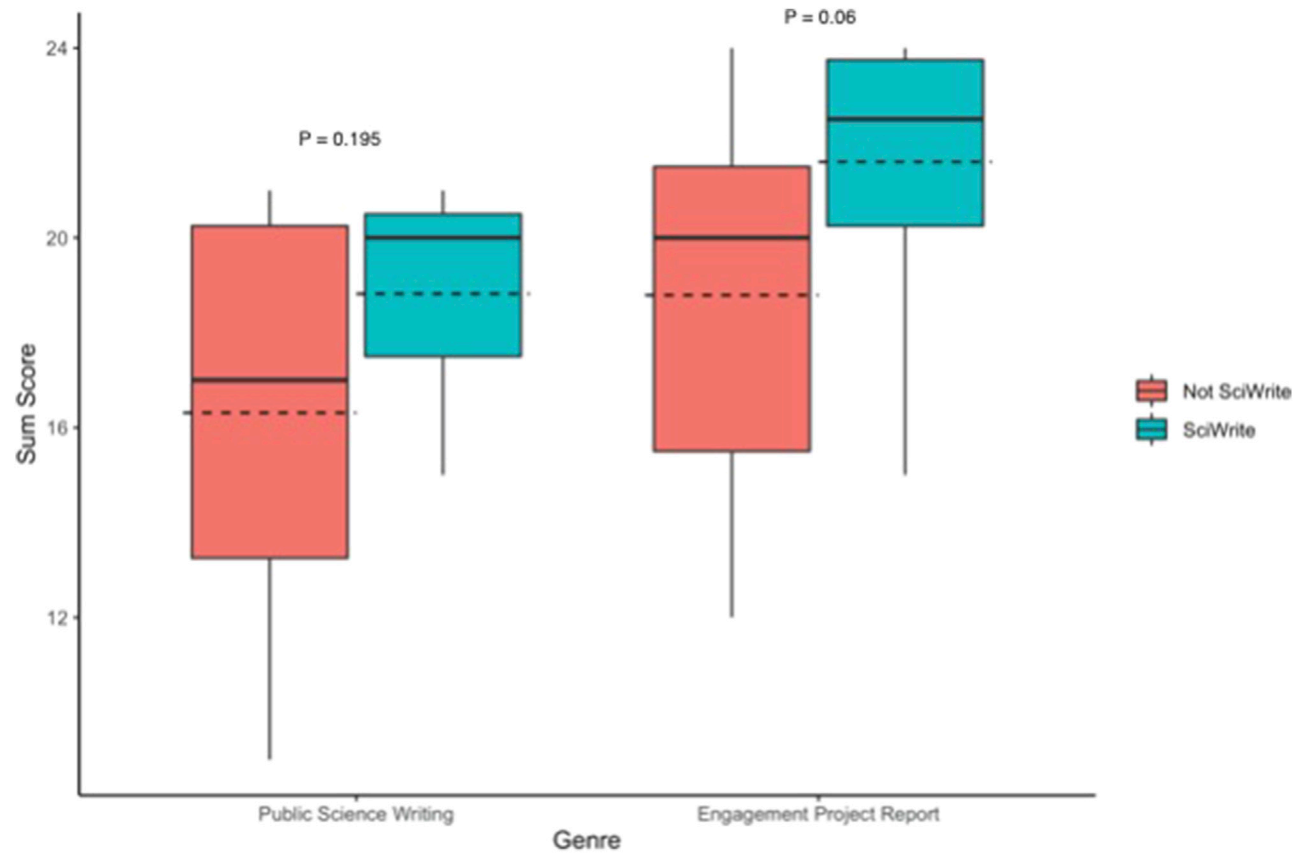

FIGURE 5 | Box and whisker plot of SciWrite versus non-SciWrite total score for the Public science writing piece and Public engagement project report. For the public science writing pieces, minimum possible score was eight and maximum possible score was 21. For the public engagement project reports, minimum possible score was eight and maximum possible score was 24. Boxes show 50% of the values for reported scores, solid lines within boxes show median score, dashed lines show mean score, whiskers show minimum and maximum reported scores. *P*-values are from a Mann-Whitney U test comparing scores of SciWrite versus non-SciWrite students for each of the two genres.

DISCUSSION

The rubric developed as a part of SciWrite allowed us to evaluate how well students wrote in multiple genres for multiple audiences (Learning Outcome Two) and also provided an effective, holistic framework for feedback. We determined that higher-order concerns best explained the variation in rubric scores for the proposals. A number of these higher-order rubric items were specifically developed to assess the writers' command of genre and audience. This indicates that using such a rubric to assess Learning Outcome Two was an effective choice. Our findings also support what Reynolds et al. (2009) found with their BioTAP rubric and what other studies have found about writing feedback geared towards long-term learning (Nordrum et al., 2013; Panadero and Jonsson, 2013). For example, writing and rhetoric scholars such as Neman (1995) report that heavy sentence-level revision with a focus on "errors" rarely helps students learn to assess and revise their own writing and this has become common knowledge for writing and rhetoric practitioners (Neman, 1995). Furthermore, scholars have found that when faculty members heavily revise their students' papers and provide mostly directive (rather than facilitative) comments it becomes difficult for students to consider that there are a variety of choices to make in their revision process, especially if these edits are made without any sort of feedback framework to provide students with reasoning for those revisions (Neman, 1995; Straub, 1996; Reynolds et al., 2009). Such directive approaches prevent students from having autonomy over their own writing and revision process (Neman 1995; Straub 1996). Studies have found that rubrics, if constructed with higher-order concerns in mind, can reduce the potential negative impact of directive feedback and help students learn self-assessment of their own writing which can promote writing autonomy and long-term learning (Nordrum et al., 2013; Panadero and Jonsson, 2013; Fraile et al., 2017). Therefore, this rubric, if implemented in concert with rhetorically-informed courses and workshops, may be especially useful for science faculty and graduate programs with limited experience in providing holistic writing feedback for both higher- and lower-order concerns.

The rhetoric-based SciWrite training program required graduate students to write early and often, for multiple audiences, and to frequently review their own and others' written works, and we maintain that such training helped SciWrite students improve their writing skills. We found that graduate students who received SciWrite training scored higher on average on three different genres of writing than students who did not receive the training, and most notably produced higher quality proposals. The largest differences in scores on specific rubric items between SciWrite and non-SciWrite student thesis/dissertation proposals were primarily higher-order concerns (e.g., the *Depth of content* and *Student's research goals* rubric items). Furthermore, our PCA results indicated that higher-order concerns (e.g., *Appropriate for audience* and *Argument for significance of research*) were a better predictor of writing quality for the proposal. These findings indicate that SciWrite students better met audience expectations, and therefore had a better awareness of their rhetorical situation. There are other programs and courses similar to SciWrite that have also focused their training on higher-order rather than lower-order concerns in their curriculum (Smith et al., 2013; Heath et al., 2014; Kuehne et al., 2014; Clarkson et al., 2018). However, none of these programs placed an emphasis on learning outcomes designed specifically for helping students learn how to better understand the rhetorical situation of their writing projects. SciWrite is unique because we developed specific learning outcomes and best practices based on rhetorical tenets that, according to our assessment, better prepared them to write in different genres for a variety of audiences. Research has shown that genre conventions and communication strategies within the sciences, and other fields of scholarship, can be highly discipline-specific; students will only be successful communicators in their field if they are adequately prepared to adapt to the discipline-specific conventions and audiences for which they are writing and communicating (Darling, 2006; Dannels, 2009). Given that all science graduate students must produce proposals as well as other writing products for a variety of audiences, and must adapt to discipline-specific modes of communication, we maintain that such rhetoric-based training may be helpful for improving students' scientific writing for both academic and public audiences across a broad cross-section of science disciplines.

The written assignments from the two courses were not as clearly different for SciWrite students compared to non-SciWrite students as the proposals. As expected, both groups of students in the first course (Graduate Writing in the Life Sciences) produced assignments that were similar in total rubric score. We believe this is because Writing in The Life Sciences was taken during the first few months of the SciWrite students' participation in the SciWrite program. The mean score of SciWrite student assignments in the second course (Public Engagement in Science) tended to be higher on average than non-SciWrite student assignments ($p = 0.062$). It's important to note that the intended audience for the Public science writing piece was a general public audience, whereas the intended audience for the Public engagement project report was a specialized professional audience that may or may not have had an academic background. Although there was not definitive individual improvement over the course of a year in the SciWrite program, we conclude writing performance may have varied depending on genre and intended audience and SciWrite students were able to successfully compose assignments intended for highly specialized audiences and rhetorical situations. Other studies have suggested that teaching science communication for different types of audiences may require different courses and methods of instruction (Heath et al., 2014). And though many experts cite using a genre approach for writing instruction, almost no studies have investigated the ways in which an individual students' writing abilities may vary depending on the genre at hand (Rakedzon and Baram-Tsabari, 2017). We were not able to investigate the potential factors that may contribute to variation in writing quality according to genre, and so we recommend future programs investigate these factors.

Our findings corroborate what practitioners in writing and rhetoric have emphasized as perhaps the most important tool for helping students to improve their writing—following a hierarchy of concerns when giving feedback (Elbow 1981; North 1984; Reynolds et al., 2009). Writing and rhetoric scholars have long argued that higher- and lower-order concerns are two different components of writing that should not necessarily be given equal weight when helping students improve their writing (Elbow 1981; North 1984). According to our analyses, a written product with a strong awareness of the rhetorical situation is more likely to be higher in quality than a paper that is merely free of errors. Put another way—true to the argument often made in the field of writing and rhetoric, "free of errors" does not necessarily equate to "good" writing. In the context of the SciWrite program, specifically, these findings seem especially pertinent. Our learning outcomes and program design were all framed around writing and rhetoric best practices, so SciWrite training placed virtually all of its focus on higher-order concerns rather than lower-order concerns.

Recommendations for Use of the Rubric and Implementation in Courses

One goal of the SciWrite program was to assist faculty members and other institutions in providing their students with holistic writing feedback that helps students improve their writing skills over time. As such, we wish to provide readers with recommendations from well-established, evidence-based writing and rhetoric best practices that will help readers use this rubric in their own programs and courses.

As mentioned previously, science faculty mentors are usually only equipped to help their students with less complex, lower-order writing concerns, and rarely receive training in giving holistic writing feedback. Adapting the BioTAP rubric allowed us to create a writing rubric for science students and faculty that encourages faculty to give "reader-based" feedback (Brannon and Knoblauch, 1982) and make comments on drafts from the perspective of a member of the target audience rather than as merely an editor or grader (Elbow 1981; Reynolds et al., 2009; Druschke and McGreavy 2016). For example, instead of using a rubric to take off points for typographical errors, faculty members could use this rubric to encourage their students to think deeply about their rhetorical situations. Faculty members could engage their students in facilitative questions (rather than directive statements) standard to the writing and rhetoric field such as: "who is the intended audience?", "what strategies did you use to make this text engaging and persuasive, given the intended audience?", and "as a reader I'm confused by . . . because . . . how could you explain this more clearly?" (Straub 1996; Reynolds et al., 2009). Faculty members could also give their students suggestions for ways to make the text more engaging, and the tone more appropriate, depending on the audience, using the rubric as a feedback framework. In addition, we recommend faculty assign multiple drafts for writing projects, and use this rubric to provide feedback on earlier drafts rather than saving feedback for one final draft (Reynolds et al., 2009). This scaffolded, reader-based feedback approach not only helps students to see writing as a long-term, complex process, but it also reduces the amount of time a faculty member must invest in making copious sentence-level edits on the final product (Reynolds et al., 2009).

We recommend faculty do not simply integrate this rubric into a course that is not designed with rhetorical tenets in mind. For those interested in building off of the SciWrite model, there are a number of writing and rhetoric best practices one can incorporate into a course, in addition to using our rubric (Petersen et al., 2020). For example, writing assignments can be scaffolded into simpler, shorter assignments. This approach of assigning "chunks" of lower stakes writing, rather than complete drafts, helps students get into the habit of writing early and often (Petersen et al., 2020). In addition, students can be assigned different genres of writing with different intended audiences to help them learn how to adjust their approaches according to the needs and expectations of different audiences (Druschke et al., 2018). Lastly, students can be encouraged to engage in peer review, placing an emphasis on higher-order rather than lower-order concerns, and facilitative feedback rather than directive feedback (Elbow, 1981; North, 1984; Neman, 1995; Straub, 1996). We were not able to extensively discuss these strategies in this article, so recommend readers consult Reynolds et al. (2009) and Druschke et al. (2018) for more detailed program design suggestions.

Lessons Learned

Despite the success of the SciWrite program, there is still much progress to be made with helping science graduate students improve their writing and communication skills. Further collaboration between science departments and Writing and Rhetoric departments is highly recommended as this will allow for development of comprehensive and interdisciplinary program learning outcomes. Such an interdisciplinary approach allowed us to create a holistic writing rubric that could assess written products of multiple genres, so this approach will likely allow other programs to develop a broader variety of program outcomes and assessment strategies as well.

Our assessment approach had limitations that future programs should address. First, using course data for overall program assessment may have complicated our results. Because courses are only 3 months long, it may be difficult to quantify writing growth over such a short time span. (Heritage and The Council of Chief State School Officers, 2010; Panadero and Jonsson, 2013). If we had assessed a writing sample from all students before taking each course, this would have given us baseline data to compare for each student to their final writing assignment for each course. We may have been able to more effectively quantify differences between SciWrite and non-SciWrite students using this repeated-measures design. Furthermore, rather than merely looking for statistically significant differences in rubric scores over relatively short time periods, future programs would be wise to supplement this information with additional assessment strategies that are formative, student-centered, and qualitative in approach (Samuels and Betts, 2007; Panadero and Jonsson, 2013; Cockett and Jackson, 2018).

We found that execution of different genres of public science writing may be more, or less, difficult for individual students, depending on a variety of factors. We were not able to investigate what those factors may be (in part, because we did not develop a formative, qualitative assessment method for looking at individual growth over time). Future programs similar to SciWrite could use our rubric to determine whether there is in fact variation in an individual's writing performance depending on the genre at hand. We would recommend future programs use formative, qualitative self-assessment methodologies, such as rubric-guided self-assessment activities and portfolio self-assessment, in order to investigate learning on a more individual level (Panadero and Jonsson, 2013; Reynolds and Davis, 2014; Fraile et al., 2017). This study design would allow an investigation of individual growth over time in a formative, student-centered, and qualitative way (Samuels and Betts, 2007; Cockett and Jackson, 2018). Investigating individual students' learning progress, and potential contributing factors to such learning, could then help programs to develop more pointed, research-informed training strategies with a variety of learning outcomes and best practices depending on the rhetorical situation in which students are engaging.

We recommend that future programs like SciWrite that wish to assess students' written products use an adaptable rubric such as ours that prioritizes higher-order concerns. This approach will be crucial in order to assess multiple genres of writing for a variety of audiences, because it allows assessors to evaluate whether students' writing was audience appropriate, followed genre conventions, and used techniques appropriate to the genre and rhetorical situation. We were somewhat surprised that there appeared to be differences in writing quality depending on genre, and perhaps different genres of public science writing require different types of training with varying learning outcomes and assessment, depending on genre.

In addition, we recommend that future programs take a similarly interdisciplinary approach to program development, because this will encourage novel program design and a wider variety of assessment approaches. Programs with similar goals to SciWrite would likely benefit from creating learning outcomes and program assessment rubrics with this interdisciplinary, rhetoric-based approach in mind.

CONCLUSION

It is imperative that scientists improve their communication skills with the public, and one way to address this issue is to better prepare graduate science students for any kind of writing that will be required in their future careers. Our research suggests that our graduate fellows benefited from being in the SciWrite program, in large part because they are now better prepared to communicate science effectively to a variety of audiences. After successfully implementing our program for 3 years, it seems that what likely had the most impact was focusing our program activities and writing feedback on higher-order concerns such as thinking about audience needs and expectations, clearly describing research goals, and making an argument for the significance of the research (rather than placing emphasis on "fixing" SciWrite fellows' writing). Somewhat unexpectedly, many fellows anecdotally reported to us how helpful it was to their writing process that their SciWrite cohort created a supportive community of practice. Fellows also gave some anecdotal reports of instructors in other classes who focused on directly "fixing" student writing, and this felt discouraging and not as helpful as the supportive, facilitative approach that their fellow SciWrite members took when giving writing feedback. Perhaps the long-term quality of the program helped to slowly build a sense of trust and community for the fellows and being in a community of practice provided them with confidence in their writing process and ultimately helped them to learn more about writing from one another. Lastly, the rhetoric-based approach of our program is likely what helped better prepare fellows to skillfully write in a variety of genres for a variety of audiences. We believe all of the experiences in the SciWrite program will help our fellows in their future careers and will prepare them to respond flexibly and adeptly in any rhetorical situation.

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 University of Rhode Island Institutional Review Board. The participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

SM, IEL, CGD, NK, and NR conceived and designed research and acquired research funding; SM, IEL, CGD, NK, and NR developed SciWrite rubric; EH collected data; EH and IEL supervised assessment; EH analyzed data; EH and SM interpreted results; EH prepared figures; EH drafted article; EH, SM, IEL, CGD, NK, and NR edited and revised article; EH, SM, IEL, CGD, NK, and NR approved final version of article.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2021.715409/full#supplementary-material

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RETHINKING Science Communication Education and Training: Towards a Competence Model for Science Communication

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Science communication is at a pivotal stage in its development due to the emergence of digital communication platforms that are not only presenting new opportunities but are also leading to new challenges. In this context, science communicators, who can include scientists, researchers, curators, journalists and other types of content producer, may require new types of preparation and support to engage with multiple audiences, across multiple channels. Despite the increasing need for adequate science communication training, research in the field is sparse and oftentimes refers to single case studies, calling for more comprehensive perspectives on what is needed and what is offered to equip future science communicators with relevant competences to cope with the changing science communication ecosystem. Against this backdrop, this paper takes two approaches, drawing on data from RETHINK, a European project comprising seven countries, Italy, the Netherlands, Poland, Portugal, Serbia, Sweden and the United Kingdom. First, we report on findings from a questionnaire survey completed by 459 science communicators across the seven countries, focusing on how science communicators develop their communication skills, the types of training they have received and the types of training they would like to undertake. Second, we assess exploratory data collected from 13 different science communication degree programs regarding how they seek to embed and consider issues of digital transformation within their curricula. On the basis of both analyses, we will introduce ideas for a competence framework that addresses not only working knowledge and skills but also professional (self-)reflection and the overall mindset and worldviews of students, whilst offering capacity for increased consideration of the role of digital transformation.

Keywords: science communication, training, digital transformation, skills, competencies, public engagement

INTRODUCTION

Science communication is at a pivotal stage in its development. In the so-called knowledge society, science is a core driver of societal development thus emphasizing the importance of science communication for economic growth, societal welfare and political decision making (Kahan et al., 2012). These developments are being further accelerated by digital transformation that has profoundly changed the ways in which science and society interact. In this regard, we have witnessed a tremendous increase in the volume of science communication even if differences in the development of science communication can be identified in different countries (Gascoigne et al., 2020). There is now a sense in which “science communication is at a moment of transition - sometimes even described as a moment of crisis” (Davies et al., 2021, p. 7), whereby science content is communicated by a diversity of actors such as scientists, science journalists, university PR professionals and more (Milani et al., 2019; Weitkamp et al., 2021) and there has been a growth in science PR and contraction of science journalism. In addition, we find a broad range of “new” communicators such as influencers, corporate communicators, activists or political actors who refer to science to make their voices heard in the noisy, fragmented and dynamic networked public sphere (Fähnrich, 2021). The emergence of new players, especially digital communication platforms that determine sociotechnical features such as algorithms which influence the distribution of public communication, presents further opportunities but also challenges for science communication.

These digital communication developments have been debated intensively in different fora and with different foci in recent years. However, there has been relatively little discussion of these changes in the context of science communication training. This is astonishing given that adequate training for those involved in science communication is essential for the quality of science communication in the long term (Baram-Tsabari and Lewenstein, 2017). The question then is how can training contribute to enhance science communication in the context of the digital science communication ecosystem? Moreover, little research has compared training across international (or at least European) contexts, making international differences in approach to coping with issues of the digital transformation within science communication training a relevant field of inquiry.

To address these issues three sub-questions come to the fore:

RQ1: What types of training do science communicators receive in different European countries?

RQ2: Which competencies are required in the changing science communication ecosystem?

RQ3: How well are existing programs across Europe suited to equip science communicators with required competencies?

To respond to these questions, this paper draws on data from the European project RETHINK and takes two approaches. First, we report on findings from a survey completed by 459 science communicators across seven countries (Italy, the Netherlands, Poland, Portugal, Serbia, Sweden and the United Kingdom) focusing on how science communicators develop their communication skills, the types of training they have received and the types of training they would like to undertake. Second, we present exploratory data collected from 13 science communication programs from seven European countries regarding how these seek to embed and consider the digital transformation within their training programs. On the basis of both analyses, this article will conceptually examine whether a multi-level training approach is better suited to prepare science communicators for the steadily changing science communication landscape and will introduce ideas for a competence framework that addresses not only working knowledge and skills but also professional (self-) reflection and the overall mindset of students.

Science Communication Training and Programs

Science communication training equips students with the ability to reflect certain circumstances of communication practices, for example topics they communicate or specific requirements of the platform they use (e.g., interactive features) (Howell and Brossard, 2020). Often, short training courses for scientists and practitioners teach practical communication skills, for example how to use media or how to approach audiences (e.g., Miller et al., 2009; Silva and Bultitude, 2009). In contrast, degree programs in science communication encompass theory and professional development in a more comprehensive approach (Mulder et al., 2008) and therefore can help to provide “a bigger picture” (Turney, 1994).

In both cases, research highlights the need to develop generalizable learning outcomes for science communication, especially with regard to different contexts of information and communicator roles (Baram-Tsabari and Lewenstein, 2017). Frequently, the need to understand societal and media changes is emphasized as these developments are crucial for science-society interactions. Furthermore, science communicators’ self-perceptions and an understanding of their roles in the new communication environment can be promoted through reflection on new relationships between science, society and the media (Pieczka, 2002; Baram-Tsabari and Lewenstein, 2017).

Although research on science communication training has been sparse, we acknowledge an increase in interest in both what science communication training comprises and how the quality of science communication training is evaluated (Silva and Bultitude, 2009; Rodgers et al., 2020; Akin et al., 2021; Dudo et al., 2021; Heslop et al., 2021).

Baram-Tsabari and Lewenstein (2017) identify a range of learning goals pertinent to science communication training programs (both short courses and degree programs); they argue for six broad areas in which communicators require training: affective, content knowledge, methods (practical skills), reflective practice, participation and identity. To these we might add an understanding of how people learn, a specific focus on assessing the credibility of information and skills in evaluation (Longnecker and Gondwe, 2014). There is also a strong emphasis on the need for science communicators to understand the audience (e.g., Longnecker and Gondwe, 2014; Longnecker, Forthcoming 2021). These broad categories offer a starting point to assess the training available to science communicators, though to our knowledge there is no comprehensive assessment of whether the training available addresses all of these aspects.

Digital Competences

Given the rapid increase in digital media, it is notable that neither Longnecker and Gondwe (2014) or Baram-Tsabari and Lewenstein (2017) explicitly highlight digital skills within training goals, instead embedding these within other categories. Nor do they address how science communicators' competences might need to expand to cope with the changes and challenges of science communication in the digital media landscape in general, or which competencies are needed for effective communication on these new platforms in everyday practice. Though a variety of training and degree programs do incorporate specific digital skills training, such as podcasting or blogging (Rifkin et al., 2010; Bartle et al., 2011).

In related fields such as journalism or public relations (PR) education we see comparable developments. In this regard, Pieczka (2002) distinguishes three levels of PR expertise that professional communicators need to encompass. Though writing in 2002, Piezcka addressed the rising importance of digital communication. She describes these competences on the basis of observations of communication training. The competence levels include the "picture of the world", the "conceptual frame" and "professional knowledge". Based on her research and observation, Pieczka (2002) describes societal changes due to digitalization and related demands for professional (science) communicators that are mirrored in their "picture of the world". To develop the picture of the world within training thus means to develop the mental models of students and the ways in which they perceive the changing media landscape and how it affects the conditions for the interaction of science and society. The second layer of the competence model refers to specific attitudes and norms that professionals take up to distinguish themselves from non-professionals. For instance, considering ethical standards and being aware of the importance of evaluating science communication would refer to this level of competences. Also being aware of one's and others' roles and related demands and being able to fill these roles are important competences. Moreover, according to Pieczka (2002), communicators need to be equipped with competences and skills to work in the digital world. This encompasses technical knowledge of the media and digital tools or practical skills to transfer communication through different channels. Following Baram-Tsabari and Lewenstein (2017), the will to keep up with new developments displays a dimension in its own which refers to this category. Developing these competences calls for the teaching of models, methods and techniques required in professional science communication. The competence levels developed by Pieczka (2002), and the agile nature of the framework, can be used basis to analyze science communication training.

Science Communication Trainers and Trainees

Research conducted on the perspectives of trainers has tended to focus on those who train scientists in public communication. This research suggests that trainers view scientists and researchers as seeking training to address individual goals (such as enhancing personal skills) and external goals (such as promoting the value of science), rather than communication oriented goals (such as building trust) (Besley et al., 2016). Possibly as a result of this view of trainees' desires, training does not always develop strategic communication skills or assist with creating and prioritizing objectives, often being more skills focused and concentrating on a relatively limited set of implicit objectives, such as increasing knowledge (Besley et al., 2016). Similarly, although trainers recognize the importance of two-way communication, Yuan et al. (2017) found trainers assess scientists as having relatively limited awareness of or interest in two-way communication approaches. As a result, trainers do not integrate these competences consistently in training programs, focusing primarily on the importance of understanding audiences as a means of achieving effective two-way communication. These studies indicate that trainers primarily focus on "professional knowledge" rather than "picture of the world" or "conceptual frames". In the context of the increasing importance of digital media, Yuan et al. (2017) argue that scientists' combined lack of interest and skills in two-way communication suggests few achieve real dialogue with their publics. The presence of educational and information-based goals in science communicators motivations, albeit alongside a desire to create conversations is something we have also identified in previous work (Milani et al., 2020).

Turning to scientists themselves, Altman et al. (2020) found scientists recognizing a need for training, though this was limited to practical skills, such as face-to-face communication and use of plain language, rather than strategic goals (all would be classed as "professional skills"). Similarly, in a study specifically focusing on online science communication, Besley et al. (2015) suggest scientists' value training in the areas of crafting understandable messages and ensuring trustworthiness rather than issues such as framing. Previous studies have suggested that scientists' use of social media for communication can be limited by a lack of knowledge as to how platforms work (Collins et al., 2016). Besley, Dudo and Storksdieck's study extends this to also suggest a perception that communication goals align with ethical goals, and is also an important aspect of scientists' willingness to communicate, which does suggest some interest in the conceptual framing of their activities.

Training Impacts

More recently we have seen increasing research that seeks to quantify, model and scale the impacts of training initiatives (Copple et al., 2020; Rodgers et al., 2020; Akin et al., 2021). Recent research exploring how training contributes to scientists' and researchers' propensity and ability to communicate has suggested mixed results, with inconsistent findings regarding the positive associations between a scientist's training experiences and their ongoing communication intentions (Silva and Bultitude, 2009; Copple et al., 2020). However, Copple et al. (2020) model based on a survey of over 500 scientists working at United States universities found that training can influence willingness to engage by building confidence, contribute to more positive attitudes towards audiences, and that the more training a scientist receives, the more willing they are likely to be to engage. Stylinski et al. (2018) also identified multiple benefits, including that training can assist scientists to build their communication strategies, have more confidence in their abilities, and encourage them to engage more frequently. Research has also identified that communication training can have positive aspects on other areas of a researcher's work, such as teaching and presenting in general (Illingworth and Roop, 2015; Stylinski et al., 2018). However, most research or evaluation of the impact of training has focused on the impacts that trainers or trainees perceive, rather than whether audiences perceive improved communication skills as a result of training (Rubega et al., 2020). Several authors have highlighted the importance of considering all the beneficiaries of training, which includes the audiences who participate in communication activities undertaken by trainees (Rodgers et al., 2018; Rubega et al., 2020).

Training Gaps

In regard to current training provision, a variety of critiques have been made. This includes that training is often too focused on specific communication techniques, as opposed to the broader goals or strategies for communication, which may have longer-term impacts (Besley et al., 2016), and that relatively few trainers are focusing on equality, diversity and inclusion (EDI) topics (Heslop et al., 2021). In the United States and United Kingdom, attendees tend to be self-selecting and lack cultural and ethnic diversity, and whilst trainers may equip trainees with how to communicate, this rarely extends to locating opportunities to communicate (Dudo et al., 2021; Heslop et al., 2021), though there are examples of innovative training programs designed to enable scientists to reach out to underserved audiences (Weber et al., 2021). There is also a recognized need for both further evaluation of the impacts of training, including by specific programs (Dudo et al., 2021), and increased professional recognition for the trainees that are involved (Illingworth and Roop, 2015). Nevertheless, trainers themselves have mixed feelings about accreditation of training programs (Heslop et al., 2021).

However, many of these gaps and criticisms have been drawn by the science communication community itself, rather than reflexive insights of those involved in training, or longitudinal consideration of impacts. Much of the evidence around science communication training has also currently focused on training aimed at scientists and researchers communicating as a part of their career (Miller et al., 2009; Besley et al., 2016; Copple et al., 2020; Akin et al., 2021; Weber et al., 2021), as opposed to those who may be specifically working as science communicators, though a few studies of training in specific contexts, such as informal science learning, do exist (e.g. Walker et al., 2020). There is also a tendency to focus on specific countries, with many studies of science communication training currently emerging from the United States context with few studies that explore training provision in developing countries (Walker et al., 2020) or non-western contexts (Ishihara-Shineha, 2021).

In addition, our knowledge of the overall development of science communication training against the backdrop of the digital transformation is sparse. The same applies to international comparisons of science communication training (Mulder et al., 2008). However, science communicators, which can include scientists, researchers, curators, and journalists but also new types of science related content producers such as influencers, activists, corporate communicators or political actors (Fähnrich 2021), may require new types of preparation and support to engage with multiple audiences, particularly in the context of the digital transformation. The diversification of communicators and new logics of public attention are influencing the working conditions and day to day routines of those involved in science communication and related competences that should be taken up in science communication education and training.

MATERIALS AND METHODS

Survey of Science Communicators

To address the first and second research question - types of training that science communicators have (RQ1), and required competences and training (RQ2)—a survey was conducted in seven countries—Italy, the Netherlands, Poland, Portugal, Serbia, Sweden and the United Kingdom. These countries were selected on the basis of project partners' locations and access to science communication networks and communities within those geographical countries and we recognize the focus is limited to Europe.

The survey aimed to investigate the working practices, motivations and barriers faced by actors communicating science, technology and/or health. It also analyzed the sources they used, how they curate content, and consider the audiences they are working with, as well as the training they had and would like to receive (Milani et al., 2020; Milani et al., 2021). The questionnaire included several questions adapted from previous surveys and studies of scientists, those who enable science to be communicated, such as press officers, as well as science journalists (Royal Society, 2006; TNS-BRMB, 2015). The questions were also informed by a previous scoping study conducted as part of the RETHINK project (Milani et al., 2019).

The questionnaire was developed in Qualtrics, and pilot-tested with 22 respondents. After editing to incorporate feedback from the pilot, the questionnaire was then translated and uploaded to Qualtrics to collate the responses from the seven countries. The final questionnaire was distributed between September and November 2019 via official mailing lists, networks, associations, and societies of journalists, writers, press officers, communication officers, scientists, and public events organizers that communicate science. Snowball sampling was also applied and individuals identified in the scoping study (Milani et al., 2019) were contacted to enrich the diversity of participants. The variety of ways in which participants were recruited means it is not possible to estimate a response rate and any percentages we present should be viewed in the context of the sample size. Univariate and bivariate analysis was conducted using excel and SPSS. The questionnaire received ethical approval from UWE Bristol, and included GDPR compliant consent and information materials.

Exploratory Study of Science Communication Programs

To respond to RQ3—how well are existing programs suited to equip science communicators with required competences?—we used an exploratory approach to analyze the content of 12 science communication programs in seven European countries including Germany, Italy, the Netherlands, the Portugal, Russia, Sweden and the United Kingdom (Fähnrich, 2020). For reasons of comparability, our sample comprised only science communication degree programs offered by universities (undergraduate and graduate level). These academic programs run over a longer period than short course training programs (for instance, usually four semesters at postgraduate level) and are organized in a modular approach.

To explore the content provided in the curricula and to see how the programs addressed demands and challenges of science communicators against the backdrop of the digital transformation, we contacted program managers of 43 programs in the selected countries via e-mail and invited them to take part in an online survey with open and closed questions.

The questionnaire was developed on the basis of the theoretical categories of learning outcome and competence by Baram-Tsabari and Lewenstein (2017) and Pieczka (2002). The focus was on the role of digital media and the ways in which the digital transformation was addressed in the programs. Moreover, we wanted to understand how courses prepare students to adapt their communication to the digital information environments and thus address different levels of competences beyond mere skills. More specifically, we asked about the general orientation of programs towards theoretical or practical skills and about the importance of digital media and related developments in curricula. Furthermore, we were interested in capturing to what extent specific elements of digital media such as diverse audiences and interactivity were captured by programs. Therefore, we presented a list of aspects describing digital media and asked participants for their agreement about the inclusion of these in their programs. Greater detail on how students are trained to cope with developments in digitalization was sought through an open response format.

Different roles for science communicators mentioned in related literature (Pielke, 2007; Fahy and Nisbet, 2011) served as the basis for a question on skills development. Furthermore, the questionnaire sought general program information, such as introduction and validation of courses, number of students graduating per year and common employment fields for graduates. Respondents completed the questionnaire by indicating their position, their disciplinary background, as well as experience and sociodemographic information. Data collection took place in October 2019. We conducted the online survey with the platform "Soscisurvey". Overall, we collected 13 responses from 12 programs from Italy (2), the Netherlands (2), Portugal (3), Russia (2) and the United Kingdom (3). All of these are graduate programs at masters level which require students to already have an academic degree (M.A., N = 3; M. Sc., N = 7; other graduate degrees, N = 3). Programs are taught in English (8) and/or Dutch (2), German (1), Italian (1), Portuguese (3) or Russian (2).

RESULTS

Training, Expectations and Needs of Science Communicators

Of the respondents (total n = 459) to the science communicators' questionnaire, over half were female (59%, n = 272) and 40% (n = 182) were male. The higher response rate from females occurred in most countries, except Poland, where females accounted for 40% (n = 11) of the respondents. The majority of respondents (84%) were under 45 years old; 31% (n = 141) were 35–44 years old, 30% (n = 136) were 25–34 years old, and 3% (n = 12) were 18–24 years old.

When asked about their professional roles, many respondents described themselves as working as press officers or communication officers, freelance communicators or writers, journalists, and/or researchers. The survey also reached actors who might be considered relatively recent additions to the science communication landscape, such as bloggers and social media influencers, activists, illustrators and designers. Eighty five percent (n = 388) of respondents worked for an organization rather than individually. Of these, 52% (n = 202) worked for universities and research centers, 14% (n = 54) for museums and science centers, 10% (n = 40) for non-profit organizations and charities, 6% (n = 23) for media and publishers, 5% (n = 19) worked in the business sector and 3% (n = 12) for professional associations and learned societies. Well over half (63%, n = 74) of the freelance communicators or writers said they work for an organization as well; with universities and research centers being the most common sources of employment.

Turning now to training, we asked respondents how they had developed their communication skills to convey science, technology and/or health topics (**Figure 1**). Almost three quarters of respondents (73%, n = 336) indicated that they had developed their skills through experience in public engagement or communication, whilst watching and learning from others also appeared to be important, with 57% (n = 260) of respondents indicating that they have watched how other people (either professionals or amateurs) communicate with non-specialist audiences. Thirty four percent (n = 156) of respondents also indicated other communicators and/or journalists had informally mentored them. These results combined suggest there is still a strong component of informal training, learning by doing and from others, taking place in science communication as an approach to build competence.

In regard to more formal training, just under half of respondents (48%, n = 221) indicated that they had received training in public engagement or communication, whilst 28% (n = 130) of respondents had or were completing a degree in journalism, media or science communication. A similar number of respondents (31%, n = 143) also indicated that they had consulted resources such as books, handbooks, blogs, and YouTube videos to develop their science communication skills. Finally, 51 (11%) respondents indicated that they had developed

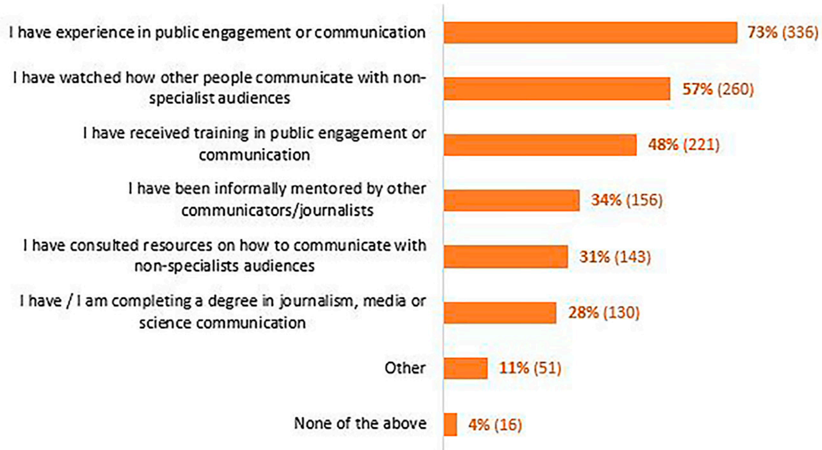

FIGURE 1 | Development of communication competences to convey science, technology and/or health topics. Respondents could select multiple answers.

TABLE 1 | Development of communication competencies to convey science, technology and/or health topics by country. Respondents could select multiple answers. Note: The variety of ways in which participants were recruited means it is not possible to estimate a response rate and any percentages we present should be viewed in the context of the sample size.

	United Kingdom	Netherlands	Sweden	Portugal	Italy	Poland	Serbia
I have experience in public engagement or communication (e.g. writing, public speaking, social media)	98 (80%)	38 (61%)	32 (73%)	75 (86%)	45 (58%)	22 (76%)	16 (64%)
I have watched how other people (either professionals or amateurs) communicate with non-specialist audiences	79 (65%)	27 (43%)	24 (54%)	47 (54%)	31 (40%)	26 (90%)	16 (64%)
I have received training in public engagement or communication (e.g. writing, public speaking, social media)	71 (58%)	20 (32%)	20 (45%)	48 (55%)	39 (51%)	11 (38%)	4 (16%)
I have been informally mentored by other communicators/journalists	47 (38%)	24 (39%)	13 (29%)	26 (30%)	25 (32%)	5 (17%)	10 (40%)
I have consulted resources on how to communicate with non-specialist audiences (e.g. books, handbooks, blogs, YouTube videos.)	45 (37%)	17 (27%)	11 (25%)	32 (37%)	16 (21%)	9 (31%)	6 (24%)
I have/I am completing a degree in journalism, media or science communication	34 (28%)	25 (40%)	12 (27%)	28 (32%)	19 (25%)	4 (14%)	2 (8%)
Other, please specify	16 (13%)	4 (6%)	8 (18%)	7 (8%)	9 (12%)	5 (17%)	0 (0%)
None of the above	7 (6%)	1 (2%)	1 (2%)	3 (3%)	1 (1%)	0 (0%)	3 (12%)

their skills in other ways. Comments in response to this question included that they were self-taught, used networking to develop skills, had built up professional experience or had experience in the disciplines they were communicating. Only 16 respondents said they had completed none of these activities in relation to their skills development.

Examining this question in conjunction with the gender of participants and the country in which they were located, there are some small variations to note. Gender appeared to play very little role in the likelihood of participating in certain types of training. Percentages of women and men developing their skills via experience in public engagement or communication, watching and learning from others, through training in public engagement or communication, and via the consultation of resources were within 1–2% of each other when analyzed. However, more women recorded that they had or were completing a degree in journalism, media or science communication (32%, n = 86 of female respondents compared to 22%, n = 40 of males) and women (35%, n = 95) were also slightly more likely than men (32%, n = 58) to have taken up mentoring.

There also appeared to be some minor differences in terms of training in relation to where communicators were based (**Table 1**). Experience in public engagement or communication was the most common way to increase skills across all countries. However, uptake of formal training, including training in public engagement or communication was more common amongst communicators in Italy (51%, n = 39), Portugal (55%, n = 48) and the United Kingdom (58%, n = 71), whilst completing a degree in journalism, media or science communication was more evident in countries including the Netherlands (40%, n = 25) and Portugal (32%, n = 28). Although the response rate was lower from Serbia, these communicators mainly build their skills via experience (64%, n = 16), watching others (64%, n = 16) and informal mentoring (40%, n = 10) with fewer communicators participating in training (16%, n = 4) or formal degree programs (8%, n = 2).

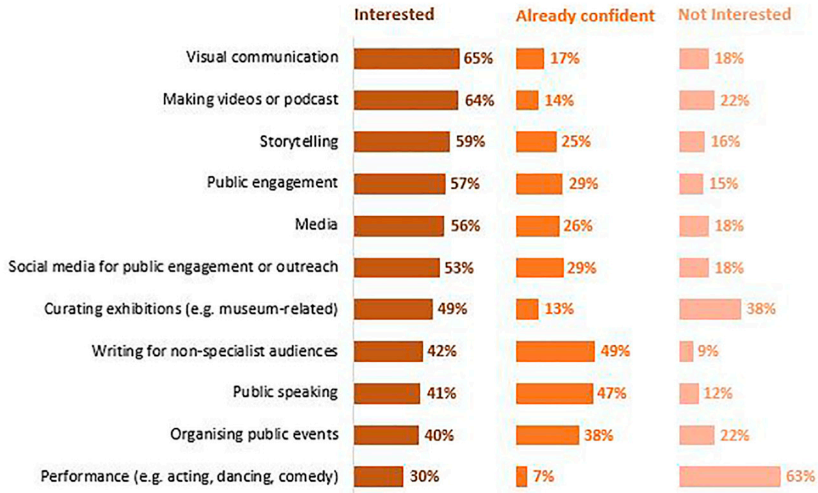

FIGURE 2 | Areas of training in communication and public engagement that respondents would be interested to undertake. Respondents could tick multiple answers.

Although the recording of a degree in journalism, media or science communication was relatively scarce amongst our respondents, the majority of those completing the survey did have a background in science, technology, engineering, math or health. Three quarters (75%, n = 343) of respondents had studied at school, 58% (n = 269) had or were completing an undergraduate degree, 40% (n = 186) had or were studying a postgraduate degree, and 34% (n = 158) were completing a doctorate in one or more of these subjects. Eighteen percent (n = 83) of respondents indicated they were self-taught when it came to science, technology, engineering, math or health.

We asked about the focus of training they had received and 214 respondents completed this question. The most common training areas were: public speaking (66%, n = 142), writing for non-specialists (65%, n = 139), and media training (60%, n = 129). 50% (n = 107) had received public engagement training, with 48% (n = 102) having some form of training in social media, and similarly, just under 100 respondents (48%, n = 98) had training in storytelling. Training in the organization of public events (40%, n = 86), making videos or podcasts (33%, n = 70) and visual communication (31%, n = 67) were also evident, whilst 20% (n = 43) had training in curating exhibitions, and 14% (n = 31) also had training in performance. Twenty five respondents indicated training in other areas; this included journalism, data mining and analysis, statistics, and scientific animation.

We also took the opportunity within the survey to ask about the areas people would like training in (**Figure 2**), with many responses coinciding with aspects of the training already undertaken to a lesser degree by others in the previous question. Visual communication (65%, n = 272), making videos or podcasts (64%, n = 271), storytelling (59%, n = 248), public engagement (56%, n = 234), media training (56%, n = 234) and social media for public engagement or outreach (53%, n = 224) were indicated to be of interest by over half of the respondents to this question. The remaining categories all proved popular amongst some respondents, though training in performance was the least popular option (30%, n = 124) which may be reflective of the high number of respondents working in areas such as journalism, public relations and blogging who may not require skills to directly interact with the public.

We also provided the opportunity for respondents to suggest areas of training they would like to receive, which had not been listed or discussed in the survey. Responses to this question included training in web design, statistics, publishing including the production of magazines and books, teaching, working with young people, financial aspects of project management including fundraising, as well as public-centered design and how to involve people in research not just communicate to them.

One respondent also suggested that training in how and for whom science communicators should evaluate their work was important: "Assuming that we do it seriously and not as a hobby once a year, it becomes an important barrier or springboard for action". In a further question on the survey we asked respondents specifically about their experience in evaluation. Almost three quarters (70%, n = 313) of respondents said that they personally, or others they worked with, gathered evaluation data. Of the 25% (n = 114) of respondents who said they did not gather evaluation data, 8% (n = 38) said they did not have evaluation skills. The remaining respondents either reported that they did not have the time to undertake evaluation (10%, n = 47), or that it was not relevant to their work (6%, n = 29) suggesting this is not an issue of training alone.

Competences Taught in Science Communication Programs

Turning to the question of how science communication programs equip science communicators with required competences, we now take a closer look at those programs across Europe. Due to the exploratory nature of our study, we cannot say much about differences in training and also have refrained from indicating national differences. Rather, our attempt is to give a general impression of how programs address competences required for contemporary science communication.

The sample of respondents consists of 13 participants; their position in the organization can either be described as program managers (n = 11) or lecturers (n = 7) or as a combination of these occupations. Men and women were roughly equally represented (46 and 54%). Concerning different age groups, most individuals were between the age of 40–59 (n = 9). Their highest academic qualifications were Master (n = 2), Doctorate (n = 10) or other postgraduate degrees (n = 1). Regarding experience in science communication, they stated work experience of 5–10 years (n = 4), 11–15 years (n = 2), 16–20 years (n = 2) or over 20 years (n = 4) in the field. With respect to how long they had been teaching science communication, there were slight differences. 5–10 years was stated by 5 individuals, 11–15 years by 2 individuals, 16–20 years by 2 individuals and over 21 years by one respondent. Furthermore, the respondents showed a diversity of disciplinary backgrounds from which they draw their experience, including sociology or Science and Technology Studies (n = 4), communication science and media studies (n = 7) or physical and life sciences (n = 7).

The 13 programs that were involved in our exploratory study were introduced between 2000 and 2010 (N = 4) or between 2011 and 2019 (N = 7). One course had been running since 1993, whilst for one course it was not clear when the program was introduced (one respondent provided a "don't know" answer to that question). Most of the programs were evaluated and revised on a regular basis. We also asked for the number of graduates of these science communication programs; these ranged from 10 to 25 students per year, with most of the programs running with approximately 20 students. Most graduates work in communication related fields, specifically in strategic communication, journalism and media production and presenting. Other common employment amongst graduates included teaching/tutoring, administration, management, research, museums and science centers or scientific publishing. We asked surveyed program managers for the content of curricula of their science communication programs, especially with regard to the competences taught and the ways in which programs address the changes seen in science communication due to the digital transformation.

We first investigated to what extent different kinds of competences and knowledge are taught in programs by asking about learning goals. Results show that both science communication knowledge, such as knowing the public sphere and the media system, and competences to build a trustful relationship with audiences are seen as highly relevant for graduates in the field. Affective goals, for example to experience excitement about one's profession, are also desirable outcomes as is the capacity to think outside the box. Moreover, results show that all of the master programs deal at least to some extent with the digital transformation and related implications for science communicators (**Figure 3**). However, their perspectives differ as to how much attention this is given. One third of program managers emphasize that the digital transformation of science communication is such an important and pervasive topic that it is part of the entire curriculum and integrated into every module, whereas other program managers explain that digital media are only taught in parts of the program.

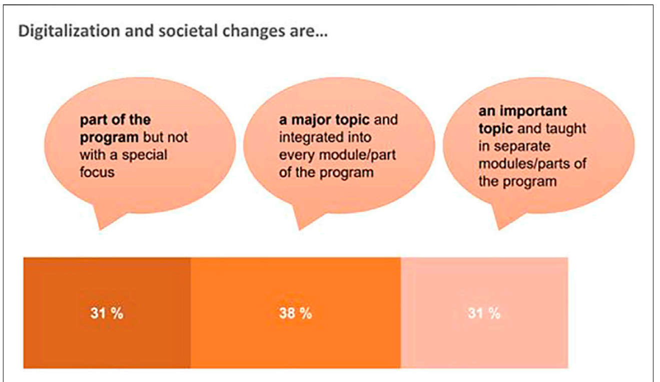

FIGURE 3 | Relevance of digitalization and related changes in the surveyed programs, in %; N = 13.

Overall, participants answered that their programs were either practical skills oriented (6 mentions) or equally theoretical and skills oriented (7 mentions) which indicates that working knowledge is regarded as the most important level of competences taught in most cases.

However, our research shows that most of the programs still address different levels of competences, which are required to perform as a professional communicator in the complex and digitalized science communication landscape. Most program managers indicate that curricula are developed to educate students for communicator roles that foster interaction between science and the public, rather than serving as traditional gatekeepers (**Figure 4**). The "mediator role" is considered especially important to serve the need for interactive communication in digital contexts. However, traditional journalistic role perceptions like agenda setting or gatekeeping/-watching, with science communicators primarily "watching" and editing external information for audiences, still remain important for some program managers. These traditional science communication roles indicate that the conception of science communication as expressed in the deficit model is still prevalent in some programs.

An important part of science communication practice is to recognize the risks and opportunities of public communication. Against this backdrop, we asked how programs address the development of competences. Our results indicate that programs anticipate the features of digital communication, thus referring to interactivity, diversity of communicators and audiences. Also, programs highlight opportunities afforded by digital media like diversity of content or positive impacts on public engagement, as is the need to be aware of critical aspects like the strategic misuse of communication. According to surveyed program managers, students are encouraged to develop critical thinking, and are trained to be able to evaluate scientific information and its reliability, as well as to assess the

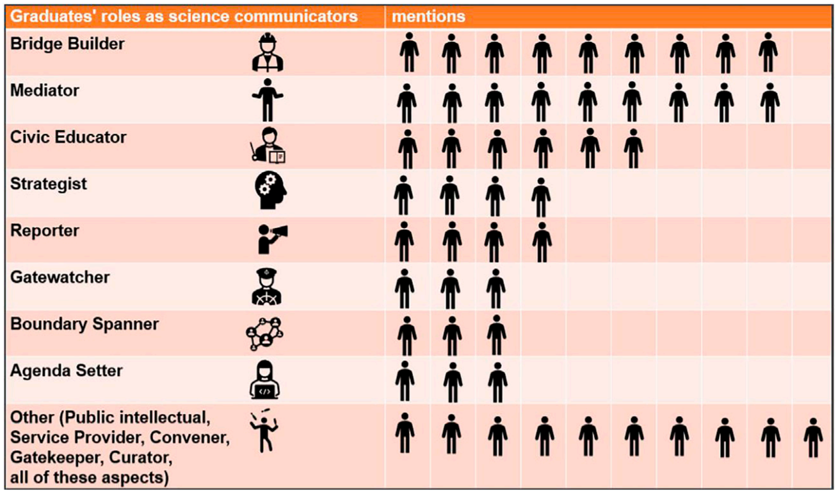

FIGURE 4 | Graduate roles as science communicators up to five mentions.

reliability of different types of sources. Furthermore, we were interested in capturing specific elements of digital media, such as whether programs address opportunities to reach diverse audiences and interactivity. The research suggests that most programs consider the availability of different multimedia content, the need for diversity of communicators and perspectives, as well as the diversity of audiences on digital platforms. Other dimensions of the internet environment, for example currency of information and interaction possibilities, received moderate support which means that these issues are included to a lesser extent in programs.

DISCUSSION

Previous research into science communication training is fragmented, with much literature focused on the training experience and needs of scientists. Little work has explored the training experiences of a broader range of science communicators, with little known about the ways in which "new" communicators, such as social media influencers, corporate communicators or activists acquire their skills and knowledge. Similarly, there is no standard curriculum for science communication postgraduate programs (e.g. Davies and Horst, 2016; Bankston and McDowell, 2018), though propositions for curricula exist (e.g. Longnecker and Gondwe, 2014). Our research has sought to fill this gap by exploring the ways in which a broad range of science communicators acquire competence in science communication and their perceptions of training needs. This has been combined with an explorative survey of European postgraduate science communication programs. In framing this discussion we return to the approaches articulated by Baram-Tsabari und Lewenstein (2017) and Pieczka (2002), seeking to enunciate a framework in which competences could be understood.

Pieczka (2002) outlines three mutually enforcing layers of competence, which we have reformulated for science communication drawing on the work of prior scholars and exploring the ways in which these competences are illustrated through our data. These are organized as "working knowledge", "professional norms and roles", and "picture of the world". **Table 2** gives an overview of competence levels and how they can be addressed in science communication training.

"Working knowledge": this refers to the communication skills (e.g., writing for non-expert audiences) and knowledge of communication tools (e.g., specific digital platforms). Responses to our survey of practitioners suggests that, like scientists (e.g., see Besley et al., 2016; Altman et al., 2020), practitioners tend to focus on acquisition of specific skills in communication, though these may be different skills than those sought by scientists. Altman et al. (2020), for example, identifies scientists as seeking skills around the use of plain language or face-to-face communication, while survey respondents focused on areas such as training in visual communication, making videos and podcasts or storytelling. Open responses to the survey also tend to focus on core "doing" skills, rather than conceptual knowledge (picture of the world) or professional roles. A similar picture is seen in the focus of science communication postgraduate programs, with nearly half indicating their program as primarily skills oriented.

Baram-Tsabari and Lewenstein (2017) highlight that this working knowledge must keep up with new developments, which would include developments in digital technologies. Within this context it is notable that practitioners tended to focus on specific skill sets rather than the tools or conceptual knowledge that would be needed to critically engage with the rapid transformations taking place. All of the postgraduate programs surveyed focused on digital skills, though the extent to which these were integrated or feature as distinct modules varied. Nevertheless, program managers were concerned about developing skills relevant to digital contexts, such as

TABLE 2 | Competence layers as basis for science communication training (adopted categories from Pieczka, 2002).

Competence level	Refers to	Develops through
Picture of the world	–Overall "mental models" –Perceptions of the changing societal framework in which science communication takes place and how it affects the conditions for the interactions of science and society	–Offering new insights and perspectives –(Guided) observation and reflection –Challenging existing mind sets and world views
Professional norms and roles	–What it means to be "professional" –Guiding norms, values, demands and role models developed by science communication as a field of practice –Self-perceptions and others' perceptions of roles	–Getting to know and adapting professional standards –Interaction, (self)reflection, feedback, developing and adjusting of professional attitudes
Working Knowledge	–Skills and practical knowledge –Capability to deal with technical, strategic and operational demands of every day science communication practice	–Getting to know models, methods and techniques –Practical training, e.g. use of examples and application to other cases –Analyzing problems and failures and searching for ways of improvement

understanding of interactivity, as well as the nature of digital audiences.

"Professional norms and roles": Following Pieczka (2002) idea of the "conceptual frame" and other authors, competences in this area can refer to specific attitudes that distinguish professional communicators from others. For instance, applying integrated communication on different channels (Longnecker, 2016), considering ethical standards (Besley et al., 2015) and being aware of the importance of evaluating science communication (Jensen, 2014), might be considered professional norms. In this context, it is encouraging that the majority of practitioners responding to the survey undertake evaluation of their activities. Practitioners responding to the survey highlight a number of informal ways in which they acquire science communication expertise, including through watching and learning from others, informal mentoring and degree programs, all of which might be expected to play a role in learning and developing an understanding of professional norms and roles. Nevertheless, relatively few have undertaken formal qualifications in journalism, media or science communication. Within this context, based on our surveys, we argue that being aware of one's own and others' roles and related demands (e.g., knowledge broker, curator, bridge builder, enabler) and how to fill these roles may also be considered as important competences, competences which might be acquired through observation and mentoring within training. Our results also suggest science communicators develop these competences formally, within taught programs through learning approaches that foster interaction and self-reflection and allow for feedback, development and adjustment of professional norms and roles.

Yuan et al. (2017) suggest that scientists have limited understanding or interest in two-way methods of science communication, and as a result that few are likely to achieve real dialogue with their publics. There was considerable variation amongst our survey respondents as to whether they had received training in public engagement or communication, and we recognize that definitions of these approaches can vary, but it is encouraging that over half of respondents identified this as an area in which they would like training. Furthermore, program leaders indicate that graduates tend to take on roles that foster interaction, such as bridge builder or mediator, rather than more traditional "translator" roles such as gatekeeper, suggesting that formal education has a role to play in fostering and developing professional norms in the field. A further aspect of professional norms which has been identified particularly in a digital context is a concern with the ethics of communication (Besley et al., 2015). Although not directly raised by survey respondents or program managers in this research, this is an important facet of competence in the area of professional norms and roles.

Turning to "Picture of the world": science communication is currently contending with societal changes due to globalization and digitalization and these are creating associated demands for professional (science) communicators. Emerging formats for science communication are characterized by activity and pace and their ability to allow citizens to take part in an environment with "new orders of knowledge" (Neuberger et al., 2019). These provide positive effects like new fora for deliberation and more flexible modes of communication but there are also risks that science communicators should be aware of, for example the misuse of science related information. The COVID-19 pandemic has demonstrated not only the vital role of science communication in public health and combating misinformation, but also how social inequalities, in who has both access to and how communities are served with information, remain during such times of crisis (Judd and McKinnon, 2021).

We observe that many of the practitioners responding to our survey had backgrounds in the natural sciences. At this stage it is unclear to what extent this background shapes their picture of the world, but it seems likely that many practitioners engaging in science communication will be science enthusiasts. Equality, diversity and inclusion have previously been identified as issues that need to be addressed in science communication (Dawson, 2019) and which are often missing from training programs (Heslop et al., 2021). Responses from program managers suggest that a focus on inclusion and diversity (both of communicators and audiences) is a focus for education, though based on our survey responses, practitioners may not pro-actively demand training in this area.

For science communication programs and trainers to develop science communicators' picture of the world means to develop the mental models of students and the ways in which they perceive the changing societal framework in which science communication takes place and how it affects the conditions for the interaction of science and society. Competences that refer to the picture of the world can be developed by offering students new insights, by taking on new perspectives, by supporting them to make their own observations and reflect those and by challenging mindsets and world views in the context of interactional approaches. Digitalization may offer opportunities for a wider range of communicators to contribute to the science–society discourse, though it remains unknown whether this will be a more inclusive space. There remain important questions around misinformation in social and digital media and how this is regulated, but in the meantime we may require science communication training not only to be more agile but also open, reflexive and responsive (Roedema et al., 2021). Further, new tools may offer ways to include more diverse audiences in the conversation; whether this promise can be enacted needs further analysis.

Our results are limited, due to the exploratory nature of our study and the focus on a small number of European countries. Though we extended our survey of science communicators to a broader range of science communicators than some past work on the context of training, and we were also able to access programs throughout Europe, we also recognize limitations in the self-reported nature of our results. Therefore future studies on a more representative European sample, as well as a wider range of cultural settings, would be beneficial. The survey of science communicators' data also formed part of a much wider questionnaire encompassing the motivations, working practices and constraints communicators work under, affording limited opportunity to ask specific questions relating to Piezcka's three levels of expertise. So while this aspect of the analysis should be treated as exploratory, it still provides useful insights.

The creation of one centralized online resource with course information could also be a useful starting point to further consider programs against this model (Bankston and McDowell, 2018). Those training resources could be tested in future studies to evaluate whether these would improve learning outcomes.

Our research provides a starting point for the development of a competence framework that draws on the experiences of science communication professionals and the curricula offered through science communication degree programs. In this context, we have specifically focused on the ways that science communication training can contribute to equip prospective science communicators with competences needed to cope with the demands posed by the complex digital media landscape. These results point to the usefulness of comparing programs and training in different countries, albeit all European, in order to ascertain understanding and knowledge of science communication training, as well as the value of researching the views of both trainers and science communicators themselves.

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 UWE Bristol and Zeppelin University. The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

BF, CW, EW, LH, AR and EM contributed to conception and design of the study and analysis of data. BF, CW, and EW wrote the first draft of the manuscript. LH and EM designed figures and contributed to the first draft of the manuscript. All authors contributed to manuscript revision, read, and approved the submitted version.

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Using African Indigenous Languages in Science Engagement to Increase Science Trust

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1 INTRODUCTION

In 2018, The Wellcome Global Monitor reported that only an average of 15.6% (average calculated from chart 3:1) of the African population have high trust in scientific institutions and scientists (WGM report, 2018). This report (p. 58) cited two primary factors associated with the level of trust of a person in scientists: 1) learning and understanding science at school or college and 2) confidence in key societal institutions (the government, military, and judiciary). In a study interrogating how courtroom linguistic choices impact confidence in the institution of the justice system, Liu and Baird discovered that confidence levels are lowest when only a majority language is used in the courtroom, and that use of either a minority language and/or a *lingua franca* increases confidence levels in the judicial institution (Liu and Baird, 2012). Examination of both teacher (Alidou et al., 2006; Njoroge, 2011; Kibirige and Mogofe, 2021; Semeon and Mutekwe, 2021) and student performances (Prophet and Dow, 1994; Rollnick and Rutherford, 1996; Manzini, 2000; Mwinsheikhe, 2002; Brock Utne, 2004; Mammino, 2010; Mahlasela, 2012; Charamba 2019) using more familiar languages as opposed to Western languages has consistently shown increased understanding of scientific concepts. Students taught in languages familiar to them also produced better results in exams and there were fewer repeaters (Wilmot, 2003; Bender et al., 2005; Alidou et al., 2006; Kioko et al., 2014).

Policies that address the importance of using "understandable" or "familiar languages" to discuss science topics have been proposed in documents like the Lagos Declaration and Call to Action on Science Communication and the Public Learning and Understanding of Science (PLUS), which was produced during the 2nd African Conference on Emerging Infectious Diseases and Biosecurity in 2016 (African Gong, 2016). This concept is also addressed within "Priority 3" and expanded in chapter six of the 10-year Science, Technology, and Innovation Strategy for African Union (2014) (STISA-2024), which was drafted during the 23rd Ordinary Session of African Union Heads of State and Government Summit in June 2014 (African Union, 2014). Thus, we believe that if we continue to encourage a commitment to promote science and its implications in daily life, culture, and environment (science engagement) in more African indigenous languages (AILs), then understanding, confidence, and ultimately trust in science across large audiences on the African continent will increase.

1.1 Status of science engagement on the African Continent

Historically, while there have been science engagement efforts in Africa, they have not been without barriers (Joubert, 2001; The African Technology Policy Studies Network, 2010). An assessment (Ndlovu et al., 2016) of the science engagement of African researchers from a prominent university in Zimbabwe cited barriers such as 1) precarious research funding which can lead to low priority of science engagement, 2) low institutional rewards, 3) government censorship of certain research topics in the public domain, 4) perceived low public science literacy, 5) lack of training programs to equip academics with science communication skills, and 6) high teaching loads and lack of time that prohibit extracurricular activities. Other barriers include the challenge of making science engagement materials in the many languages on the continent (The African Technology Policy Studies Network, 2010; Karikari et al., 2016). Additionally, many past science engagement programs in Africa have used models that are tailored to Western donor mandates and little to no relevance to the local context (The African Technology Policy Studies Network, 2010, p 23–24), or are largely one-time events with no long-term evaluation, coordination, infrastructure, or sustainability plans (Joubert, 2001).

In recent years, there has been an increase in impactful science engagement initiatives both at the nonprofit and institutional level. At the nonprofit level, some of the organizations doing meaningful science engagement all around Africa include: Eh! Woza, ProjeKt inspire, Yiya Solutions, Ikala STEM, Practical Education Network (PEN), Global Lab Network, Super Scientist, Travelling Telescope, Mavis Talking Books, MOBILELABO, PlayAfrica, Under the Microscope (UTM), New Education for Radical Development (iNERDE), Fun and Education Global Network (FEGNe), and The STEM Impact Center Kenya, to name a few (Stephanie Okeyo, personal communication, September 28, 2021). There has also been an increase in science, technology, engineering, arts, and mathematics (STEAM)-based mainstream media television shows for children like Ubongo Kids and Super Sema. To equip and train science engagers, there are institutional programs like the Training Center in Communication at the University of Nairobi (Okeyo, 2021), the Centre for Research on Evaluation, Science, and Technology (CREST) at Stellenbosch University, and workshops from the Pan-African Network for the Popularization of Science and Technology and Science Communication in Africa (African Gong).

1.2 Strides to increase the feasibility of science engagement in African indigenous languages

1.2 1 Strategies to overcome the barrier of language multiplicity on the continent

The first glaring topic to address regarding feasibility of science engagement in AILs is the fact that there are over 2,000 African languages (Obanya, 1999; Skutnabb-Kangas et al., 2003). Which languages should be used and why? Linguists have categorized African languages based on: 1) languages that are common across multiple countries, yielding ~20 or so languages called "inter-African" languages (Appendix C; UNESCO, 1981; Roy-Cambbell, 2006), 2) the highest number of language-speakers, which generates a list of ~10–15 languages which are spoken by over 15 million speakers each (Appendix B; Roy-Campbell, 2006), and 3) language harmonization, where languages are grouped in linguistic families, and common orthographies are developed (Prah, 2003 p 27; Appendix B; Roy-Cambbell, 2006). Thus, while indeed there are many languages spoken in Africa, there are ways to pick regionally relevant languages to use for science engagement.

1.2.2 Resources that will increase throughput of translation for science engagement in African indigenous languages

The next concern to address is the issue of translation. To develop fast, accurate, and accessible translation of technical content in different AILs, we think that this process must be automated. The organization (Ghana, 2020) NLP (Natural Language Processing) is one of many organizations developing matched lists of words and sentences that allow a computer to connect and correlate meanings in two or more languages. In January 2021, this organization developed a parallel bilingual machine translation training corpus for English and Akuapem Twi, spanning 25,421 sentence pairs in total (Azunre et al., 2021a; Azunre et al., 2021b). The social enterprise Zindi regularly hosts competitions to generate data sets that can be used to train computers to translate African languages. So far, they have received training data set contributions from African data scientists that cover the Wolof (Senegal), Hausa, Igbo, Yoruba (Nigeria), Fongbe, Ewe, Kabiye (Benin and Togo), Tunisian Arabic (Tunisia), Kiswahili (Kenya and Tanzania), and Chichewa (Malawi) languages (Zindi, 2020, 1st Round of A14D-African Language Data-Set challenges, 2020).

Additionally, the pan-African Open Access platform *AfricArxiv* recently announced a "Decolonize Science'" project in collaboration with the NLP research organization Masakhane. In this project, they aim to translate original research papers into six diverse African languages that include isiZulu, Northern Sotho, Yoruba, Hausa, Luganda, and Amharic (Obanda, 2021; Wild, 2021). Translating technical subject matter in different languages is also under way at the FAO (Food and Agriculture Organization) of the United Nations (AGROVOC, 2021).

1.3 Do African indigenous languages contain the range for technical Discourse?

Digital translation capacity is all well and good, but someone might ask: "Can AILs convey scientific concepts?" Broadly, there are several ways that scientists introduce words to scientific lexicon: 1) words with two meanings (For example, the word "ring" can have two meanings depending on context: mathematics or jewelry. People with an academic background in mathematics have that in mind. For nonmathematicians, this is a prime opportunity for a science engager to start building concept bridges), 2) words that remain unchanged from another language, or 3) new words altogether (Gillet, 2021; Flood, 1960; Ademowo, 2012). Furthermore, dialogue across languages is not unusual, because while current science culture is heavily monoglot, multilingualism was historically a big component of scientific knowledge production (Gordin, 2015).

There are examples of scholars who have developed technical words in AILs. For example, Dr. Thembla Dlodlo has laid out a comprehensive template for how to devise new words to describe Physics concepts in the Nguni language (Dlodlo, 1999), and Dr. Christopher Chetsanga published, a Science–English dictionary in the Shona language (Chetsanga, 2014). The Kenyan scholar–author Nanjala Nyabola, along with a team of linguists has created translation cards to communicate digital rights and data literacy vocabulary in various dialects of the Kiswahili language. Nyabola and efforts of her team are timely and relevant especially considering the recent efforts of Kenya to digitize population biometric data (Betteridge-Moes, 2021; Nyabola, 2021).

1.4 Just like other languages, African indigenous languages can develop and adapt adequate Terminology

Borrowing from concepts in evolutionary biology, which describe how an organism can evolve and adapt to its environment (Morgan, 1903; Newberry et al., 2017), so can languages evolve, drift (Ventura et al., 2021), and adapt to the new content that they will need to describe (Greenhill et al., 2017; Tirosh, 2021). Languages like Sheng (Kang'ethe-Iraki, 2004; Kim, 2015) from Kenya and various Pidgin and Creole languages morph and adapt to changing times all the time (Roberge, 2011; Tirosh, 2021). Formal language-modernization approaches are not new, and we point our readers to the work of Eliezer Ben Yehuda, who was instrumental in modernizing the Hebrew language (Haddad, 1998). Another example of language modernization is the work of Fukuwa Yukichi (Havens, 1971), who was responsible for translating many subjects ranging from chemistry and the arts from English to Japanese language. Both the works of Yehuda and Yukichi were seminal in modernizing the Hebrew and Japanese languages, respectively, and their success makes one believe that a similar outcome is possible for African languages.

2 DISCUSSION

2.1 Where the responsibility to start engagement initiatives in African indigenous languages lies

We believe that integrating more science engagement in AILs will need to be supported by both institutions and individuals. Governments and institutions can provide the resources and incentives for scientists and linguists to create words which can be integrated into NLP translation algorithms, which can then equip individual science engagers and journalists with the words to create educational content in AILs. We strongly encourage the inclusion of native language speakers in the creation and selection of words. A recent paper (Clark et al., 2021) detailing the development of an organic chemistry American Sign Language (ASL) lexicon for the deaf and hard of hearing scholars provides a good model for how to build an inclusive team to develop new words. An example of native language speakers to include on such teams could be vernacular language musicians because they often possess both the linguistic aptitude to find innovative ways to communicate, and they already have established audiences.

2.2 Is there a precedent for science engagement in a non-African vernacular language?

At this juncture, a question that might arise is: are there any documented successful vernacular language science engagement efforts? The audio–science digest *Janasuddi*, produced in the Indian language of Kannada is a prime candidate. The word *jana* means both smart and knowledge, and *suddi* means news in Kannada (Barath, 2019). This initiative is run by Kollegala Sharma, a scientist from Karnataka, India (Sharma, 2019). He has been producing this weekly ~20-min science podcast since September 2017 (Barath, 2019). His program reaches over 2,000 people via WhatsApp, and over 100,000 people via local radio shows which broadcast his show (K. Sharma, 2021). As of the writing of this essay, according to theTwitter page of Mr. Sharma, he has produced 880 episodes of *Janasuddi* in the last 4 years. Furthermore, while Mr. Sharma scripts the show, he does involve his audience both locally and in the diaspora, to provide voiceovers, and counts the principal scientific advisor for the Indian Government as a fan (Barath, 2019). The work of Mr. Sharma is a powerful case study to show that the use of vernacular languages can be used to engage audiences in science topics.

3 CONCLUSION

At this moment in time, scholars are using Data Science, Artificial Intelligence, and Machine-Learning to solve age-old complex problems like protein folding (Jumper et al., 2021), building models to predict the safety of self-driving vehicles in the human context (Pekannen et al., 2021), and reconstructing paintings from the 1900s (Gaskin, 2021). These same fields are generating NLP translation tools to translate beautifully diverse and complex African languages. So, using AILs to facilitate conversations about technical topics is possible.

At an individual level, what can African scientists do? We can reflect on whether we ourselves can explain aspects of our scientific expertise in African languages. Some examples include the linguist Bienvenu Sene Mongaba, who has created an interpretation of the Periodic Table in the Lingala Language (Sene Mongaba, 2009), a Youtube channel run by one of the authors of this paper (Kago, 2021), where she creates short videos about cell biology topics in the Gikuyu language of Central Kenya, and a book on South African frogs in isiZulu and English (Phaka and Ovid, 2021).

One of the outcomes of the current COVID-19 pandemic is an increased urgency to establish robust biotechnology infrastructures on the African continent. Both the African Union and Africa-CDC have articulated goals to increase the production of vaccines on the continent from 1% to 60% by 2040 (Irwin, 2021). To achieve these goals, African countries need not only logistic and technical capacity, but also societal trust in scientific interventions. We posit that using AILs in scientific engagement will go a long way to increase sustainability and longevity of efforts such as these.

"African governments must look at the languages spoken by their citizens in terms of how they can be utilized to contribute to the welfare of the citizens. It is in preparing our languages for enhanced gainful utilization that we develop them; paradoxically so they may develop us."—Okoth-Okombo (2001).

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MC: Conceptualization and original draft. GK: Current Manuscript. Both authors edited and contributed to the final manuscript revision and read and approved the submitted version.

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Scientific Institutions Should Support Inclusive Engagement: Reflections on the AAAS Center for Public Engagement Approach

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Scientists' engagement with society on critical environmental and health issues is essential to reaching positive and equitable long-term outcomes. We argue that stronger institutional support for public engagement is necessary and that inclusive practices should be built into public engagement training and relationships. The American Association for the Advancement of Science (AAAS)'s Center for Public Engagement with Science and Technology provides a model of support for scientists that we believe other scientific institutions can replicate and expand on. This model prioritizes representative and accessible science communication training, resources (e.g., funding and staff and peer support), opportunities to practice engagement, and rewards and incentives for doing engagement. We describe our programs in each of these areas and reflect on how well each builds scientists' engagement skills and institutional capacity, and whether each embodies and models thoughtful, accessible, and representative engagement. Through these various approaches, the Center communicates to other scientific institutions that engagement by scientists should be valued, celebrated, and supported, and builds capacity for individual scientists to do effective engagement. We argue that these supports can be applied by other scientific institutions to reflect and incorporate society's diverse needs and concerns, thus truly serving the public and making science and scientific institutions stronger for it.

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INTRODUCTION

Scientists' engagement with society on pivotal environmental and health issues is essential to reaching equitable outcomes. To be successful, scientists require support in the form of training, resources, and incentives. We argue for increased institutional support for public engagement and reflect on our holistic approach as a catalyst for discussions on doing this well, considering especially whether our programs are inclusive, accessible, and representative.

The Center for Public Engagement with Science and Technology ("the Center") at the American Association for the Advancement of Science (AAAS) was founded in 2004 with the vision of facilitating dialogue between science and society and providing scientists with training and opportunities to thoughtfully engage the public in two-way dialogue (Leshner, 2003).

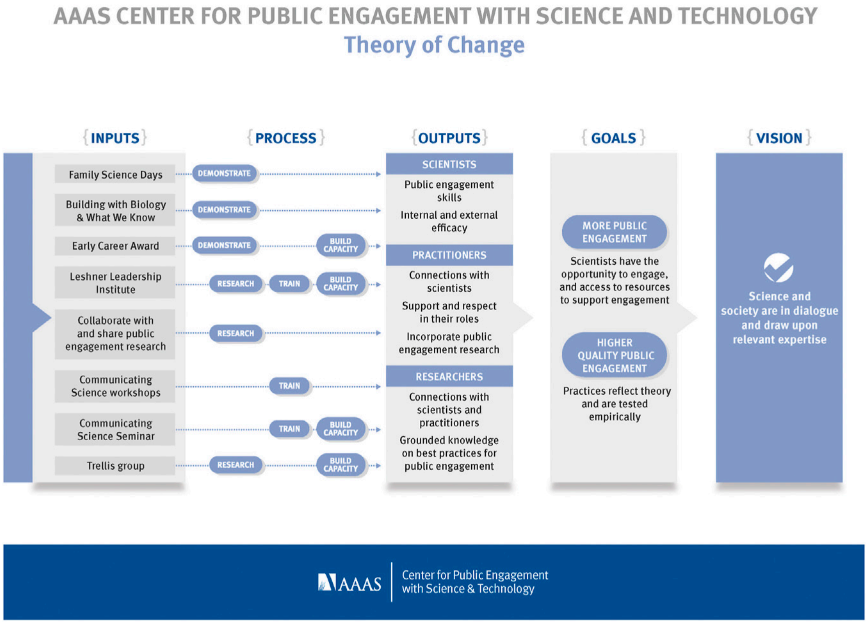

FIGURE 1 | Theory of change for the AAAS center for public engagement with science and technology (2015).

We encourage scientists[1] to use the public engagement with science approach, defined as "intentional, meaningful interactions that provide opportunities for mutual learning between scientists and members of the public," (Braha, 2015, 18) hereinafter "public engagement." This practice incorporates, but is distinct from, the skills-centric discipline of science communication (MacArthur et al., 2020, 63), specifically encouraging scientists to learn from the public. Building on this definition, inclusive public engagement is intentional, reciprocal, and reflexive (Canfield and Menezes, 2020, 1–2), focusing on longer-term relationship-building with communities and on communities' self-defined needs and assets.

We recommend scientists incorporate inclusive public engagement into their scientific work and use it to improve both their research and public outcomes -- for which institutional support is critical. We argue that a holistic approach, beginning with 1) training, and incorporating 2) resources, 3) opportunities to practice engaging, and 4) rewards and incentives for doing public engagement, is essential. Here, we reflect on our Center's approach to institutional support by examining how some of our programs demonstrate these pillars of support. Our goals and approach stemmed in part from several meetings and workshops AAAS held in 2014 and 2015 to help us develop a theory of change for the Center (**Figure 1**), as well as a visual model (**Figure 2**) and theory of change for public engagement with science more broadly (AAAS Center for Public Engagement with Science and Technology, 2016).

TRAINING

Institutions providing science communication and public engagement training signal that public engagement is a priority and provide scientists with tools to succeed. Our primary training program is an example of this.

Communicating Science Workshops Program

The Center launched the AAAS Communicating Science Program[2] in 2008 and has trained more than 16,000 scientists. The program was created to fill an institutional gap: graduate degree programs in science do not often offer science communication curricula, despite evidence that effective communication and engagement skills are useful within science and more broadly (Aurbach et al., 2019; Bartel et al., 2019). Our goal for the program is to give scientists the tools they need to effectively engage in conversations within broader society, especially on critical societal issues informed by science.

AAAS trainings use our Public Engagement Framework, which provides structure for planning, implementing, and evaluating audience-centric, dialogue-based, inclusive public engagement, with the intent that this structure or manner of

[1]We use the term "scientists" to refer to researchers and practitioners identifying with the scientific community, including but not limited to research scientists, applied scientists, engineers, and medical professionals.

[2]https://www.aaas.org/programs/communicating-science

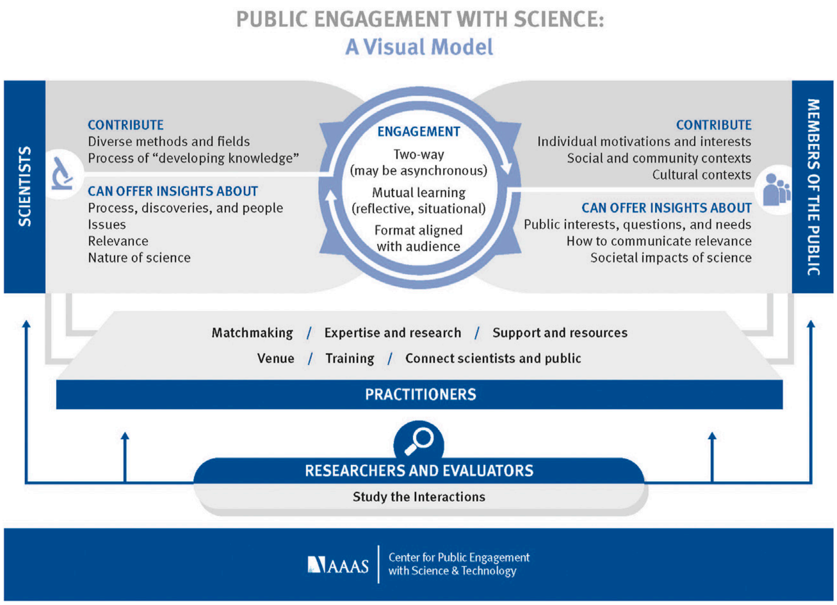

FIGURE 2 | Visual model for public engagement with science (2015).

thinking is integrated into both projects and careers (Risien and Storksdieck, 2018). This approach prioritizes thoughtful planning and responsiveness to audiences (including listening and being openminded–e.g., what can the scientist learn from the public?) while also providing guidance on how to be clear and succinct to capture attention and enable conversations. The training also introduces different methods of engagement, including 1) informal "public dialogue" with the goal of learning occurring both by experts and the public, 2) "policy deliberation" with the goals of exchanging views about science policy, 3) "knowledge co-production" wherein scientists partner with members of the public to collaboratively do research, and 4) "University-led cooperative engagement" such as engagement done through university extension offices (Storksdieck et al., 2016).

To reinforce both the importance of approaching public engagement thoughtfully and strategically, and that support for this work exists, we encourage institutional leaders to make remarks during workshops and, when possible, point participants to resources at their institutions. Post-workshop survey results tell us that trainings establish some momentum for scientists wishing to engage or increase their engagement. In 2020, three-quarters of participants reported being more aware of and feeling more connected to colleagues doing public engagement, likely a result of small-group discussions with colleagues during workshops, and two-thirds reported new awareness of their institution's support for public engagement. Often, hosts ask us how to build on this momentum and we encourage them to highlight or create resources to support scientists who wish to engage, the pillar we explore next. Training, when provided in isolation, is not enough to enable scientists to effectively engage.

An additional critical component of this program is accessibility: ensuring everyone has access to quality training that meets their needs is one part of ensuring public engagement itself is inclusive and representative. AAAS models this in our trainings by employing accessible design (Murchiea and Diomede, 2020), informed by a style guide with one simple typeface and a colorblind-compliant color palette (Crameri et al., 2020), and making plain-text versions of presentations available. When facilitating training events or giving talks, staff use microphones and Microsoft PowerPoint closed captioning (Cooke et al., 2020).

We have seen this commitment to accessibility influence our customers. During planning calls with hosting institutions, we ask about participants' accommodation needs. Often, hosts have not thought about this. In 2021, one host shared that this question made them realize their program needed to think more about accessibility.

In 2020, the Center launched virtual training products, opening them to individuals, and to institutions with remote staff, for the first time. Although opening workshops to individuals has allowed us to reach more scientists, we acknowledge that our registration fees are a barrier to entry and are exploring developing additional resources to meet this need. The program continues to evolve with insight from pre- and post-workshop evaluations, longitudinal feedback, and facilitator experiences.

RESOURCES

Providing scientists with training and inspiring them to act is an important first step, but it must be combined with dedicated resources to enable action, including funding, staff support, and peer networks. These resources sustain public engagement efforts to drive societal change, inspire new generations of scientists, and fulfill institutions' missions. Here we examine two programs providing such resources.

IF/THEN® Ambassador Program

In 2019, the Center created the AAAS IF/THEN® Ambassador program in partnership with Lyda Hill Philanthropies' IF/THEN® Initiative[3], which aims to close the representation gap for women in STEM, particularly as viewed through the media and pop culture. The program is designed to help middle school girls see themselves as the scientists of the future, engaging them at a critical time when science curricula become more challenging, and girls are not encouraged to pursue science in the same way boys are (Geena Davis Institute on Gender in Media, 2018).

Through the AAAS IF/THEN® Ambassadors project, the Center recruited and empowered a diverse cohort of 125 women in a range of STEM careers. Ambassadors received initial professional development via a 3-day summit. They also received a monetary award, the opportunity to apply for a $10,000 "She Can Change the World Project" grant, an online network of ambassadors and support staff, weekly resource emails, and connections with IF/THEN® Coalition members including the Girl Scouts, Nepris (which connects industry professionals with classroom educators), and the Association of Science and Technology Centers (ASTC). Continuing professional development and one-on-one coaching from AAAS staff help assist ambassadors in becoming high-profile role models in the media and in developing learning materials, engaging directly with middle-school girls, and writing grants for public engagement project funding.

The IF/THEN® "She Can Change the World Projects" have allowed ambassadors to apply their training and invest in engagement projects with audiences they care about. For example, Tiffany Panko, a deaf physician, created a women's health book, *H is for Hormones*[4], to promote accessible health information and elevate the visibility of deaf women in STEM. Panko began by engaging focus groups of her desired audience, deaf 5th grade girls, using their feedback to inform the book currently in production.

Paula Garcia Todd, along with Science ATL[5], set up partnerships between teachers and STEM professionals in the Atlanta region. Todd reported that because of the partnerships and the activities they spawned, "schools got new gardens, some classrooms got creative with "brown bag" STEM kits that were picked up at the school for activities to be done at home, we had winners in the local Rube Goldberg competition, and an underwater robotics team that won their regional competition and advanced to nationals thanks to help from their STEM professional" (Todd, 2021).

In a 2020 survey, ambassadors said they found the program valuable, reportedly doing more public engagement thanks to the support, and had positive attitudes about their abilities to engage. Evaluation of the IF/THEN® "She Can Change the World Projects" projects is currently underway.

Leshner Leadership Institute

The AAAS Alan I. Leshner Leadership Institute for Public Engagement with Science[6], launched in 2015, provides both training and resources for enabling public engagement, including seed funding, staff support, and peer networking, to cohorts of 10–15 scientists working within a related subject area (e.g., climate change, infectious disease). These scientists commit to a year of intensive public engagement and advocating for support within their institutions, as one of the goals of the program is to shift institutional culture and capacity through empowering these leaders.

AAAS Leshner fellows have reported that AAAS' credibility helps them drive institutional support for public engagement within their professional communities, including through seeking out engagement-related leadership positions, establishing awards (such Wendy Jepson's work on the Public Engagement Award for faculty at the Texas A&M University College of Geosciences), co-writing articles in society journals (Jefferson et al., 2018; Kenney et al., 2020), and organizing engagement-related sessions at society meetings, in one case resulting in an engagement-focused section in *Freshwater Science* (Hopfensperger et al., 2021). At the University of Minnesota's Institute on the Environment (IonE), three Leshner fellows, including Institute director Jessica Hellmann, infused a greater public engagement focus and incorporated AAAS material into the IonE Associates program[7] which supports early-career faculty doing public-oriented research.

Fellow Kate Brauman illustrates the effectiveness of bridging training and resources to enable long-term, influential science-society interactions. In 2019, Brauman was invited to participate in a Congressional hearing on biodiversity losses based on her work as a coordinating lead author on the Global Assessment of the Inter-Governmental Platform on Biodiversity and Ecosystem Services.[8] At her request, Center and AAAS government relations staff provided coaching that helped her prepare for providing testimony and answering lawmakers' questions. Brauman later became a AAAS Science and Technology Policy Fellow[9] placed at the U.S. Department of Defense where she helped to develop a methodology for assessing water security risk at military installations.

AAAS conducted an external evaluation of the program in 2021 with a 70 percent response rate from the five cohorts of fellows. The results were encouraging, with 72 percent of respondents saying the fellowship contributed to their career advancement, 78 percent of respondents saying they are now regularly advocating for placing a higher value on public engagement with their leadership, 65 percent saying they had

[3]http://www.ifthenshecan.org
[4]https://www.tiffanypankomdmba.com/abc-book
[5]https://scienceatl.org
[6]https://www.aaas.org/lli
[7]http://environment.umn.edu/fellows-grants/ione-associates
[8]https://www.congress.gov/event/116th-congress/house-event/109573
[9]https://www.aaas.org/programs/science-technology-policy-fellowships

started or increased expectations for students, advisees, or junior staff to participate in public engagement, and 48 percent saying their engagement is influencing audiences' lives, work, or decision-making. Findings from this evaluation (publication forthcoming) will inform ideas for future cohorts including improved training, stronger peer networking, and guidance for pursuing collaborative public engagement, such as community partnerships.

New to this program, AAAS is holding focus groups to gather input on the framing, focus, and goals for the next cohort of fellows, and future resources will also incorporate existing inclusive public engagement guidance from sources such as the Equity Compass (YESTEM Project UK Team, 2020), the 2020 Inclusive SciComm Report (Canfield and Menezes, 2020), and the CAISE Broadening Perspectives Toolkit (Center for Advancement of Informal Science Education, 2021).

PUBLIC ENGAGEMENT IN PRACTICE

A third pillar of support is facilitating opportunities to practice engagement and highlighting examples of replicable engagement. Institutions can provide logistical support and connections to underserved audiences for individuals, who should not bear the sole responsibility of creating and maintaining engagement efforts. We reflect on two projects as examples for scientists and institutions.

Family Science Days

The Center launched the AAAS Family Science Days[10] program in 2004 as a free public science festival with hands-on activities for children and their families. Held alongside the AAAS Annual Meeting, which takes place in a different city each year, the program sought to increase engagement between meeting attendees and the local public.

An essential element of the program is demonstrating the concept of public engagement and its value to Annual Meeting participants, again with an aim of creating overall culture change. Booth exhibitors include local science groups, such as the neuroscience and genome sciences departments at the University of Washington for the 2020 event in Seattle, and repeat exhibitors, including Science Storytellers[11] and Math Matters to Me.[12] The "Meet a Scientist" stage show features scientists, including meeting participants, who give interactive performances incorporating visuals or props.

In recent years, the Center committed to assembling a more diverse lineup of scientists for the stage show by featuring both a range of scientific disciplines and scientists with a broad spectrum of identities and lived experiences, ensuring a wider range of children could see themselves represented. This was a change from a tradition of featuring well-known scientists, often from similar backgrounds. When able, Center staff also worked with local organizations or schools to provide transportation and lunch to children who otherwise would not have been able to attend, actively pursuing a representative audience to increase access to science. The Center also committed to being inclusive, providing accommodations including a sensory friendly hour.[13]

Attendees have indicated in post-event surveys that the event had an impact, sharing reflections such as, "My daughter . . . put up a "lab" in her room and is recording her experiments in the notebook she got at the event. Great inspiration to make science fun!" In a 2020 survey, three-quarters of exhibitors and stage show speakers agreed that "this public engagement activity provided me with an opportunity to learn from the broader community" and four out of five agreed they "felt enlightened by ideas shared by participants at this public engagement event."

How We Respond

In addition to opportunities to practice engagement or see it in action, scientists need to see varied examples of effective, two-way engagement. The Center launched the How We Respond[14] climate communication project in 2019 to demonstrate the many ways scientists can collaborate with communities to respond to climate change. The project highlights community-level responses via 24 multimedia stories and a plain-language report about climate change responses and includes Spanish translations.

The Center sought to be inclusive by convening representative advisory committees and focus groups to shape the project. The project also featured a diversity of responses and communities, considering geography, population density, demographics, and ways of knowing. Based on participant feedback on the first round of stories in 2019, the Center actively recruited more communities of color to feature in 2021, aiming to support and highlight them and not appropriate their stories and images. A 2019 accessibility audit also informed modifications to the project's website, including increasing color contrast for better readability and incorporating alt text.

REWARDS

Institutions who highlight successful, replicable engagement show they prioritize it and provide a bridge from training to application. A final pillar for demonstrating the value of public engagement is offering incentives. Awards and incentives recognize scientists for excellent public engagement, encouraging others to pursue similar paths and elevating the profiles of scientists who engage. AAAS's public engagement awards provide an example of ways to meaningfully reward scientists whose efforts might otherwise go unrecognized.

[10]https://www.aaas.org/programs/center-public-engagement-science-and-technology/family-science-days

[11]http://www.sciencestorytellers.org

[12]https://mathmatterstome.com

[13]A sensory friendly hour provides attendees with clear expectations for what they might experience, such as light and sound stimuli, giving them more agency to choose how to interact with an event.

[14]https://howwerespond.aaas.org

Public Engagement Awards

AAAS offers two awards recognizing scientists for significant contributions to public engagement[15], the AAAS Mani L. Bhaumik Award for Public Engagement with Science, established in 1987, and the AAAS Early Career Award for Public Engagement with Science, established in 2010. Recipients of each award receive a monetary prize, a commemorative plaque, and recognition at the AAAS Annual Meeting. In providing monetary awards, AAAS reinforces that public engagement is important, encouraging other institutions to prioritize it in professional portfolios. We also publicly recognize finalists for the Early Career Award, to amplify additional excellent public engagement and because recognition is particularly impactful for early-career scientists who might be discouraged from pursuing activities deemed outside of professional responsibilities.

Awards also highlight scientists modeling replicable engagement strategies. Fairfield University professor and former college basketball player John Drazan, the 2020 AAAS Early Career Award recipient, engages sports enthusiasts. Early in Covid-19 pandemic, Drazen connected infectious disease experts with sports podcast hosts, bringing scientific expertise to a community grappling with impacts such as the 2020 NBA season's cancellation (Brockmeier, 2020). University of Illinois Urbana-Champaign Assistant Professor Esther Ngumbi, the 2021 AAAS Mani L. Bhaumik Award recipient, works with farmers, using insights from her research on insects, plants, and soil microbes to introduce them to new techniques, for example, and engages university students in Kenya in projects to reduce rural hunger there (Cohen, 2021).

Recently, the Center prioritized making the awards nomination process more equitable and engagement-focused. Previously, letters of support–often written by high-profile academics prioritizing academic prestige–were the primary nomination vehicle. Now, the Center requests statements addressing nominees' efforts to prioritize dialogue and curriculum vitae highlighting public engagement work. The result has been more representative nomination pools, increases in self-nominations from researchers in unsupportive academic environments, and letters from community members who say more about nominees' impacts. To build on this, we are collecting demographic information, providing reviewers with anti-bias training, considering review committee composition, and ensuring evaluation metrics aren't inadvertently exclusionary.

CONCLUSION

Through training, resources, practice, and rewards, the AAAS Center for Public Engagement with Science and Technology builds capacity for scientists to engage the public on societal issues and signals that public engagement should be valued, supported, and celebrated. Even for larger organizations like AAAS, there are barriers to implementing and sustaining public engagement programs including funding and staffing constraints, limiting our ability to more adequately and equitably serve scientists. For example, we recognize that registration fees for Communicating Science workshops are a barrier to entry, we see a need for more sustained alumni networks with staff support, and we acknowledge that greater fellowship and ambassadorship project seed funding might allow them to do more. Despite these and other areas for improvement, we encourage other institutions to consider these approaches and we welcome conversations about inclusive public engagement support mechanisms that serve the public and strengthen the scientific enterprise.

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.

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

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[15]https://www.aaas.org/page/awards

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Check for updates

Sci/Comm Scholars: A Facilitated Peer-To-Peer Working Group for Integrating Rhetorical and Social Scientific Approaches for Inclusive Science Communication

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Graduate students emerging from STEM programs face inequitable professional landscapes in which their ability to practice inclusive and effective science communication with interdisciplinary and public audiences is essential to their success. Yet these students are rarely offered the opportunity to learn and practice inclusive science communication in their graduate programs. Moreover, minoritized students rarely have the opportunity to validate their experiences among peers and develop professional sensibilities through research training. In this article, the authors offer the Science Communication (Sci/Comm) Scholar's working group at The University of Texas at San Antonio as one model for training graduate students in human dimensions and inclusive science communication for effective public engagement in thesis projects and beyond. The faculty facilitated peer-to-peer working group encouraged participation by women who often face inequities in STEM workplaces. Early results indicate that team-based training in both the science and art of public engagement provides critical exposure to help students understand the methodological care needed for human dimensions research, and to facilitate narrative-based citizen science engagements. The authors demonstrate this through several brief profiles of environmental science graduate students' thesis projects. Each case emphasizes the importance of research design for public engagement via quantitative surveys and narrative-based science communication interventions. Through a faculty facilitated peer-to-peer working group framework, research design and methodological care function as an integration point for social scientific and rhetorical training for inclusive science communication with diverse audiences.

Keywords: science communication, citizen science, hispanic serving institutions, human dimensions research, public engagement, peer mentoring, STEM equity, validation

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INTRODUCTION

Graduate students emerging from STEM programs face inequitable professional landscapes in which their ability to practice inclusive science communication with interdisciplinary and public audiences is essential to their success. Yet these students are rarely offered the opportunity to learn and practice inclusive science communication in their graduate program. Moreover, minoritized students rarely have the opportunity to validate their experiences among peers and develop professional sensibilities through training. This gap can perpetuate inequitable representation within science communication which is intended to benefit society as a whole. While the number of opportunities for STEM graduate students to engage in all kinds of science communication has arguably never been more abundant, many opportunities are presented as "one-and-done" science communication workshops. We acknowledge programs are often restricted to these models, and that they can be a good first step. However, we urge programs to look beyond them where possible as they rarely provide the breadth of skills needed for graduates to succeed in the workplace (Druschke et al., 2018; Priest et al., 2018; AAAS, 2016; Nisbet and Scheufele, 2009), and we know these models often lack the capacity to engage in meaningful mentoring that addresses inequities in STEM professions. Simply put, there is still a need for models that directly integrate inclusive science communication training into STEM graduate student research training (Dewsbury, 2017; Canfield et al., 2020). While research training can provide the necessary technical know-how, inclusive science communication training can cultivate facility with translating technical information with diverse public audiences. Thus, one question moving forward is how to achieve integration among science, communication, and equity when, by-and-large, STEM graduate curricula simply lack capacity to embed inclusive science communication into their graduate programs of study.

The repercussions for inadequate training in inclusive science communication may be especially relevant for graduates of environmental science and ecology at minority-serving institutions who often work in landscapes where conservation and management decisions can be governed by a complex mix of politics, economics, social norms, and the values and attitudes of diverse stakeholders (Brook et al., 2003). Here, graduates of our programs may face resistance to actions which promote sound management of natural resources, especially where property rights dictate access to land (Moon et al., 2021), where laws and regulations restrict land use practices, or where actions may result in economic losses (Olive and McCune, 2017; Brook et al., 2003). Several suggestions relevant to preparing our students for working in these complex landscapes have been described (Ranjan et al., 2019; Smith et al., 2019; Carr and Hazel, 2006), including training in human dimensions research and science communication. Indeed, calls for human dimensions in graduate research training are increasingly common because they provide the skills needed for understanding how people influence natural resource management, and how natural resource management affects people (Smith et al., 2019; Jacobson and McDuff, 1998). Thus, integrating social scientific approaches from human dimensions with broader rhetorical approaches from inclusive science communication can provide an ethical approach to understanding and communicating effectively with diverse stakeholders, while promoting scientifically informed natural resource management (Priest et al., 2018; Druschke and McGreavy, 2016; Pace et al., 2010). Furthermore, doing this integrative work for minoritized graduate students at minority-serving institutions helps to ensure that access to this professional training is provided for those who may not have this exposure otherwise.

As we know, learning about science communication and human dimensions for a few hours is not a substitute for doing this work in research-based settings and for diverse public-facing engagements. One path toward meeting the demands for dynamic science communicators is to integrate inclusive science communication and human dimensions training early and often in STEM graduate programs (Canfield et al., 2020). Furthermore, this integration should not limit opportunities for technical scientific learning, but rather complement it so training in inclusive science communication becomes a motivation for increasing content knowledge. While scientific learning deals in data, creating social knowledge from technical information is an applied rhetorical practice where stochastic contexts shape knowledge in consequential ways for building trust across various levels of expertise (Walsh and Walker, 2016). In short, translating scientific information to create social knowledge is context dependent, and creating knowledge for technical/scientific communities will not be the same process as creating knowledge for diverse publics. Thus, the goal of any integrative human dimensions and science communication training should be a dexterity and dynamism that allows graduate students to develop a deep contextual knowledge of human dimensions and science communication in ways that validate their experiences from peers, professors, and publics (Walker, 2017).

In this context, we developed the Sci/Comm Scholar's working group at The University of Texas at San Antonio (UTSA) through Project ASSIST (Advancing and Strengthening Science Identity Through Systematic Training), a program funded through an NSF-NRT-IGE[1] grant (Linton, 2013; Bush et al., 2016). The ASSIST grant was conceptualized to develop science leaders from minoritized groups enrolled in the Master of Science (MS) in Environmental Science program through holistic mentoring with systematic training in science writing and science communication. As UTSA is a minority-majority Hispanic Serving Institution (HSI), it was vital that the support being provided was tailored to support the specific needs of our students, many of whom are from underserved communities. Thus, the ASSIST interventions were specifically formulated based on literature indicating the importance of effective mentoring and communication training in supporting Latinx students, and minoritized students more broadly (e.g., Nora and Crisp, 2007; Cerna et al., 2009; Galvez et al., 2014; Simpson et al., 2015). Through a series of graduate courses, professional workshops, and peer and near-peer mentoring activities the project sought to support and validate minoritized students' identities as scientists. While this team successfully implemented science communication training into the MS Environmental Science program—*via* course-based

[1]National science foundation-national research traineeship-innovations in graduate education.

science communication projects, science narrative workshops, and community outreach—the team also saw a need to provide robust training in human dimensions research and science communication practices to support students' MS thesis projects. Once the COVID pandemic hit in the Spring of 2020 and all activities were required to move online, the science communication team from Project ASSIST—which consisted of scholars with expertise in science communication, education, and science identity (Dr. Kenneth Walker and Dr. Amelia King-Kostelac)—collaborated with Dr. Jennifer Smith—Assistant Professor in The Department of Integrative Biology and PI of the Smith Lab at UTSA—to create the Sci/Comm Scholar's working group. The working group provided a virtual format through which environmental science MS students could develop science communication and human dimensions research skills which were relevant to their thesis projects.

Given the broad scope of Project ASSIST to integrate inclusive science communication early and often, the Sci/Comm Scholar's working group allowed us to deepen that exposure and apply this knowledge to specific thesis projects. Placing focus on students' current research was key to providing training which could bridge social science and science communication theory with practical application in human dimensions research. The purpose of UTSA's Sci/Comm Scholar's working group, and Project ASSIST more generally, was to promote diversity, inclusion, and equity in science by fostering a sense of belonging and science identity for minoritized students at HSIs like UTSA (Chen et al., 2021). We now recognize this project to be part of a larger effort to support and develop inclusive science communication where inclusion, equity, and intersectionality ground all research and practice (Canfield et al., 2020, 2; Dewsbury, 2017). In bringing education and science communication researchers and practitioners into a STEM department, the project embraced varied forms of expertise and ways of knowing through a focus on holistic mentoring and validation theory (Ko et al., 2014; Crisp, 2011; Rendon and Muñoz, 2011; Crisp and Cruz, 2010; Nora and Crisp, 2007; Rendon, 1994), science writing via writing-to-learn (Druschke et al., 2018; Schultz and Gere, 2015), and public science communication (Pielke, 2007; Nisbit and Scheufele, 2009; Scheufele, 2014; Druschke and McGreavy, 2016; Walker, 2017). Much like inclusive science communication, UTSA's Sci/Comm Scholar's working group was an intentional investment in supporting and recognizing inclusion, equity, and intersectionality from its initial ideas to implementation and evaluation (Canfield et al., 2020).

MATERIALS AND METHODS: INSTITUTIONAL SITE AND CONTEXT FOR THE FACILITATED WORKING GROUP

Working Group Model

We chose a facilitated working group model to promote faculty-to-peer and peer-to-peer interactions around science communication, human dimensions, thesis research, and inclusion, equity, and intersectionality in STEM. Although research on working groups, specifically, is sparse, our team drew from robust bodies of literature on both Communities of Practice (Wenger, 2007; Wenger et al., 2002; Wenger, 1998) and peer and near-peer mentoring (Abeywardana et al., 2020) in developing the Sci/Comm Scholar's working group. Research suggests that Communities of Practice can be integral to creating programmatic and institutional change, provided that such communities have well-defined goals, a clearly articulated structure for collaboration, and commonly shared understanding of how to support minoritized students' success in STEM in both the near- and long-term (Kezar and Gehrke, 2017). For the Sci/Comm Scholars, a key component of this collaborative structure was faculty and peer mentoring, which has been shown to be influential on both academic and professional success for minoritized students, as it provides space for students to experience validation, to engage in realistic self-assessment, and to develop self-efficacy (Trujillo, et al., 2015; Ko, et al., 2014; Nora and Crisp, 2007; Lave and Wenger, 1991). Furthermore, studies have also indicated that not having access to mentoring relationships can result in students having access to fewer field research experiences, and increase the likelihood that minoritized students leave STEM for other disciplines (Carlone and Johnson, 2007; Johnson, 2007).

Prior studies have also indicated that inclusive, culturally responsive experiential learning and exposure to research can be significant factors in student success, particularly for minoritized STEM students (e.g., Bowser and Cid, 2021; Núñez, et al., 2019; Posselt, et al., 2019; Schultz, et al., 2011); however, the success of such interventions cannot be taken as a foregone conclusion, much as we cannot assume that all science communication training is *de facto* beneficial. Dewsbury (2017), for example, emphasizes the need for curriculum and program design to be attentive to the social, cultural, institutional and geographic context for the learning, as well as to cultivation of a culture of trust among faculty and students. Kezar and Gehrke's (2017) mixed-method study of four such inclusive STEM programs demonstrated the degree to which the success of such programs may be determined by the cultivation of distributed program leadership (inclusive of all stakeholders) who can provide a broad base of support to create and/or cultivate a transformative community of learning which is committed to creating a culture of inclusivity (Kezar et al., 2015).

In this regard, the research described here demonstrates the high degree of consistency in factors cited as important to supporting minoritized students through mentoring and validation, inclusive and culturally relevant pedagogy, and inclusive science communication. Institutional commitment—in terms of resources, programming and curriculum—is essential, a fact driven home by research on Communities of Practice. But also important to student success is developing strong mentoring relationships, cultural validation, and access to a breadth of opportunities to engage in field and lab research with faculty. The format of the Sci/Comm Scholar's working group was conceptualized to provide the mentoring, validation, and research experience to create a complementary relationship to the larger ASSIST grant, which provides students with additional financial resources and professionalization opportunities. Given the unique methodological demands of research engaging human dimensions and science communication we saw the working group as an ideal mechanism for our students to have access to robust faculty and peer mentoring within a setting which centered the students' role as scientists engaging the public through their thesis research.

Institutional Context

The University of Texas at San Antonio (UTSA) is a designated HSI with 57% of UTSA students identifying as Hispanic/Latinx. As a majority Hispanic/Latinx institution with a large percentage of first-generation students, cultivation of committed Communities of Practice is particularly important considering educational persistence and belonging may be higher for minoritized students who attend HSIs (e.g., Rodríguez and Calderon Galdeano, 2015). Furthermore, racial and ethnic identity salience and academic self-conceptualization may be higher for students identifying as Hispanic/Latinx who have attended an HSI (Garcia, et al., 2018; Cuellar and Johnson-Ahorlu, 2016). Nonetheless, this is again contingent on the robust provision of programs and resources developed to specifically address the needs of the student population, institutional resources, and the social and cultural context at that particular institution. For UTSA, there continues to be rigorous debate around how the "Hispanic Serving" component of its educational mission is reflected in programming, resources and student support. However, this is not unique. It is, rather, reflective of the manner in which HSIs differ, definitionally and historically speaking, from other minority-serving institutions (MSIs) such as Historically Black Colleges and Universities (HBCUs) and Tribal Colleges and Universities (TCUs), as HSIs are legally defined based on enrollment (25% or more Hispanic/Latinx students) rather than by an historically-rooted educational mission to serve a specific racial or ethnic group (Santiago, 2006). UTSA's identification as a "Hispanic Thriving Institution" comes from this debate: what does it mean to not merely enroll, but to serve students identifying as Hispanic/Latinx at the institution? Organizations like the Hispanic Association of Colleges and Universities and Excelencia in Education have helped provide structure and direction, by providing resources, research and guidelines for building and supporting institutional missions that explicitly aim to serve Hispanic/Latinx students (Santiago, 2006).

This debate is particularly germane for UTSA, an institution whose educational mission has been entwined with reform movements seeking improvement in educational access and quality for underserved communities across South and West Texas. Founded in 1969, UTSA's funding and growth as an institution is linked to several key legal cases and legislation which lead to investment of money and resources to support research universities in South and West Texas. First, the Mexican American Defense League's (MALDEF's) represented two class action lawsuits (LULAC vs. Clements, 1987; LULAC vs. Richards, 1993) which articulated the disparity of educational attainment and employment rates in North Texas (higher per capita income and high density of higher education institutions, despite being geographically smaller) compared with South Texas (Carales and Doran, 2020). Concurrently with these cases moving through the legal system, the South Texas/Border Initiative (ST/BI, 1989) aimed to increase access to both undergraduate and advanced degrees through expansion of resources and programs across previously under-served regions of South and West Texas. UTSA's identity as a HSI was touted early, with university president Arleight Templeton stating that UTSA would offer "specially designed program (which) will allow Mexican American students to take half their degree requirements in Spanish" (quoted in De Oliver, 1998, 274); a dream which did not materialize. In addition, the location of the main campus far outside the city center, and far from the predominantly Hispanic/Latinx neighborhoods of the south and westside of San Antonio, created a contradiction between the mission to increase educational equity, with a choice of location that placed greater financial and transportation burdens on the same students who institutional leaders stated a desire to serve. This underlines the extent to which institutions, even when ostensibly created to serve minoritized communities, struggle to follow through on this promise of equity.

Many recent initiatives from UTSA have aimed to address these historically-rooted and persistent inequitable distribution of resources and opportunities for the universities minoritized students, the majority of whom are Hispanic/Latinx through a combination of internal strategic initiatives and external grant-funded programs. ASSIST is one of several grant-funded initiatives [e.g., RISE Initiative and Geoscience Pathways Program (Haschenberger, et al., 2021)], which focus on providing more access to robust mentoring, experiential learning, and discipline-specific professionalization opportunities for minoritized students. The Sci/Comm Scholar's working group represents one targeted component of this larger effort, one which focuses on developing key components of a transformative learning community—distributed leadership and interdisciplinary expertise to develop key communication and human dimensions focused ecological research.

This background is provided to underscore the degree to which successful interventions focused on inclusive science communication skills must reckon with institutional and geographic contexts of inequity to realistically engage broader publics and communicate with communities that continue to be marginalized in much scientific discourse. It also situates the degree to which UTSA's students' research and perspectives are precisely those which need to be empowered and supported via inclusive science communication work.

Development and Structure of the Sci/Comm Scholar's Working Group

Sci/Comm Scholars for the working group were recruited from students enrolled in the MS Environmental Science (ES) program housed within The Department of Integrative Biology at UTSA. The Sci/Comm Scholar's working group was optional and participation was voluntary. The ES Master's program is designed to prepare students for careers in both private and government sectors. Students enrolled in the program may elect to follow a thesis track or professional (non-thesis) track. The purpose of the thesis track is to gain experience and competency in a research topic by following the scientific process that culminates in a written thesis suitable for peer-reviewed publication. Research opportunities are available to thesis students from diverse fields including freshwater ecology, microbial ecology, restoration ecology, terrestrial ecology, and wildlife ecology. The non-thesis track provides exposure to a wide range of areas of environmental science and ecology through a coursework-focused curriculum. Following graduation, available data reflecting employment status of 55 graduates from the program suggests that a majority of students gain employment in industry (34.55%; $n = 19$)—either as environmental scientists ($n = 15$), software developers ($n = 2$), or GIS analysts ($n = 2$)—or are employed by governmental agencies (34.55%; $n = 19$). Of those employed by governmental agencies, 47.37% ($n = 9$) work for local governmental agencies, while 31.58% ($n = 6$) work for state-level governmental agencies; 21.05% ($n = 4$) work for federal agencies. Graduates from the program also pursue additional educational opportunities (7.27%, $n = 4$), are employed at higher education institutions or in the K-12 sector (21.82%), or work for Non-Governmental Organizations (1.81%, $n = 1$).

In Spring 2021, when the Sci/Comm Scholar's working group was formed, the ES Master's program hosted 45 students, 32 of whom were enrolled as thesis-seeking students, 12 as non-thesis seeking students, and 1 as a certificate-seeking student. Of the enrolled students, 57.78% identified as Hispanic/Latinx, 40% as Non-Hispanic/Latinx, with 2.22% not disclosing their identity. In recruiting, we made an intentional effort to support women who were enrolled as thesis students, and who were conducting research that substantively integrated science communication and/or human dimensions, so participation as a Sci/Comm Scholar would support their professional/academic goals. The goal of this selection process was not only to ensure our approach promoted the success of minoritized students, but also to provide a safe and supportive space for students to discuss specific challenges they have experienced as scientists engaged in field work and public outreach. The latter of these two goals is supported by research on success factors for women and minoritized women in STEM, which indicates the development of peer-to-peer models can provide validation of students skills and competence, as well as develop supportive and long-term professional relationships (Ong et al., 2018; Kachchaf et al., 2015; McCormick et al., 2014; Carlone and Johnson, 2007). In total, six Sci/Comm Scholars were recruited to participate, four of whom are co-authors and presenting their experiences here in this article. All of the Scholars were supported through a stipend of $1,600 per semester over the course of two semesters (August 2020 to December 2020 and January 2021 to May 2021). We held virtual meetings every 2 weeks among three faculty (Drs. King-Kostelac, Smith, Walker) and three-to-five students. Two of the faculty also identify as women (Dr King-Kostelac, Smith); this selection was intentional to promote a sense of belonging and inclusion, and to provide a space in which students could more easily construct an imagined future.

The Sci/Comm Scholar's working group was designed to support graduate student thesis research with human dimensions and science communication components through a working group model. We focused on integrating science communication and human dimensions research to complement technical scientific learning through readings, discussions of methodology, and thesis projects. We also discussed equity in professional workspaces, navigating hostile interactions (sometimes within the workplace), and intersectional approaches to science communication broadly. This facilitated working group approach promoted a more informal setting that combined expertise in social science research methods (Dr. King-Kostelac), rhetorical approaches to science communication (Dr. Walker), and ecological research and associated methods (Dr. Smith), along with all the expertise and ways of knowing brought to the group by the Scholars, many of whom were already working professionals in their respective fields. Supporting student's development of science communication via research-based thesis projects allowed us to combine rhetorical and social scientific approaches in two ways: first, through development of quantitative human dimensions surveys and, second, through science-based narratives for citizen science projects (Neely et al., 2020).

Sci/Comm Scholar Expectations and Deliverables

As Sci/Comm Scholars, students were expected to: 1) design an MS thesis-level research project that integrated human dimensions, science communications, and/or public engagement as a critical component of scientific research, 2) with support from working group faculty, spend 6–8 h per week on science communication research and programmatics (e.g., examining the role that science communication plays in shaping environmental attitudes/value orientations, and how to best communicate scientific and technical information with diverse audiences across a variety of media), 3) co-create print and digital materials for sustaining the Sci/Comm Scholar's working group, and 4) communicate their science through a variety of media relevant to their research (e.g., social media, professional newsletters, etc.).

Deliverables developed as part of the Sci/Comm Scholar's working group included: 1) thesis research with a transdisciplinary environmental science or ecology focus; 2) an archive of print and digital materials created by the Sci/Comm Scholars; 3) a guidelines document for future Sci/Comm Scholars, 4) a bibliography of resources current and future Sci/Comm Scholars can use to improve their research and public engagement skills; 5) a Sci/Comm Scholar contract to be signed by both Sci/Comm Scholars and their faculty advisors indicating they understand the requirements, benefits and compensation attached to participating in the Sci/Comm Scholar's working group.

RESULTS AND DISCUSSION: PROFILES OF RESEARCH AND COMMUNICATIONS TRAINING FOR SCI/COMM SCHOLARS

In this section, we provide profiles of four Sci/Comm Scholars who collaborated with our facilitated working group over the last year of pandemic-induced virtual sessions. Each student's profile is written as a narrative to address the following questions:

1) Why were you interested in becoming a Sci/Comm Scholar? Did the objectives of the Scholar's working group align with a career you hope to pursue?
2) What is your project and who are the stakeholders? [i.e., Home Owners Associations (HOAs)/neighborhoods, private landowners, state agencies, etc.].
3) How did you integrate science communications and/or human dimensions research methods into your thesis project? To what effect? Please describe the range of approaches you engaged in your research (e.g., oral, written, visual).
4) How was your experience with the facilitated peer-to-peer working group model? Did the experience of working with your peers and faculty have an effect on your own project, or on your understanding of science communications and/or human dimensions more generally?
5) Has your participation in the Sci/Comm Scholar's working group changed your perspective on public engagement? Or on science and its careers more generally?

The following profiles are provided by four MS thesis students recruited into the Sci/Comm Scholar's working group, all of whom identify as women in STEM and who substantively integrated science communication and/or human dimensions into their thesis research design. Eres Gomez and Jamie Killian joined the ES Master's program in Fall 2018, Sarah Gorton in Spring 2019, and Mary Finucane in Fall 2020. Three of the four Scholars are currently in the professional workforce as wildlife biologists or environmental scientists. They are all co-authors on this article.

Scholar One: Eres Gomez

My name is Eres Gomez. 2021 I am a native Texan born and raised in San Antonio. I identify as a Hispanic/Latina woman with Native American/Indigenous ancestry rooted in the Tejas region. I have lived in San Antonio my whole life and was raised by a single mother in neighborhoods that are low-income working class. I am also a first-generation, non-traditional student attempting to transition into a late-life career change into research and scholarship. I chose to study at UTSA because it is the only affordable university in my city where I have the opportunity to pursue my passion. I attended community college and earned an Associate of Science in Library Technology, and I went on to work in a science and technology library for many years. I then went into veterinary medicine and worked as a veterinary technician, eventually leading me into wildlife rehabilitation. I earned my Bachelor of Arts in Humanities from UTSA and then enrolled in The Department of Integrative Biology's Master of Environmental Science program where I study raptors, which is a broad term used to describe birds-of-prey such as hawks, owls, falcons, eagles, and vultures. My research interests also include the human dimensions of human-wildlife conflicts, especially with regard to contaminants and ecotoxicology. All bird species are very special to me and I grew up referring to them as "the bird people," because in my native culture, birds are not simply distant organisms related to us phylogenetically, but instead are close family relatives experiencing life in another physical avian form. This phrase is sometimes used at the closing of native ceremonial practices, where the speaker ends by saying, "All My Relations," which is referring to our inter-connectedness to all things, living and non-living, in the natural world. The Earth is our Mother, the Sky is our Father, the Rivers are our Sisters, the Trees are our Brothers, and the Animals are our Relatives—we as Humans have a duty and honor to protect and take care of them. Raptors, to many Native/Indigenous cultures, are extra special, especially eagles, because it is believed that they fly the highest and are closest to God, the Creator.

More specifically, I study the exposure of owls to anticoagulant rodenticides (ARs) through laboratory analysis and humans dimensions research in south-central Texas. Anticoagulant rodenticides are rodent poisons used for pest control. However, they also pose a risk to non-target species, which includes raptors, like owls (Gomez, et al., In Press), that become exposed to these poisons when they depredate contaminated prey (e.g., mice and rats). I tested liver samples of owls admitted into rehabilitation for the presence of eight commonly used ARs. The owls were admitted for various reasons, such as broken wings, electrocution, and no obvious injuries. Preliminary results suggest that over half of the owls tested had ARs present in their system at the time of death (E.A. Gomez, unpublished data). Anticoagulant rodenticides have become so ubiquitous and pervasive in our environment, that they have been detected in numerous species besides the rodents they are intended to control (Gomez, et al., In Press). The thing that fascinates me about pesticides and chemical pollution, including poisons is that these surround us, envelope us, and yet we do not even know they are there until we test for them.

During my data collection at San Antonio's raptor rehabilitation center, I began to realize what an important role humans play in wildlife management, and in my thesis as a whole. People are inadvertently poisoning owls by poisoning their food source (i.e., rodents), yet people are also the ones delivering them to the raptor center for help, sometimes driving 150–200 miles from another city. I saw numerous instances where people showed just how much they cared for these birds. The owls and hawks they had grown accustomed to seeing and hearing in their own backyards were all of a sudden on the ground, not flying, and in need of veterinary care. They would rush the wild bird over to the raptor center, oftentimes transporting it in an elaborate makeshift carrier. At times, dropping off a sick raptor was a family affair involving multiple members, and other times the whole neighborhood got involved in trying to wrangle a frightened raptor into a box for transport. Concerned members of the public even called the raptor center regularly to check on birds they had dropped off, or to contribute donations to help with its medical expenses. People obviously care for these animals, so I held firm to my belief that if they were taught about the risks of ARs to wildlife and shown results of my local testing efforts, then maybe they would be willing to at least consider trying other safer alternatives to poison, or better yet, become so moved by this cause and inspired to conserve wildlife, that they would decide to venture into grassroots advocacy initiatives and become a catalyst for environmental community science stewardship in their own neighborhoods.

My experiences made me realize the importance of considering people when tackling wildlife issues, and that ignoring the interactions they have with wildlife and subsequent outcomes limits our ability to promote the conservation of species. At the same time, traditional wildlife courses often do not incorporate teachings of human dimensions that prepare students for better understanding the interactions that people have with wildlife (Smith, et al., 2019). Such curriculum is increasingly necessary as human-wildlife conflicts are rising in number, especially with urbanization. To further explore human-wildlife conflicts centered on rodents, ARs, and owls, I needed a way to learn more about, and how to assess what drives members of the public to use certain rodent pest control products (i.e., poison), something not typically done in traditional STEM studies. I had questions like, “Are people’s attitudes towards rodents and owls positive or negative?”, “If people view rodents as negative, are they more inclined to use rodenticide?” and perhaps more importantly, “Can educational intervention be used as a conservation tool to inform the public about the risks of ARs to wildlife, and thereby alter public attitudes and pest control behaviors?”. These were questions that melded into the realms of human dimensions and science communication. Humans are such an integral component of my study system, yet ironically, my academic curriculum was not setup to study them within this context. If I wanted to produce solutions to this problem of AR poisoning in non-target wildlife, I would need to try and get to the root of the issue by understanding the human component.

The Sci/Comm Scholar’s working group gave me the perfect opportunity to explore this second part of my thesis, which investigates the human dimensions of rodenticide provisioning by surveying residents in San Antonio about their attitudes towards rodents and owls, their behaviors centered on rodent pest control, and their knowledge about the potential for ARs to poison owls. Research has shown questionnaire surveys to be effective tools for collecting quantitative and numerical data (Bee and Murdoch-Eaton, 2016) and that they are becoming increasingly popular in ecology studies that involve human-wildlife interactions (White et al., 2005). Yet, despite this growing trend, survey research design is still not typically included in STEM curricula, leaving burgeoning wildlife professionals to enter the workforce unprepared for challenges that may arise when dealing with these complex landscapes that integrate wildlife management techniques for conservation with private landowners and public policy (Smith et al., 2019).

The survey also aimed to determine whether educational intervention can change public knowledge, attitudes, and behaviors, thereby potentially mitigating risk of AR exposure to non-target wildlife. The intervention consisted of a short video that utilized science communication techniques to deliver an educational message that informed the audience about the risks of rodenticide poisoning to wildlife. The Sci/Comm Scholar’s working group provided guidance on the content and delivery of this short video in order to increase its effectiveness for precautionary advocacy in risk communication. They also assisted me in navigating the Institutional Review Board (IRB) process and launching a pilot test trial run of the survey and video to improve user interface and reliability *via* Qualtrics.

The Sci/Comm Scholar’s working group also provided opportunities for discussions not typically had in my other classes with topics centered on the human element of each of the Sci/Comm Scholars’ projects. It provided a talking space for those with an interest in human dimensions research and science communication, a space seldom found elsewhere. It was insightful to see other Scholars’ projects and work through our challenges together; even though it often felt like our projects each had different themes, they all catered to a similar audience. With the working group, I had the chance to explore ideas for survey methodology and discuss science communication intervention techniques. The working group helped shape my perspective on science communication as public engagement in general and served as a vehicle for my project. By sharing each of our experiences about public engagement, we were able to compare stories and learn to navigate potential conflicts that may have arisen. We shared common concerns and questions we had about discussing our subject matter with the public including topics that are difficult to conceptualize or even controversial to discuss.

Thinking about human dimensions and science communication as part of ecological research was new to me. The fact that each Scholar integrated either human dimensions and/or science communication into their projects in different ways allowed me to understand the relevance of these disciplines in STEM, and to increase my knowledge of how they can be used. I learned a lot from other Scholars’ projects. For example, Sarah’s project highlighted personal interactions she had with the public, preparing me for potential professional interactions in my future career. Likewise, hearing Jamie’s stories about working with the public and what those interactions were like was always interesting and informative. In discussions about other Scholar’s work, each Scholar brought their own thoughts and perspective to the table. These discussions highlighted the importance of coupling human dimensions research with ecological research, especially where the applied perspective must consider diverse stakeholders with different values, attitudes, and behaviors. They also demonstrated that science communication is an essential tool that not only allows scientists to share scientific knowledge with non-scientists but can also be essential for the successful completion of an engaged ecology thesis project.

Scholar Two: Jamie Killian

I am a middle-aged woman and I work in rural Texas. Living in rural communities has influenced how I view myself. On one hand, I think the rural community allowed me to find my own identity because I was unaware of most labels. On the other hand, I felt alone and afraid to be open about my identity because of societal pressures and “norms.” My fears may be self-imposed, but they kept me from openly identifying as a gay woman. I never talked about my fears or asked for help because I did not know how, or who to ask. I did not know an openly gay person growing up or early in my career. It was normal for me to be the only woman in my working group. I tried my best to fit in with the group and not be seen as a woman much less a gay woman. I still have apprehension about my identity, but I am comfortable enough to live openly. My reluctance to openly identify started with regional and generational pressures and continued because I work in a field that is predominantly white male. I have become more comfortable in my own skin as I have aged, but also as I see new colleagues begin their careers. I do not want them to feel isolated like I did as a young professional. My identity does not determine my success as a professional but my ability to be my full self makes me more successful. I am attending UTSA because it is the first opportunity for me to continue my education relatively close to where I live and work. I am thriving in an environment that is accepting of diversity. One of the biggest benefits from the Master's program has been learning how to connect with people.

My knowledge of human dimensions and science communication research is quite limited. I am very aware of how important both are for natural resource professionals to remain relevant to society and how in general we have not succeeded in knowing our audience to communicate with them. I have participated in efforts to increase and improve hunter recruitment, retention, and reactivation, or the 3 R's my entire 15-years career as a professional wildlife biologist. The state agency for whom I work has spent many hours trying to "fix" this problem. For many years, I struggled with how to solve this "problem" too. Only recently did I recognize that the 3 R's is not a problem. The problem is not recognizing the huge group of people who participate in non-consumptive outdoor activities along with hunters. The Sci/Comm Scholar's working group has helped me find strength among other likeminded professionals. I have struggled to find my voice within my agency and have not asserted the importance of diverse user groups often enough. The Sci/Comm Scholar's working group has helped me to recognize that a non-receptive audience does not mean ideas should be suppressed. The Sci/Comm Scholar's working group has helped me hone my skills to reach diverse audiences in various forms. I will continue to do so as a professional with more confidence. I hope to remain objective when communicating with any audience regardless of my opinions. I would really like to bridge the gap between different audiences as I think we share a common passion for the resource.

Public engagement is a critical component of my research on the local distribution of Texas horned lizards (*Phrynosoma cornutum*). I underestimated the level of importance public engagement and community science would play in my Master's thesis project. Essentially, I would have no data to analyze without the community science reports of Texas horned lizards. I think I am competent when communicating with my community (especially rural communities) and although I had many people reach out to me with sightings, not a single person reported using my iNaturalist project. I did recognize that people were very excited to report sightings to me and grant me permission to use the exact same data as they were asked to report online. I reached out again with a request for sightings to be reported to me and received 50 reports between March and November of 2020. I also recognized that people responded well to hearing updates. I communicated with the community approximately five times (introduced my research 2019, requested sightings *via* iNaturalist 2019, requested sightings via iNaturalist 2020, requested sightings directly to me 2020, and updated the community on my findings along with the community sightings). I think the brief updates kept the interest among the community and I believe Dr. Amelia King-Kostelac referred to this concept as exponential interest reporting. I learned of this outcome prior to participation in the Sci/Comm Scholar's working group. I think I had some idea about the importance of communicating my need to the community, but I think luck helped me a great deal. My career has given me opportunity to develop confidence communicating with the public. The Sci/Comm Scholars program reminds me that I need to always keep my mind open to new ideas, technologies, and changing demographics.

I learned a lot about communicating with diverse audiences using a variety of media during the Sci/Comm Scholar's working group. I understand the importance of seeking new audiences and using social media to communicate, but I have not explored most media options. I am very guilty of using what is familiar to me and my agency when communicating to my community. The Sci/Comm Scholar's working group has made me realize that using the various forms of media available is the best education. I would prefer to use science communication accounts so that I do not have to create or use a personal account; I have a strong resistance to setting my own personal account because I think there is a blurred line between personal accounts and professional accounts. In addition, I do not feel that I align with the majority of my agency and I fear retaliation for my personal beliefs and identity. I have really enjoyed being among a more accepting and diverse community at UTSA. I would like the anonymity of a Sci/Comm Scholar's or school account to learn to communicate with various media forms.

I have a strong background working with students and community organizations on science projects. Most of my experience comes from my professional career but I have tried to engage as a fellow student. Since most of my experience has been through my agency, I think I have been very limited in terms of audiences and the way I communicated with them. My agency almost has a sole focus on consumptive wildlife users. Our programs, workshops, and even stewardship awards all center around land managers who use hunting as a management tool. As a Sci/Comm Scholar, I have really enjoyed learning about communicating with diverse audiences. I have lots more to learn regarding ways to reach these diverse audiences effectively. It has been a great help to discuss other Sci/Comm Scholars' projects because I learned about strategies used to communicate with diverse audiences beyond my target audience. I will continue to make an effort to learn about my audience before I speak to them. I will work hard to communicate science in a relatable way to each audience. And, hardest for me, I will work to add a personal touch to how I present science to each audience. I think it is extremely important not to approach communication with an agenda and the Sci/Comm Scholar's working group reminded me of this.

Scholar Three: Mary Finucane

I began to pursue my Master's degree in environmental science 18 years after receiving my Bachelor of Science in marine biology. Attending graduate school to earn a Master's in a scientific discipline had been a goal of mine for over a decade, but the path to graduate school was not linear for me. I grew up in an affluent area of San Antonio, and after high school graduation, I spent 14 years studying and working in California. When the timing, and quite honestly, my self-confidence, aligned for me to apply to graduate school for a Master's in environmental science, I only applied to UTSA. The primary reason for this is that my family and I are very rooted in this community and moving to a different city or state was not an option I wanted to pursue. Of the other colleges and universities in San Antonio, I was especially attracted to the research being conducted out of UTSA and the potential it offered me to be a part of the local scientific community of my hometown. At the time of my application, I did not know that UTSA was an HSI, or that a large portion of the student body were first generation college students. I am a white female that comes from a family in which every member going back two generations on both my maternal and paternal side have at least a Bachelor's degree. As I have aged, I have become more aware of this familial privilege, and know that many of my fellow graduate and undergraduate students have faced barriers to success that I have not. I do, however, hope to learn more about the needs of our student population and ways in which I can listen to, support, and serve these communities beyond my tuition and financial support of an HSI.

My thesis research focuses on a reintroduced population of an indigenous Black Bass species in an urban environment. Specifically, this research will provide valuable data on the population structure and the success of the reintroduced Guadalupe Bass (Micropterus treculii), a species of conservation concern which was one component of the ecological restoration of a 16.9 km stretch of the San Antonio River in 2013. Informal surveys and assessments by the Texas Parks and Wildlife Department (TPWD) and the San Antonio River Authority indicate that the reintroduction has been successful and that there is an actively reproducing population in the reach. However, my project will formally survey and statistically estimate the populations of both the Guadalupe Bass and the Largemouth Bass (*Micropterus salmoides*) in the restored reach. Additionally, I will be quantifying microhabitat use and availability by both species on a seasonal basis to further evaluate how both species are utilizing habitat features that were engineered for native species during the restoration. As a native San Antonian, I am thrilled to work alongside these city and state agencies to evaluate the success of the reintroduction and the river restoration. A unique aspect of my research is that all the field work data collection occurs in the heart of the city, where we are visible to walkers, runners, cyclists, anglers, and kayakers. During my first field season, I learned that many people are interested in my research, yet few know much about the Guadalupe Bass, or any other fish species that inhabit the San Antonio River. I am particularly motivated to tell the story of the restoration and the reintroduction to fellow San Antonians so they too can take pride in the steps their city has taken to restore original ecological function to our river. Discussions with the Sci/Comm Scholar's working group members based on their projects and experiences have enlightened me to the different ways I can communicate with members of the public to engage them in my research. Through continued collaborations with the Sci/Comm Scholar's working group, I hope to create and implement a public educational component focused on the value and success of the reintroduction of an indigenous freshwater fish species in an urban environment.

As a Sci/Comm Scholar, I have also been able to explore storytelling as a way to communicate with non-scientists (Neely et al., 2020). During my first semester in the Master's program, I was given an assignment to craft a scientific narrative in one of my core classes. This task initially seemed daunting and contrary to all the technical writing I was studying in different classes. We were encouraged to explore our creativity within a large range of scientific topics. I decided to use the assignment to tell the story of how my family ranch has played a role in the development of wind energy in Texas. Before wind turbines became a common sighting to anyone traveling along a highway in west Texas, our ranch was home to them because my father was one of the early landowners who worked with developers to lease our land for wind. As my sister and I have become the caretakers of our family ranch, we have witnessed how wind energy has been slowly shaping and integrating itself into the west Texas culture and livelihood. This assignment became pivotal in refining my goals as a student and for my future career. Not only did I enjoy the process of crafting my narrative, but my peers' stories also captivated me. Soon every scientific narrative book that was recommended and referred to in my class was on my nightstand, and I spent my winter break being transported into the wilderness of Yellowstone or the home office of an ecologist studying the alarming cancer rates within her community. As a former high school biology teacher, I know how imperative and challenging it can be to engage our youth, and the public at large, with current scientific research. Yet very little time or energy is spent in the endeavor of storytelling, and those who do publish articles, blogs, or books, are often doing this in addition to all their other responsibilities of conducting research. I knew that I wanted to present my research and experiences to those outside of the scientific community, yet I did not know how to take steps towards this goal, particularly with the demanding schedule of a graduate student and the responsibilities of family life.

Joining the Sci/Comm Scholar's working group provided me with the opportunity to develop my story telling and listening skills, while also creating a community and space for growth. This group provided peer feedback on my piece while also facilitating discussions surrounding the challenges of new technology (e.g., wind turbines) and their environmental implications (e.g., Smith and Dwyer, 2016). The interdisciplinary faculty mentors encouraged me to submit my piece for publication and guided me through the process of selecting and submitting to a publication. These are necessary skills for post- graduation success that are not often covered in the traditional curriculum. The Sci/Comm Scholar's working group also allowed me to work with students outside of my lab in our department. Through our meetings and discussions over Eres' and Sarah's research, I was exposed to the procedural challenges of creating an unbiased public survey and in garnering participation. Effective use of citizen scientists and social media platforms are additional components of science communication that were addressed through working meetings with Jamie's project. Most importantly, the opportunity to collaborate with students and faculty I may have not otherwise met if not for the Sci/Comm Scholar's working group highlights the importance of creating and maintaining relationships with other scientists, writers, and scholars for effective science communication as a graduate student and beyond.

Scholar Four: Sarah Gorton

I am a white, female, San Antonio native who grew up in the middle-class neighborhoods of north-central San Antonio. I have many privileges that come with this identity, and that cannot be stated enough. However, unlike my other middle and upper-income white classmates in high school I did not go to an Ivy League school. I attended UTSA because it was the only school that offered me scholarships due to my slightly inconsistent academic record. I chose to major in communications knowing it would be very difficult for me to pass the string of chemistry classes required for environmental science. After getting a full-time job in water conservation, I returned to UTSA to pursue a Master's degree since my former mentor encouraged me to return to his lab. I had the means to afford graduate school due to my full-time employment and few universities would accept an undergraduate with a Bachelor of Arts into a Master of Science program. I thought my historic inability to succeed in hard science courses (such as chemistry) was due to lack of ability, but in the last 2 years I have learned that I have a number of mental health disorders that have been the source of many of my struggles. Generalized anxiety disorder, severe recurrent depression, PTSD, and ADHD have plagued me throughout high school and college but went unnoticed and untreated as I met academic standards and excelled in areas that interested me. To further complicate things, in the midst of the Sci/Comm Scholar's working group I began experiencing symptoms for what I learned to be idiopathic hypersomnia, an incurable sleep disorder similar to narcolepsy. Where I had once ridden on the coattails of anxiety and placed my self-worth in my academic achievement, I am now no longer consistently able to stay alert enough to complete much more than an 8-hour day at work. The term "disabled" seemed far away when it was in relation to my mental health, but I now find myself struggling daily to complete more than basic tasks. Most days, itis a delicate dance to balance my former anxiety-fueled, overcommitted workaholism with the new reality of semi-coherent reduced-hour days. Once again I am privileged in that these are invisible disabilities that prevent me from facing any surface-level discrimination, particularly given that I am also a middle-class white woman.

My thesis research focuses on the uptake of heavy metals by native grasses, and thus their ability to decrease water pollution in urban areas. As urbanization spreads, so too do the associated negative impacts on water quality. Plants can be used to uptake pollutants through a number of processes collectively known as phytoremediation. Certain plants are outstanding at remediating specific pollutants and these plants are referred to as hyperaccumulators. Hyperaccumulator plants are often used for cleaning up heavily polluted soil, but they may not be ideal to introduce to an environment in which they are not native. Of particular concern is heavily polluted soils along roadsides where metal pollution can settle. Here, trees and woody plants often used in phytoremediation may be unsafe to plant (e.g., where there is potential for vehicular damage). Native grasses are easily maintained, safe to grow alongside roads, but have little research around their abilities to uptake heavy metals.

My research is applied in nature. However, the results for my research are not very actionable for most people. For example, action items following a presentation about my research might be to write a letter to local elected officials suggesting they plant native grasses for remediation purposes. Yet, I wanted my research to have a bigger impact than a letter to elected officials. Through discussions with the Sci/Comm Scholar's working group, it became apparent that I had to take a different approach and consider stakeholders. For this reason, my Sci/Comm Scholar's project merged the topics of my thesis and my professional career and looked at understanding knowledge and attitudes towards native plants and the Edwards Aquifer by HOA and neighborhood association members. The project methods involved identical pre- and post-surveys around a presentation on the benefits of native plants for water quality and conservation. Understanding where people's knowledge and attitudes lie and how they are impacted by educational outreach can help environmental science professionals craft targeted messages to encourage higher action rates. In this project, the call to action was encouraging residents to plant native plants in place of some, or all, of a turf grass lawn.

The Sci/Comm Scholars working group was a unique program that felt crafted for my background. As an undergraduate I majored in communication with a minor in environmental science. My undergraduate honors research was on acoustic monitoring of bats (Gorton and Hutchinson, 2019), but I spent my free time volunteering and educating people about the importance of bats and convincing them to love bats as much as I do. When I graduated, I went into the water conservation field where I have found myself crafting messages to encourage San Antonio residents to participate in water conservation programs through the local utility. Within the world of water conservation, there is not a lot of information on the impacts of education and communication efforts on water conservation behaviors. Most research focuses on the science of water savings from specific measures, but at this point most "passive" measures have been implemented at a policy level by requiring flow limits on fixtures.

Now water conservation efforts are focused on outdoor water use which requires education and behavior changes, which ties back into the necessity for human dimensions work.

I found the Sci/Comm Scholars working group's peer-to-peer model to be extremely beneficial. I do not learn well reading from textbooks or watching lectures. For me, learning is easiest when I have to actively participate and have an open dialogue. Having the opportunity to share my ideas with a diverse group of Scholars required me to consider a range of views. Guidance from faculty allowed me to focus on ideas and asking questions without fearing repercussions or hard-learned lessons from a lack of knowledge. Additionally, watching other Scholars develop projects led me to consider how their approaches and methods could apply in my career. For example, Jamie's experiences with landowners having government distrust is something I also experience on a somewhat regular basis. Her workarounds for these issues were unique and gave me inspiration for handling similar issues in the future. Many of the topics and concepts covered were rarely mentioned in my communication or environmental science classes, and if they were it was not explained in a way that I could enmesh for use in a human dimensions project. Our discussions on how to work through the cryptic IRB process were invaluable. Discussions around survey design helped me understand what made a survey question helpful and succinct. Perhaps what surprised me the most was how all members of the group (faculty and Scholars) were exceptionally patient and understanding throughout periods of time when my executive dysfunction was abysmal. Patience to that extent is not something I have experienced in a professional setting, and it has had a lasting impact on how I approach others in a work environment knowing how much it meant to me.

My participation in the Sci/Comm Scholar's working group has reinforced my belief that public engagement is important work. During my time as a Sci/Comm Scholar, some of the water conservation programs I assist with at work in my professional capacity have experienced lower participation rates. There is no clear explanation to why this is, but while a normal tactic might be to change up advertising or education techniques the Sci/Comm Scholar's working group has taught me that a more efficient method is to work with your audience to understand their responses directly. The Sci/Comm Scholar's working group has also strengthened my passion for science communication, and highlighted the importance of sharing information from human dimensions research. As an employee of a water utility, I would benefit greatly if another water utility published (peer-reviewed or not) the outcomes of any survey work or science communication projects they have completed. I hope to encourage others to do so by pursuing my own communication and human-dimensions work within my career and making it available to others when possible.

CONCLUSION

These Sci/Comm Scholars' narratives speak to the potential benefits of a facilitated working group model for inclusive science communication. By building a space for faculty-led and peer-supported human dimensions and science communication thesis work, these Scholars came to learn and rely on one another as much as they did faculty members. The Scholars' narratives are, themselves, evidence of the success of this group, as each narrative demonstrates their skill at communicating their research and professional identity. As the Scholars developed these narratives during the drafting process, we also witnessed the ways they validated, supported and informed each other's perspectives and contributions. Thus, the faculty facilitators deliberately chose not to add additional commentary to these student narratives because we believe they effectively demonstrate the value of peer-to-peer mentoring. While their projects are diverse, these MA thesis projects are unified by common experiences of methodological care with human dimensions and science communication research design, and the validation experienced through a supportive faculty-led peer-to-peer community. This work has not just helped these scholars navigate their thesis projects, but their professional careers as well. Additionally, they showcase how their identities as non-traditional students influenced their decision to attend UTSA, and how this minority serving institution has had a unique impact on each of these scholars' academic experiences and professional developments.

While there are limitations to integrating human dimensions and science communication (it can be difficult to cover the depth and breadth of these fields, for example), we still view this model as a largely successful method of integrating STEM, social science, and the humanities. Even as this program was formulated with intense consideration for the institutional context of UTSA, research suggests that many of the factors outlined here are important to minoritized students at a range of different institution types (e.g., Zaniewski and Reinholz, 2016; Kezar and Gerhke, 2017; Núñez et al., 2019), provided that such programs are part of larger institutional commitment to inclusion and equity (Elrod and Kezar, 2017). Of course, the work of the Sci/Comm Scholars is not yet finished. As most of these students aim to graduate in the next few semesters, everyone will be constantly supporting their work until graduation and beyond. As the National Science Foundation grant period winds down, we are also left with questions of how to sustain this work locally, as well as how to transport this model to similar institutions.

On those points, we note another common thread throughout these narratives: each scholar found immense value in a tailored methodological and communication experience not otherwise supported robustly within the program curriculum. Thus, the Sci/Comm Scholars' facilitated peer-to-peer working group model may be most effectively transferred to other minority serving institutions first before broad application elsewhere. At most institutions, access to robust conversations around research design, research ethics, and the thesis writing process often falls on a single advisor, or at best, a committee. But the faculty-led, peer-to-peer model not only exposed these students to diverse research pathways, it also led to exploring professional opportunities, and motivating their self-learning, largely based upon their peers' experiences and expertise. For faculty, sustaining this work is partly achieved by providing space for social scientists and humanists to serve as external committee members, but we also encourage other STEM departments toward another, potentially more transformative, next step, which happened for one of our own team members (Dr. King-Kostelac): hire social scientists and humanists to work within STEM departments to facilitate the work of transdisciplinary ecological research that continues to promote a vision of ecology that is deeply social and human, just as the social and the human are deeply ecological.

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.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by the UTSA Institutional Review Board. The patients/participants provided their written informed consent to participate in this study. Written informed consent was obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article.

AUTHOR CONTRIBUTIONS

KW, AK-K, and JS conceived the idea of the manuscript. KW, AK-K, JS, EG, JK, MF, and SG all contributed equally as participants of the Sci/Comm Scholar's working group that provided the foundations for this manuscript. JB and KW, along with the rest of the ASSIST team secured funding that permitted this work. KW, AK-K, JS, EG, JK, MF, SG, and JB contributed to the writing and editing of the manuscript and provided final input and approval before its submission.

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What Did They Learn? Objective Assessment Tools Show Mixed Effects of Training on Science Communication Behaviors

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There is widespread agreement about the need to assess the success of programs training scientists to communicate more effectively with non-professional audiences. However, there is little agreement about how that should be done. What do we mean when we talk about "effective communication"? What should we measure? How should we measure it? Evaluation of communication training programs often incorporates the views of students or trainers themselves, although this is widely understood to bias the assessment. We recently completed a 3-year experiment to use audiences of non-scientists to evaluate the effect of training on STEM (Science, Technology, Engineering and Math) graduate students' communication ability. Overall, audiences rated STEM grad students' communication performance no better after training than before, as we reported in Rubega et al. 2018. However, audience ratings do not reveal whether training changed specific trainee communication behaviors (e.g., jargon use, narrative techniques) even if too little to affect trainees' overall success. Here we measure trainee communication behavior directly, using multiple textual analysis tools and analysis of trainees' body language during videotaped talks. We found that student use of jargon declined after training but that use of narrative techniques did not increase. Flesch Reading Ease and Flesch-Kincaid Grade Level scores, used as indicators of complexity of sentences and word choice, were no different after instruction. Trainees' movement of hands and hesitancy during talks was correlated negatively with audience ratings of credibility and clarity; smiling, on the other hand, was correlated with improvement in credibility, clarity and engagement scores given by audience members. We show that objective tools can be used to measure the success of communication training programs, that non-verbal cues are associated with audience judgments, and that an intensive communication course does change some, if not all, communication behaviors.

Keywords: graduate training, education, evidence-based, audience, jargon, narrative, non-verbal, STEM

INTRODUCTION

Programs training scientists to communicate successfully with non-scientist audiences have been operational for decades, but rigorous long-term assessments of those efforts are rare. There is a growing need to resolve that deficit not only to ensure the most viable training is offered but also to allow an informed citizenry to decide public policy questions related to globally threatening scientific issues. Through respectful dialogue, scientists and others in society educate themselves and build support and legitimacy for scientific research (Lessner 2009; Nisbet and Scheufele 2009). Science communication training programs aim to prepare scientists for such dialogues, but how do we know if they succeed?

The few assessments reported are primarily based on anecdotes and self-report evaluations. Comparisons between methods are isolated (Silva and Bultitude 2009). Evaluation of communication training programs often incorporates the views of students or trainers themselves (Baram-Tsabari and Lewenstein 2013, Baram-Tsabari and Lewenstein 2017; Rodgers et al., 2018; Norris et al., 2019; Carroll and Grenon 2021; Dudo et al., 2021), although this has been demonstrated to provide a poor measure of actual skills (McCroskey and McCroskey, 1988; Dunning et al., 2004; Mort and Hansen, 2010). Calls are increasing for the need to assess science communication training (Fischoff 2013; Sharon and Baram-Tsabari 2014; David and Baram-Tsabari 2019), and more attempts are being made, but they still largely lack assessment from non-scientists. For instance, even a recently-developed scale to measure science communication training effectiveness (SCTE) focuses on the perspective of the scientist (Rodgers, et al., 2020). Thus, there is still little agreement about how that should be done: What do we mean when we talk about “effective science communication”? What should we measure? How should we measure it?

The need for more evaluation is made urgent by the proliferation of science communication training programs and by the breadth of approaches being used. Training programs vary from those lasting no more than an hour to full degree programs (Baram-Tsabari and Lewenstein 2017). The students range from graduate students to established STEM (Science, Technology, Engineering and Math) professionals; the pedagogical tools being used can include brief exercises as well as thick textbooks (Dean 2009; Baron 2010; Meredith 2010); and the emphasis can be on modifying communication behavior—emphasizing narrative techniques (Brown and Scholl 2014) or reducing jargon (Stableford and Mettger 2007)–or they can concentrate more on the need to understand audiences, including specific targets such as media and opinion leaders (Miller and Fahy 2009; Beasley and Tanner 2011). Training programs also have emphasized that the news media can be valuable in helping to translate scientific findings to the public (Suleski and Ibaraki 2009). Brevity, taking responsibility for statements, and the value of positive sentence construction are other values considered important for effective science communication (Biber 1995). Workshops and active exercises are a paramount tool of many trainings, although assessments of their value remain lacking (Miller and Fahy 2009; Beasley and Tanner 2011).

In a rare assessment that included experimental control and rigorous statistical analysis, Rubega et al. (2021) conducted a 3-year experiment to evaluate the effect of training on STEM graduate students’ communication ability, as judged by a large audience of undergraduate students in a large public university. In that study, graduate students who took a semester-long course in Science Communication were paired with untrained controls. Both the trained students and controls recorded short videos, both before and after the course, in which they explained the same science concept. Those videos were evaluated by an audience drawn from a large pool of undergraduates in a Communication course. Overall, audiences detected no significant change in STEM graduate students’ communication performance after training as compared to graduate students who were not trained. However, this surprising result left unanswered questions about whether student communication behavior changed in some areas but not others and whether changes were simply too slight to affect the assessment of overall communication success. Was use of jargon reduced, for instance, but not the complexity of sentence structure? Did some communication behaviors change but not others?

In this paper, we explore the usefulness of text analysis tools and behavioral coding to evaluate change in communication behavior and any resulting improvement in communication effectiveness. We analyze transcripts of short, standardized talks given by trainees before and after science communication training, and examine the relationship of body language (e.g., smiling, gesticulating) to audience assessments. Our aim was to determine whether grad student performance changed in particular areas in response to the training, even if that change did not improve their overall effectiveness as judged by audience members who may have been younger than but otherwise were representative of a specific, basically literate audience that is often a target of science outreach efforts.

MATERIALS AND METHODS

Once yearly, for 3 years (2016–2018), we taught a semester-long science communication course for graduate students in STEM disciplines; undergraduate journalism students also participated in the course. Working with non-scientists and aiding in the production of accurate news stories was one stated goal of the course. Working directly with journalists-in-training helped make the challenges concrete, and contributed to the journalists’ training, as well. We conducted the course as an experiment in which graduate students’ communication success was evaluated before the training and again at the end; the trainees were matched to controls who did not take the course and were evaluated at the same time steps. Our training focused on a communicator’s ability 1) to provide information clearly and understandably (clarity), 2) to appear knowledgeable and trustworthy (credibility), and 3) to make the audience interested in the subject (engagement). We hold that, while communication is a complicated, multistep process and communication experts disagree about the meaning of "effectiveness," it cannot be achieved in science communication or anywhere else unless each of these conditions exists. Evaluation was done by undergraduate students in a large Communication class, who viewed short videos of the STEM graduate students explaining the scientific process and rated their performance. The undergraduate evaluators answered questions (see **Supplementary Table S1**) related to the clarity of each presentation, the credibility of the presenter and the evaluators' engagement with the subject. We briefly describe the course, student selection and data collection procedures here; further details are available in Rubega et al., 2021.

The course consisted of a 4-weeks introductory phase in which readings on communication theory highlighted the role of scientists and journalists in public communication of science. We also discussed barriers to effective science communication (including jargon, abstract language, complexity and non-verbal behavior that could distract audience members), and we introduced various approaches to overcoming those barriers (e.g., Message Boxing, COMPASS Science Communication Inc., 2017; framing, Davis 1995; Morton et al., 2011; narrative structure, Dahlstrom 2014; Intellectual Humility, that is, openness to audience expertise and viewpoint: Lynch 2017; Lynch et al., 2016; for additional detail on course content, see Rubega et al., 2021 and its online **Supplementary Material**).

The 11 subsequent weeks of the semester were devoted to active practice and post-practice reflection on science communication performance. Each STEM student was interviewed twice by journalism students; the 20-min interviews were conducted outside of class and were video recorded. After each interview, the journalism student then produced a short (500-word) news story based on the interview. In subsequent course meetings, the entire class watched each video and reviewed the news story, discussing whether the news story was clear, whether there were any factual errors, whether the journalism student neglected to ask any important questions, whether analogies used by the STEM student were useful, and identifying the source of any misunderstanding by the journalist. Each student in the course was required to submit a written peer analysis/feedback form completed while watching each video. We discussed and critiqued with students the level of success the scientists had in communicating technical research issues, drawing connections between the communication behaviors of the scientist in each video with the conceptual material covered earlier. STEM grad student enrollment was limited to 10 students each semester. One student dropped out of the course too late to be replaced, leaving a total pool of 29 trainees.

STEM graduate students recruited as controls in the experiment were matched as closely as possible to the experimental subjects, based on discipline, year of degree program, gender, first language, and prior exposure to science communication training, if any. At the beginning and end of the semester, we asked both trainees and controls to respond to the prompt: "How does the scientific process work?" while we recorded them with a video camera. The prompt was unrelated to any specific tasks that were assigned in class; the aim of the training was to prepare them to apply what they had learned, and to successfully communicate about science, in any context. We selected this prompt because it is a question that any graduate STEM student should be able to answer, regardless of scientific discipline, and it removed the potential for audience bias that could be introduced by controversial subjects (e.g., climate change, evolution). In the video recordings, students were allowed to speak for up to 3 minutes but could stop as early as they felt appropriate. All recordings were made in the same studio, using the same cameras, positioning and lighting and a featureless background, under the direction of a university staff member. Videos showed only the head and shoulders of the trainee or control who was speaking.

The videos were evaluated by undergraduate students in the research participation pool of a large Communication class. Each semester, we uploaded "before" and "after" videos for trainees and controls to a Qualtrics XM (Qualtrics, Provo, UT, United States) portal. Students in the research participation pool could choose to participate in our research by selecting one of the videos to watch and evaluate. Each evaluator was assigned randomly by Qualtrics to view one video and provide ratings based on 16 questions designed to assess the trainees' communication success in the areas of Clarity (six questions such as "The presentation was clear"), Credibility (four questions such as "The speaker seems knowledgeable about the topic") and Engagement (six questions such as "The speaker seems enthusiastic about the subject"). All ratings used a 7-point Likert-type scale (1 = strongly disagree; 7 = strongly agree). Overall, 400 to 700 evaluators (M = 550) participated each semester, providing, after data quality control eliminations, a minimum of eight ratings per video, with most having 10 or more.

We downloaded survey data from the Qualtrics portal for analysis. We removed all responses from evaluators who incorrectly answered a "speed bump" question designed to eliminate ratings by evaluators who were not paying close attention to the videos. The video evaluation data were analyzed in a hierarchical generalized linear mixed-effects model, using a Bayesian statistical framework (see Rubega et al., 2021 for details). We found that trainees' overall communication ability improved slightly but not significantly differently from the change in control group scores. Here we use correlation analysis to investigate any relationships that Clarity, Credibility and Engagement scores have with individual trainee's communication behavior.

We also transcribed the audio from trainee and control videos, using the online transcription service Rev, resulting in one text document per video (N = 116). Each transcript was coded for three areas of interest: 1) overall language use; 2) jargon used; and 3) the use of metaphors, analogies, and stories. In addition, we used the videos themselves to analyze body language, and its relation to scoring by evaluators.

In order to assess language use, we used Linguistic Inquiry and Word Count (LIWC) analysis of student transcripts. LIWC analysis (Pennebaker et al., 2015) provides an automated count of the total number of words in a transcript and of the

TABLE 1 | Change in Linguistic Inquiry and Word Count (LIWC) scores of trainees after training.

	Before	After	*p*
Word count	314.1379	310.1034	0.8418
Analytic	**42.9897**	**50.8569**	**0.0363**
Clout	85.4386	84.2914	0.6806
Authentic	36.8090	43.7703	0.1534
Tone	43.2848	50.0838	0.1339

Values are means and p *values of paired t-tests of trainee Before and After scores (*$n = 29$ *in all cases). Significant results at* $p < 0.05$ *are in bold. "Function word" dimensions are composite measures of the use of words associated with traits or values: Analytic, words associated with logical or hierarchical thinking; Clout, words associated with relative social status, confidence or leadership; Emotional Tone, words indicating positivity and negativity, with higher scores indicating higher positivity; and Authentic, words associated with honesty, personal traits, vulnerability, humbleness.*

types of words used (e.g., pronouns, verbs, adjectives). Then, it matches words to a standard dictionary to generate scores of four summary dimensions: Analytical Thinking, Clout, Authenticity, and Emotional Tone. We also ran each transcript through Microsoft Word's Flesch Reading Ease and Flesch-Kincaid Grade Level calculators. While these are meant to assess the difficulty of written (not spoken) text, we believe they offer insight into the complexity of language used before and after training.

In order to measure whether trainees used less jargon after training, we submitted every transcript to the De-Jargonizer (Rakedzon et al., 2017). The De-Jargonizer is a software application that assigns words to categories based on how frequently those words appear in a corpus of more than 500,000 words published on BBC news websites from 2012 to 2015. The De-Jargonizer produces a final score (higher scores are more free of jargon) that depends on the proportion of rare or uncommon words to total words used. We cleaned all transcripts before analysis to remove partial words and "fillers" such as "um" and "uh," which the tool erroneously classified as rare words, inflating the final jargon use scores. We also modified the De-Jargonizer so that some words commonly used in spoken American English and/or not relating directly to science or scientific concepts would no longer be identified by the tool as jargon. The authors made the modification by submitting all transcripts to the De-Jargonizer, and then reviewing the list of all words identified as "Red" (or, rare, and therefore jargon) by the De-Jargonizer algorithm; all authors then reached a consensus on which should be considered scientific jargon. We eliminated words such as "fig," "burp," "yummy," "toaster" and "houseplant" that seemed in common use, and not arcane words that would be familiar only to a scientist or used in a scientific context (such as "ecosystem," "protist" and "photosynthesis"), which we felt could legitimately be considered scientific jargon. In addition, we moved some words originally assigned to a mid-frequency ("normal words") group to the jargon list ("hypothesis," "habitat" and "variable," for example). The modification reduced the total number of words used by all trainees and controls that were recognized as jargon from 125 to 73. A complete list of the reclassifications we enacted in the De-Jargonizer is in **Supplementary Table S2**. We compared STEM trainees' De-Jargonizer scores after training with those from before training, and also compared the difference to the before-and-later difference in scores from the control group.

Two of the authors (MAR and RSC) independently coded every transcript for the use of metaphors, analogies, or stories (narratives). Each coder separately counted and then summed the total number of text elements of analogies, metaphors or stories in the video transcriptions in each text.

Two research assistants independently coded videos for speech behaviors and body language. They coded for: speech rate (1 = Very slow—5 = Very fast); speech tone (1 = Very monotone—5 = Very dynamic); and how often each participant stuttered, paused, smiled, laughed, looked at or away from the camera, leaned forward, or moved their hands. Not all movements made by trainees and controls were captured in the videos so the numbers recorded represent a conservative estimate of the true number of movements. The coding sheet was developed in collaboration between the coders and one author (AOH) by watching sample videos to note possible behaviors to code. Both coders independently tested the coding sheet on a subset (10%) of the videos and discussed the results to increase consistency in coding. Coding uncertainties were resolved between coders and AOH, and the coders split the full set of videos for coding.

RESULTS

The LIWC summary variable "Analytic," which is based on eight "function word" dimensions, increased significantly, indicating that our trainees used more words associated with logical or hierarchical thinking after training than before (**Table 1**). Among other summary variables, Clout (words associated with relative social status, confidence or leadership), Emotional Tone (combines words indicating of positivity and negativity, with higher scores indicating higher positivity) and Authenticity (words associated with honesty, personal traits, vulnerability, humbleness) did not change after training. Word Count also did not change after training. The change between before and after did not differ significantly for any of the LIWC summary variables between trainee and control transcripts (**Table 2**).

The LIWC scoring of trainees' transcripts before and after training also provided output for 68 singular (non-summary)

TABLE 2 | Change in trainees' LIWC scores (After scores minus Before scores) compared to change in control scores.

	Trainees	Controls	*p*
Word count	–4.0345	–42.7586	0.2147
Analytic	7.8672	12.0079	0.4135
Clout	–0.1841	0.7031	0.8266
Authentic	9.1114	5.0328	0.5427
Tone	6.7990	–4.0114	0.1060

Results show means and p *values of paired* t*-tests of the difference in trainee scores with the difference in control scores. Trainees did not differ significantly in their change after training compared to controls in any "Function Word" dimension. Positive scores indicate the After scores were higher than Before scores.*

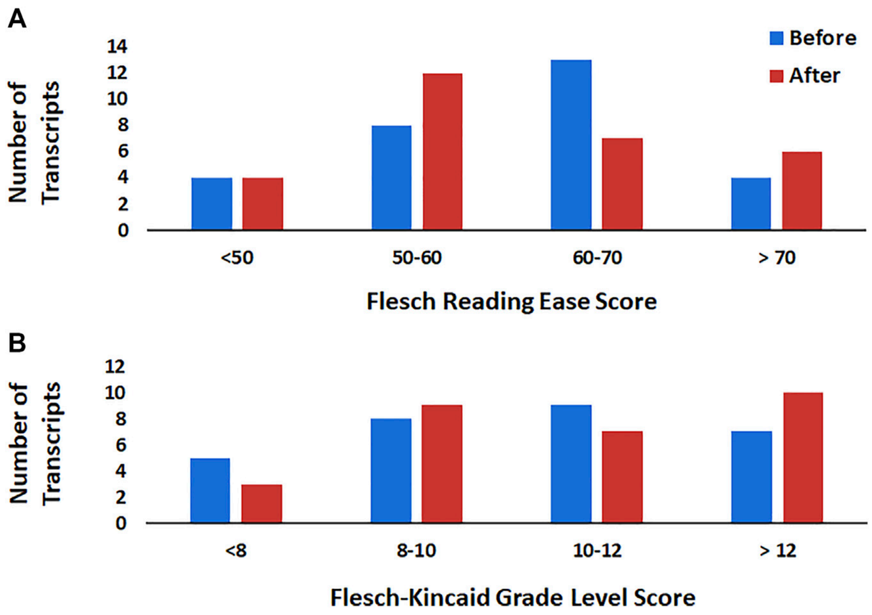

FIGURE 1 | Scores reflecting the **(A)** reading ease and **(B)** grade level assignment of the transcripts of trainees before (blue) and after (red) science communication training. There was no significant change in the mean reading ease or grade level scores after training, suggesting that, overall, trainees did not simplify the way that they spoke to audiences after training.

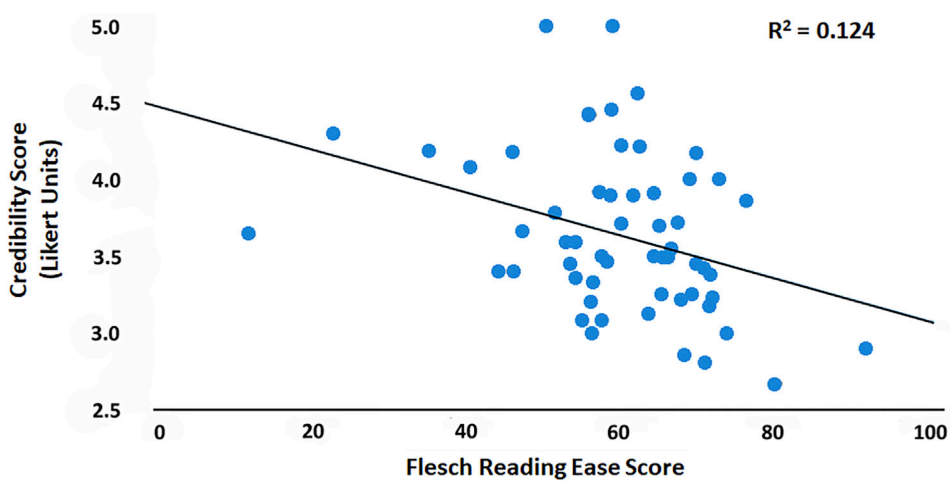

FIGURE 2 | Audience scoring of Credibility ("The subject is relevant to my interests") declines as transcript Reading Ease scores go up. The higher the Reading Ease score, the easier the text of the transcript is to read, i.e., the words and sentence structure are less complex.

variables that could be calculated (four scores could not be calculated because all of the Before or After scores were zeroes; twelve standard LIWC variables were eliminated from scoring because they related to punctuation use, which could not be appropriately assessed with video transcripts). The large number of variables LIWC creates, and the resulting large number of potential pairwise comparisons means that at least four false positive results could be expected by chance alone. Since we had no a priori hypotheses about any of the singular variables generated, we do not report those comparisons here, and did not pursue a more complex form of analysis of these variables. However, for those interested, we provide the output for each singular variable in the **Supplementary Table S3**).

The Flesch Reading Ease (**Figure 1A**) and Flesch-Kincaid Grade Level (**Figure 1B**) scores of trainees were not significantly different after instruction than before in paired t-tests. The mean Flesch score was 59.03 ± 2.7441 before training and 60.61 ± 2.0603 after training (t = −0.5693, p = 0.5737), and the Flesch-Kincaid score was 11.28 ± 0.8707 before and 11.16 ± 0.6737 after training (t = 0.1186, p = 0.9065). In

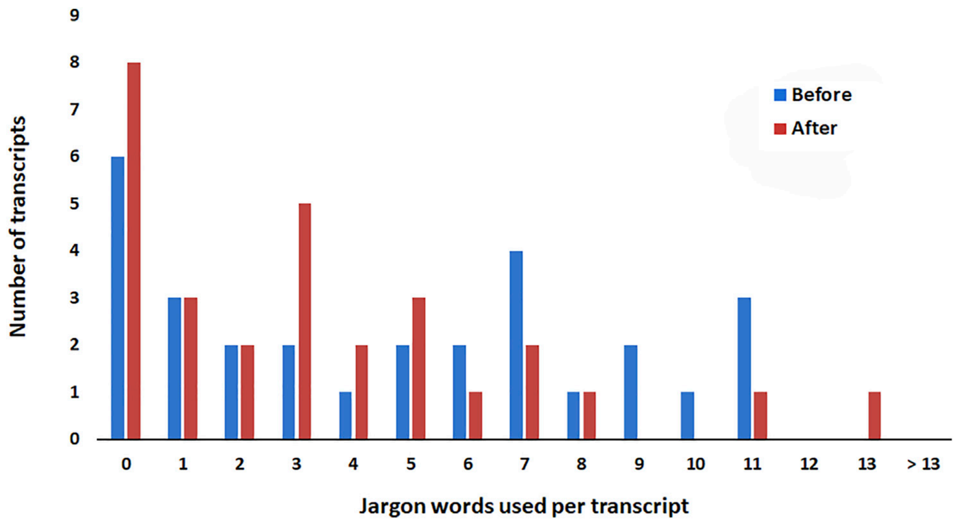

FIGURE 3 | Frequency of jargon use, per transcript, before (blue) and after (red) science communication training. After training, the number of transcripts in which trainees used jargon three or fewer times rose as the number of transcripts with high jargon frequency fell.

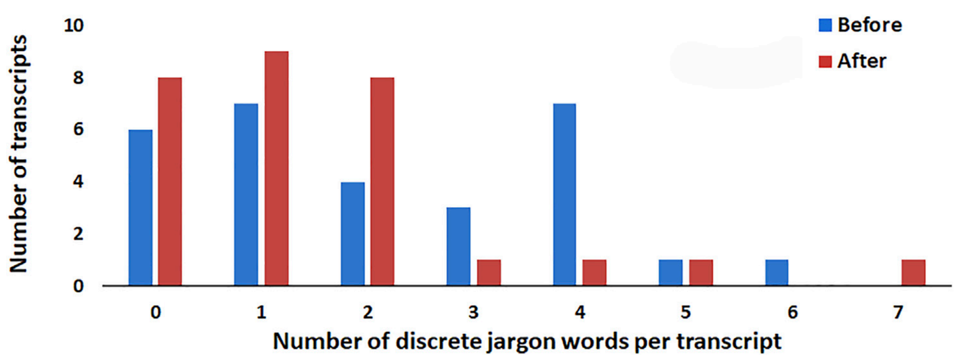

FIGURE 4 | The number of discrete jargon words used, per transcript, before (blue) and after (red) science communication training. After training, the number of transcripts in which trainees used two or fewer different jargon words rose, as the number of transcripts in which trainees used many different jargon words fell.

contrast, we found some indication that the simplicity of presentation matters, though not in the direction expected: Reading Ease scores of transcripts correlated negatively with audience responses to the Credibility prompt "The subject is relevant to my interests" (i.e., the easier the transcript was to read, the less the audience reviewers felt the subject being spoken about was relevant to them; **Figure 2**).

Overall, we did not find a significant change in the De-Jargonizer scores after training (means ± SE before/after in paired *t*-tests: 95.9 ± 0.3771/96.3 ± 0.3797; $t = -1.02$, $p = 0.31$). However, the mean number of times jargon words were used in trainee transcripts declined significantly (**Figure 3**; 4.7 ± 0.7142 before and 3.3 ± 0.6342 after; $t = 1.95$, $p = 0.0307$ in a one-sided test of the hypothesis that training reduced jargon use). In addition, the mean number of discrete jargon words that were used by trainees, on average, declined significantly (**Figure 4**; 2.2 ± 0.3257 before, 1.5 ± 0.3003 after; $t = 1.74$, $p = 0.0450$ in a one-sided test of the hypothesis that training reduced jargon use). The apparent contradiction in these results–no change in De-Jargonizer scores, even though jargon use declined–results from the way the De-Jargonizer score is calculated; specifically, it is the proportion of rare or uncommon ("normal" words is the term used in the De-Jargonizer; uncommon but not jargon) words to total words used. Although trainees used fewer rare (= jargon) words, they used more uncommon words, rather than replacing jargon with common words. Thus, any gain in the De-Jargonizer score that would have resulted from reducing jargon words was largely erased by the increase in uncommon words, on average.

Neither the mean number of times jargon was used nor the mean number of discrete jargon words used in a transcript changed in the control group (5.1 ± 0.9249 before, 4.9 ± 0.7187 after for total number of times jargon words were used, $t = 0.3060$, $p = 0.7619$; 2.0 ± 0.2914 before and 2.0 ± 0.2829 after for the number of different jargon words used, $t = 0$, $p = 1$).

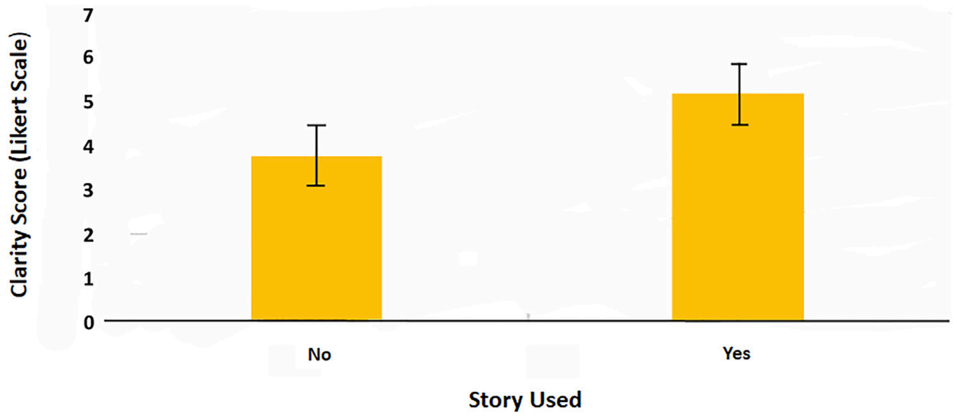

FIGURE 5 | Clarity scores for transcripts in which trainees did (right hand panel) and did not (left hand panel) use elements of story, metaphor and/or analogy.

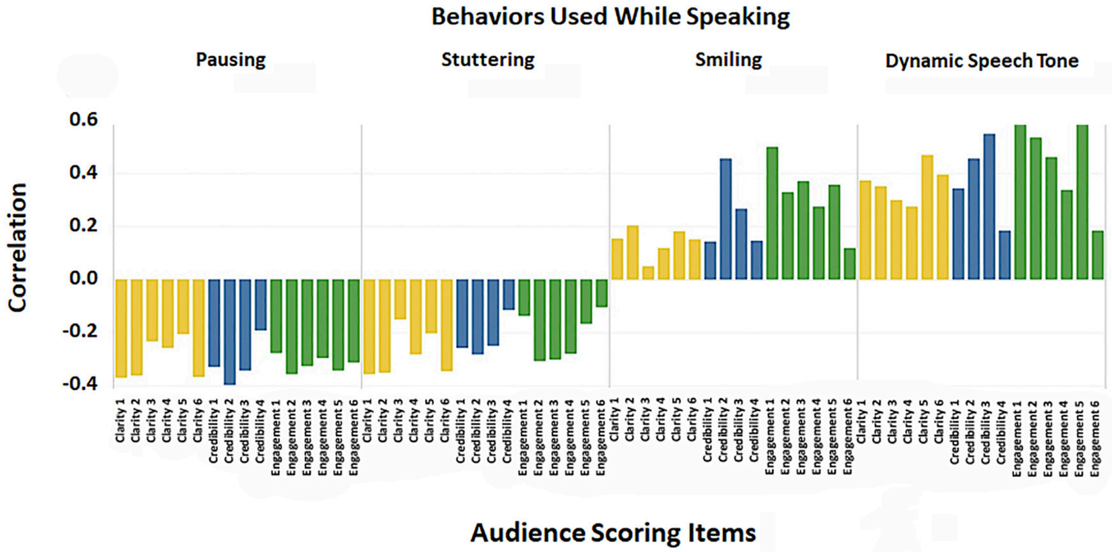

FIGURE 6 | The relationship of behaviors exhibited during speaking to clarity (yellow, left bar in each panel), credibility (blue, middle bar in each panel) and audience engagement (green, right bar in each panel). Pausing and stuttering during speaking are associated with low scores from audiences on all dimensions of communication performance; smiling and a dynamic speaking tone are associated with high scores from audiences. See **Table 3** for correlation values.

Further evidence that trainee jargon use declined came from examining the number of trainees using jargon at low vs. high frequencies. The number of trainees who used jargon three times or fewer rose from 13 before to 18 after training. The number of trainees using jargon words seven times or more dropped from 11 before to 5 after. The number of trainees using two or fewer different jargon words increased from 17 (59%) before to 25 (86%) after. Before the class, 12 trainees used three or more different jargon words, but after the class only four trainees did. Overall, we conclude that training reduced the use of jargon.

In contrast to the shift in jargon use, we found that training did not significantly increase the number of trainees who used metaphors, analogies, or narrative techniques in explaining the scientific method to a non-scientist audience. In one coding (RSC), 17 of 29 trainees used at least one story, metaphor or analogy before training and 22 of them used at least one such tool afterwards. In a second, independent coding (MR), 16 of 29 trainees used at least one story, metaphor, or analogy before and 21 used at least one after training. The increase was not significant in Fisher's exact test, regardless of coder ($p = 0.263$ in the first analysis and $p = 0.274$ in the second). However, audiences responded to the use of stories when it occurred; frequency of story or metaphorical elements in a transcript correlated with higher scores on an element of Clarity related to audience understanding (**Figure 5**).

TABLE 3 | Correlations among trainee communication behaviors and audience ratings on measures of Clarity, Credibility, and Audience Engagement (see **Supplementary Table S1** for specific items).

	Clarity						Engagement						Credibility			
	1	2	3	4	5	6	1	2	3	4	5	6	1	2	3	4
Laughs	—	—	—	—	—	—	0.295**	—	—	—	0.211*	—	—	—	—	—
Stutters	−0.357**	−0.352**		−0.283**	−0.203*	−0.347**		−0.306**	−0.303**	−0.279**	—	—	−0.259**	−0.283**	−0.251**	—
Pauses	−0.370**	−0.363**	−0.232*	−0.258**	−0.205*	−0.368**	−0.276**	−0.357**	−0.326**	−0.295**	−0.342**	−0.313**	−0.328**	−0.398**	−0.342**	−0.193*
Speech rate	0.304**	0.309**	0.333**	0.262**		0.363**	0.414**	0.334**	0.229*	—	0.285**	0.301**	0.389**	0.352**	0.347**	0.195*
Speech tone	0.374**	0.351**	0.298**	0.274**	0.470**	0.395**	0.623**	0.535**	0.462**	0.337**	0.642**	0.185*	0.342**	0.456**	0.549**	0.184*
Smiling	—	0.202*	—	—	—	—	0.500**	0.330**	0.370**	0.275**	0.357**	—	—	0.456**	0.266**	—
Verbal fillers	−0.416**	−0.410**	−0.290**	−0.293**	—	−0.417**	−0.287**	−0.305**	−0.206*	−0.244**	−0.396**		−0.260**	−0.341**	−0.323**	
Looking away	−0.188*	−0.213*	—	−0.219*	—	—	—	—	—	—	—	—	—	—	—	—
Hand movements	—	—	—	—	0.222*	—	0.317**	—	—	—	0.483**	—	—	0.218*	0.240*	—
Head movements	—	0.213*	—	0.201*	—	0.230*	0.249**	0.240*	—	—	0.308**	—	—	0.241**	0.191*	—
Body movements	—	—	—	—	—	—	0.187*	—	—	—	0.237*	—	—	—	—	—

*$p < 0.05$, **$p < 0.01$. Only significant correlations are presented.*

We found no change in elements of non-verbal communication after training compared with behavior before training when we analyzed the number of stutters, pauses, laughter, use of "verbal fillers," incidence of smiling, changes in speech tone, or frequency of head movements, hand movements or body movements used by trainees. However, we found that some behaviors were clearly correlated with the scores for Clarity, Credibility and Engagement given to students by undergraduate audiences in our experiment (**Figure 6**; **Table 3**). Pausing and stop-and-start speech were negatively correlated with both Clarity and Credibility. Smiling was correlated positively with Clarity, Credibility and audience Engagement. Varying a speaker's tone was correlated with higher Clarity, Credibility and audience Engagement.

DISCUSSION

Our results show that it is possible to gain insight into the effects of science communication training on the specific ways in which trainees do, and equally importantly, don't change their approach to communicating science. On one hand, our analysis shows that, on average, training reduced the number of jargon words trainees used, and the number of times they used them. On the other hand, most trainees still used some jargon, and overall, their speech remained pitched at about the same level of difficulty in understanding for the audience as before training. In some dimensions, such as their use of words associated with logic and hierarchical thinking, their speech became more complex, rather than simpler. They were no more likely after training to use metaphors, analogies or stories, which are widely viewed as effective science communication techniques, and which were covered extensively in their training.

These results underpin, and help explain, our earlier results (Rubega et al., 2021) showing that audiences did not find the communication of trainees more effective after training than before. To a large, and disheartening, degree, trainees simply are not enacting the techniques and behavior that training aims to instill. Our data cannot address why this might be, though our anecdotal observations during the after-training video recordings suggest strongly that trainees simply did not actively prepare by using techniques they had been trained to use in class, such as the Message Box: they just extemporized in the same way that they had before training. While none of the trainers expected, and we would not have allowed, the use of notes or an outline, it is not too much to say that we were astonished at the lack of strategic preparation. A 3-min time limit is a demanding form, and the difficulty of being brief while also being clear and engaging was often discussed in class. Acknowledging that, it is all the more surprising that they apparently did not prepare. They were informed at the beginning of the course that they would be expected to re-record their attempt to explain how the scientific process works; they had control over when they were scheduled to do so; they spent 15 weeks in active practice and engagement with the ways in which communication fails without active preparation. Why didn't they prepare for this relatively simple, predictable task? We suspect that the lack of preparation for the after-training communication task that we saw in our students is a side effect of the inflated sense of self-efficacy demonstrated in a variety of other training contexts, as well as in our study (McCroskey and McCroskey, 1988; Dunning et al., 2004; Mort and Hansen, 2010; Rubega et al., 2021): a trainee tends to conflate understanding with the ability to perform.

Although behaviors often addressed in science communication training (e.g., smiling to increase the impression of friendliness and relatability; speaking without verbal fillers), did not change, we did find evidence that these behaviors matter: audiences rate students who frequently pause during speaking lower on scales of Clarity and Credibility; they rate students who smile frequently, and who avoid speaking in a monotone, as more clear, more credible, and more engaging. Those students who did employ stories were rated more highly for Clarity. As an illustration of the complexity of what we might view as "success" in science communication training, the more simply a student spoke (as measured by the reading ease of transcripts of speech), the less relevant the audience found their topic. This surprising result ought to give us pause when thinking about how science communication training is structured, and for whom. In some contexts, such as interactions with policy makers, the goal of making the subject relevant and credible may have to be balanced against other goals, such as jargon reduction.

What are we to take away from these results? One point that stands out clearly is the importance, before beginning any science communication training program, of defining what will count as successful training in terms of metrics that are clearly defined, repeatably measurable, do not rely on self-reporting or assessment by either the trainer(s) or trainees, and are related to evidence-based effects on audiences. While the results of our work were not what we hoped for in terms of students' communication effectiveness, this failure did nothing to shake our belief that objective measurement of communication success is both possible and essential. Some tools are available already and more are needed. While we felt it needed adjustment, the De-Jargonizer was easily adapted to use with written transcripts of video recordings of short talks for non-professional audiences. The reading ease and LIWC tools were even more easily applied, and both provided valuable information on student performance, free of the bias associated with student or teacher assessments.

While a cognitive grasp of the barriers to communication is unquestionably a necessary precursor to successful performance, it is clearly insufficient, just as you can't improve your backhand by only reading about following through with the racket. Assuming the analogy is correct, introduction to evidence-based concepts underlying successful science communication is only one component of training, distinct from, and arguably less important than, an emphasis on the need for active preparation for every encounter, and actual practice. A single, short training is likely to be valuable for making trainees aware of science communication concepts; it is unlikely to have any effect on performance. How much practice, and what kind of practice, is necessary before changes in communication behavior begin to take hold for trainees? We are unaware of any rigorous study of that question but view it as an important question for future development of time- and cost-effective science communication training programs.

It's plausible that no science communication training course can provide enough time and practice to change communication behaviors within the time stamp of the course itself. Instilling a growth mindset in trainees–getting them to acknowledge that they will fail repeatedly on the way to succeeding–may be more important than any other component of science communication training. The biggest barrier to creating skilled science communicators may well be the willingness of trainees to continue using preparation techniques, and practicing, instead of just "winging it" on the mistaken belief that knowing about how to communicate is the same as being able to do so successfully.

DATA AVAILABILITY STATEMENT

The anonymized data supporting the conclusions of this article will be made available by the authors; direct requests to margaret.rubega@uconn.edu. In accordance with the terms of our human-subjects research approvals, and in order to protect the privacy of the participants, the videos from which the raw data derive will not be made available.

ETHICS STATEMENT

Permission for human subjects research was granted by the University of Connecticut Institutional Review Board, Protocol #016-026. The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

RSC, AO-H, RW, and MAR designed the experiment from which the data are drawn; RSC, RW, and MAR designed and taught the classes on which the experiment was based. RSC and AO-H conducted the data analyses. KRB recruited and managed the controls, conducted the video recordings, maintained datasets, and contributed to analysis. All authors contributed to the writing of the paper.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fcomm.2021.805630/full#supplementary-material

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An Epidemic Analogy Highlights the Importance of Targeted Community Engagement in Spaces Susceptible to Misinformation

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The study of the misinformation and disinformation epidemics includes the use of disease terminology as an analogy in some cases, and the formal application of epidemiological principles in others. While these have been effective in reframing how to prevent the spread of misinformation, they have less to say about other, more indirect means through which misinformation can be addressed in marginalized communities. In this perspective, we develop a conceptual model based on an epidemiology analogy that offers a new lens on science-driven community engagement. Rather than simulate the particulars of a given misinformation outbreak, our framework instead suggests how activities might be engineered as interventions to fit the specific needs of marginalized audiences, towards undermining the invasion and spread of misinformation. We discuss several communication activities–in the context of the COVID-19 pandemic and others—and offer suggestions for how practices can be better orchestrated to fit certain contexts. We emphasize the utility of our model for engaging communities distrustful of scientific institutions.

Keywords: misinformation, community engagement, epidemiology, COVID-19, science communication

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INTRODUCTION

Over several decades, the science of information has effloresced into a sophisticated technical field, comprising scholars of the humanities, psychologists, communication theorists, computer scientists, and others. Exemplars include the study of how misinformation and disinformation can spread faster than truths (Vosoughi et al., 2018) or how "hashtag activism" manifests in social justice movements online (Jackson et al., 2020). More recently, perspectives from the science of epidemiology have been invoked towards the general science of information contagion. The "misinformation as disease" analogy has grown into its own subfield, with public health experts suggesting practical, disease-oriented interventions (Scales et al., 2021). These studies identified the basic reproductive number of misinformation campaigns (Cinelli et al., 2020), and even discussed ways to "immunize" populations against misinformation by pre-emptive campaigns (Maertens et al., 2021). At the very least, the infectious disease analogy highlights the seriousness of the misinformation crisis, and how information has features that allow it to spread through digital spaces. Moreover, these analogies have now provided the language and methods for one to describe how misinformation spreads over networks of interconnected individuals, and highlighting the centrality of social media spaces (e.g., Facebook) as hubs.

That a science surrounding the contagiousness of information was already developing prior to the 2010s was critical, as the decade would present two global events--a worldwide neo-fascist movement and the COVID-19 pandemic--where the spread of misinformation would be central and carry dire consequences. For example, believing in COVID-19 conspiracy theories is predictive of a number of troublesome outcomes, including a higher chance of testing positive for COVID-19, job loss, reduced income, social rejection and decreased overall well-being (van Prooijen et al., 2021).

During the COVID-19 era, evidence-based social science has provided important insights into what makes misinformation contagious and pernicious, especially on social media(Ferrara et al., 2020; Krittanawong et al., 2020). What is clear from such work is an acute need to transfigure the study of science communication into practical means through which one can stymie the propagation of mis- and disinformation as recently exemplified by the COVID-19 pandemic. Here, we develop a qualitative schematic-analogy based compartmental infection model (as classically used in epidemiology) of misinformation. We use this schematic to deconstruct the many routes that mis- and disinformation can propagate through an ecosystem of individuals and how science driven community engagement can be appropriately used as an intervention.

This is especially applicable to marginalized and low-resource communities that are affected by structural violence or poor health outcomes, justifying ongoing mistrust of science or medical information. For example, in the COVID-19 pandemic, communities of color in the United States had infection and mortality rates higher than whites for the much of the American wing of the pandemic (CDC, 2019; Chowkwanyun and Reed, 2020; APM Research Lab Color of Coronavirus, 2021; Tai et al., 2021). These communities are examples of settings where nonspecific approaches to addressing misinformation are ineffective. Alternatively, the context that surrounds marginalized communities implores very specific interventions.

In sum, the many forces that foster the spread of misinformation have created a status quo where scientists, journalists and public health officials must regularly compete with anti-science messaging for the dominant narrative surrounding scientific and health-related information. The model we propose helps to identify specific groups of people and the communication efforts which may be most effective to utilize. Further, it addresses a critical challenge of science communication: how to ensure the programming that we've designed is addressing the specific needs of the audience that it is intended for.

The Public Misinformation and Education Model (PME)

For many decades, mathematical modeling efforts have been crucial for organizing available information, transforming the unknowns into testable hypotheses, and providing projections of how disease may progress under a set of assumptions (Lofgren et al., 2014; Cobey, 2020). Epidemiological modeling has been a centerpiece for thinking about contagion from actual diseases to supernatural contexts (França et al., 2013; Adams, 2014), or even in purely fantastical digital worlds (Lofgren and Fefferman, 2007).

The most widely used of the modeling efforts involves the compartmental Susceptible (S)-Infected (I)-Recovered (R) framework. While it is based on simple differential equations, the entire S-I-R approach has been so successful because the model building process is abetted by a visual instrument, whereby the modeler can build mathematical relationships between the actors in a model based on a structured notation and logic. This method is widely taught in introductory coursework in epidemiology, dynamical systems, even calculus courses.

In this perspective, we use the structure of S-I-R models to build a non-mathematical analogy for a system where misinformation steers a population of individuals towards being misinformed. Our model, called the PME model (**Figure 1**; Public Misinformation and Education Model) uses original names for the individual compartments and uses the framework as a guide to anchor a new qualitative model for considering how to build interventions based on the specific scope of a misinformation problem.

Person-Compartments. Our model comprises two sets of populations, corresponding to people (**Table 1**), and information (**Table 2**). The people compartments include the broader population of individuals susceptible to conversion to a misinformed (***M***) or informed (***E***) status. The model also contains a population of science communicators (***SC***). These are individuals in society who are equipped with the scientific knowledge and tools to properly create accurate content and counteract misinformation. These can be professional scientists who, because of formal science communication training or a related experience, regularly engage the public. Also, educators (at all levels) who teach members of the public in formal or informal settings qualify.

Information-Compartments. The information compartments in our model correspond to the body of information that the individuals in the person-compartments interact with. The ***IM*** component, corresponding to misinformation, serves as the body of misinformation that the public might become exposed to *via* social media and other sources. The *IA* box, alternatively, is the body of accurate information that comes from formal education (e.g., coursework), scientific engagement activities, and accurate social media memes all of which are generated by science communicators (***SC***).

As demonstrated in **Figure 1**, the PME model coordinates these compartments into a dynamic system where information interacts with populations of individuals. Arrows correspond to different relationships and interactions between compartments. In **Figure 1**, [*a*] corresponds to the rate at which the public becomes misinformed. [*b*] corresponds to the rate at which the public becomes properly educated. [*c*] is the rate at which the misinformed become properly educated, and [*d*], the rate at which the educated become science communicators (***SC***). Solid arrows (→) correspond to full transitions. That is, when one compartment becomes another, as in the transition from the

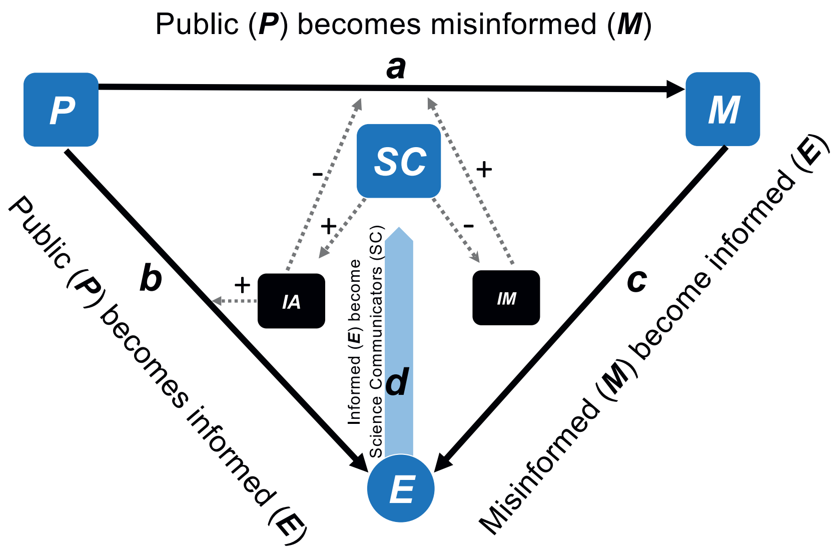

FIGURE 1 | The PME Model. This is a simplified visual compartmental flow diagram of misinformation and disinformation. Solid arrows correspond to transitions between individuals. ***[P]*** corresponds to the public that is undecided with regards to scientific understanding surrounding a scientific phenomenon. ***[M]*** corresponds to those members who are misinformed. ***[E]***, those individuals who are informed and acting on accurate scientific information. Letters a – d correspond to different transition states. For more details, *see* **Tables 1–3**. Several dashed arrows describe places where a compartment influences another process or compartment. Positive (+) and negative (–) signs correspond to type of effect on the process.

TABLE 1 | PME model person-compartments.

Person-compartment	Definition
P	The broader public of individuals who are susceptible to misinformation, but can also be educated with accurate information
M	The population of individuals who are misinformed
SC	The population of science communicators. They function in stymying the propagation of misinformation [IM] and the growth of misinformed individuals (M). Note that these need not be formally trained scientists
E	The population of individuals are properly informed, equipped with the facts

These describe the compartments in the model that correspond to people.

TABLE 2 | PME model information-compartments.

Information-compartment	Definition
IA	Resources and memes containing accurate technical information, corresponding to that agreed upon by a scientific consensus at a given time
IM	Resources and memes containing inaccurate information. This might have been the product of more passive processes (as in standard misinformation)

*These describe the compartments in the model that correspond to bodies of information that interact with the people discussed in **Table 1**.*

TABLE 3 | Terms that define the transition between certain compartments.

Transition	Explanation
a	***P*** → ***M***: process through which the public (***P***) becomes misinformed (***M***)
b	***P*** → ***E***: process through which the public (***P***) becomes informed
c	***M***→ ***E***: process through which the misinformed become informed
d	***E***→ ***SC***: process through which the informed become science communicators

TABLE 4 | Example interventions and their connection to the PME model.

Class of intervention	Example(s)	PME model explanation
Curricular changes to STEM education	Laboratory-based courses that teach complex ideas such as evolution Efforts to improve critical-information skills in primary and secondary schools	Enhances the process associated with [b]: through which the public becomes informed (***P*** → ***E***). Decreases the process associated with [a]: rate through which people become misinformed (***P*** → ***M***). Also increases the amount and quality of accurate information, [***IA***]
Community engagement	Engagement with faith leaders on COVID-19 science and vaccine advocacy (e.g., scientists speaking to local churches in the Harlem neighborhood in New York City about the COVID-19 vaccine) Scientists and physicians appearing on popular cultural podcasts or radio stations to address public health issues	Enhances process [*b*]: the rate through which the public becomes informed (***P*** → ***E***). Also potentially increases the process through which the misinformed become informed, [*c*]
Science communication training	Courses that teach science students how to write broadly across genres Social media driven events that highlight diversity in science communicator space (e.g., "Black in Science Communication Week"), Norton (2020)	Enhances process [d], that through which individuals who are already gain skills in science communication (***E***→ ***SC***)
Social media engagement activities	Live Q & A sessions with public health experts or science communicators producing shareable content related to public health issues	Can actively debunk and decrease the amount and quality of misinformation, [***IM***]. Can increase resources and memes containing accurate technical information [***IA***]. Can amplify [c]; that through which the public becomes informed (***P*** → ***E***)
"Pre-bunking" activities	Courses developed to help students spot misinformation. Understanding the susceptibilities that conspiracy theorists exploit helps us identify ways to better safeguard the trustworthiness of health science and public trust in it	Decreases the rate in which the public becomes misinformed, [*a*]

We identify the types of interventions, and specifically where they may aid in the preventing the spread of misinformation. This can facilitate the anchoring of activities to meet specific challenges and community contexts.

public to misinformed (***M***) or educated (***E***) at rate [*a*] or [*b*]. Dashed arrows, on the other hand, correspond to the relationship between a compartment and the rate at which one of the transitions is occurring (*a-d*). For example, science communicators (***SC***) produce accurate information (***IA***), remove misinformation (***IM***), increase the rate, [*b*], through which the public becomes educated (***E***), and decrease the rate through which the public becomes misinformed, [*a*].

The PME model comes with several features that may foster a new perspective on the modern problem of misinformation in vulnerable and marginalized communities. As observed in **Table 4**, interventions can be engineered that address certain transition points of the model. Below we outline these transition stages, discuss the types of suitable intervention, and how they interact with the ecosystem outlined.

P → *M*: Process Through Which the Public (*P*) Becomes Misinformed (*M*)

As has been measured and documented in many studies, social media has emerged as a major instrument in the propagation of misinformation, across various paradigms, for over a decade. Further, conspiracists have actively exploited COVID-19 science for manipulative purposes (Jamieson, 2021). This played a particular role in the spread of misinformation and disinformation, especially with regards to the COVID-19 vaccine (Loomba et al., 2021). For example, in the United Kingdom, 5G masts were set on fire based on misinformation linking 5G to COVID-19 a theory that was trending on twitter under the #5GConronavirus hashtag (Ahmed et al., 2020). This is but one of the many types of misinformation campaigns which have helped to undermine effectiveness of good public health practices.

"Immunizing" P Against the P → M Dynamic

Tools for preparing the public to engage misinformation. Pre-bunking is based on the idea of "psychological inoculation," whereby an individual learns how to identify misinformation tropes, which would decrease susceptibility to misinformation (Maertens et al., 2021). It is based on the idea that misinformation often has a fundamental structure, and knowledge of this structure may aid our quest to lower its contagiousness (Douglas et al., 2019). A number of tools and content have been created to help people identify their own vulnerabilities and the weaknesses of media and also improve individual evaluation of quality of information. These include courses aimed at spotting misinformation (Breakstone et al., 2021) and games (Basol et al., 2020).

P → *E*: Process Through Which the Public (*P*) Becomes Informed

Just as social media has been weaponized for misinformation, the powers of social media are also being put into use by educators, scientists, physicians and public health experts in innovative ways towards educating people on science and thus aiding in the public becoming informed. For example, during the COVID-19 pandemic, multiple social media platforms including

Instagram and TikTok were used to create and share content related to the biology and evolution of SARS-CoV2 the virus which causes COVID-19, the messaging behind non-pharmaceutical interventions, as well as pharmaceutical interventions like vaccines. This social media content increased the [*IA*] *pool*, corresponding to the availability of quality information. Ideally this information (and its sources) is reliable, trustworthy, factual, multilingual, targeted, accurate, clear, and science-based information. In addition, there is a growing literature on the utility of podcasts as a mechanism for science outreach and education, an additional means through which the public can be properly informed (Birch and Weitkamp, 2010; Hu, 2016).

Targeted practice. In addition, live social media sessions can be effective, where scientists can engage with the public and help them navigate health decision-making processes in an empathetic manner by answering questions. For example, during the early stages of the pandemic, Black physicians and scientists gathered on Clubhouse (a voice-only social media application) to interact and provide accurate information to the public (Turton, 2021). That Black healthcare workers and scientists led the effort was critical, as they were answering a specific call to engage members of the Black community who were curious or distrustful. And this is demonstrative of the type of targeted interventions that are necessary to generate an educated public (***E***), using context-specific tools. In general, these efforts highlight the need for culturally-sensitive and inclusive science communication (Manzini, 2003; Canfield and Menezes, 2020), especially for neglected communities (Wilkinson, 2021).

*STEM education activities to improve science literacy***.** As science literacy is largely the responsibility of public education systems, an individual's or a community's understanding of basic scientific facts and the scientific process more broadly are closely linked to the level of formal education received (Trapani and Hale, 2019; Besley and Hill, 2020). Thankfully, the STEM education paradigm has begun to develop original and provocative education curricula that tackle complex topics such as molecular evolution, using laboratory-based methods. These courses have had a demonstrated positive effect on how students perform on assessments targeted to Next Generation Science Standards (Cooper et al., 2019).

M→ *E*: Process Through Which the Misinformed Become Informed

Any communicator who has firsthand experience addressing this transition (including the authors of this perspective) will testify to its difficulty. In general, it cannot occur until the misinformed individual is prepared to embrace new information. At the level of the community, this challenge is amplified. In this scenario, a vulnerable community is identified, and programming is engineered to fit the needs of that community. Grassroots efforts are often the best examples of this and involve the recognition of that faith leaders are influential in some communities (Abara et al., 2015; Santibañez et al., 2017). In marginalized communities, science communication requires empathy and acknowledgment of why communities may distrust scientific institutions.

Practitioners of science communication collaborating with knowledgeable and trusted members in minoritized communities, who curate spaces for discussions, have several goals: to uncover how distrust pervades and impacts a community, while simultaneously addressing misinformation and defusing hesitation among members of the community. This creates an ideal ecosystem for the delivery of accurate information which aims to result in behavior change.

Relatedly, communication efforts with minoritized communities need to be carefully tailored to incorporate politics, history and how these factors interact to affect these communities' engagement with science. Practitioners must embrace the complexity inherent in these spaces by expressing humility and asking respectful questions, acknowledging the valid concerns of the community (i.e openly recognize historical oppressions, discrimination and inequities which contribute to mistrust in science and authorities). Note that many of these ideas are similar to the tasks associated with the $\underline{P} \rightarrow \underline{E}$ transition discussed above.

There are myriad examples of science communication where the cultural sensitivity of interventions has been critical to the effectiveness of messaging. For example, the 2014 Ebola virus pandemic, which affected several countries in West Africa, provided a scenario from which lessons can be learned about effective science communication that results in behavior change. In this scenario, practitioners tapped into the folklore and indigenous communication practices of the region's communities, specifically their rich heritage of traditional modes of community engagement. One such mode was partnering with Griots—West African troubadours, storytellers, historians, poets, praise singers and musicians. These figures utilized story and music to communicate key scientific and public health messages to communities. This proved an effective platform through which science communication and public engagement could engender the trust and buy-in of local communities, which resulted in behavioral change that had a positive impact on containment of Ebola (Deffor, 2019).

Such approaches illustrate the transformative power of language, culture, and Indigenous knowledge in attempts to communicate in settings that are potentially rife with misinformation. They also emphasize the benefit of culturally assertive approaches and practices which build on and harness the values of communities in question (Canfield and Menezes, 2020; Finlay et al., 2021; Wilkinson, 2021).

E→ *SC*: Process Through Which the Informed Become Science Communicators

There is a dire need to increase the pool of scientists and healthcare professionals who are properly trained to communicate complex science matters in a simple format to the public. The challenge in training science communicators is in the fact that science communication (or "Sci-Comm") is a multifaceted skill, involving:

- Ability to gain public's trust and be relatable
- Ability to explain complicated concepts using simple language
- Building on current expertise, while not speaking on matters too far outside of one's area of expertise

Impactful science communicators often make use of the power of combined visuals and storytelling to improve the effectiveness of their messaging, improving recall and enhanced understanding as well as increased engagement with content. These attributes can be especially beneficial for communities with low health literacy/scientific literacy. That is, marginalized communities, like the ones who suffer disproportionately from the COVID-19 pandemic, need effective science communicators.

Because of the many skills necessary to be an effective science communicator, training them can be challenging. It is a skillset that is rarely taught at any level of education, nor directly emphasized in scientific training. Additionally, many science communicators attribute their growth in the craft to being self-taught or learning by practice. Thankfully, there are several new initiatives that are aimed at improving the ability of scientists to communicate with the public. For example, newer curriculum aimed to teaching science graduate students to write across different genres has been effective in improving writing ability through aiding in students' ability to gauge audience, and other important dimensions of science communication (Harrington et al., 2021). This is just one example of many initiatives that falls under the umbrella effort to train professionals in science communication (Silva and Bultitude, 2009; Besley and Tanner, 2011). Though this perspective hasn't focused on journalists, they are a critical actor in how information propagates. And many modern effects in training professionals to communicate science with the public has focused on journalists specifically (Menezes, 2018; Smith et al., 2018).

More broadly, we argue that the amplification of refined education programs that transform science practitioners into communicators is an underappreciated means through which one can intervene in the spread of misinformation. The PME model highlights how the science communicator compartment affects the dynamics of the system in multiple ways. They produce accurate information that is digestible to the public [IA] and help to debunk inaccurate or misleading information [IM].

SUMMARY

In this perspective, we offer a conceptual model that adds further depth to epidemiological analogies for the spread of misinformation. We offer that the existing models, while effective for a more general dialogue around preventing the spread of misinformation, have undervalued the context-specificity of the misinformation ecology. We offer a new qualitative model, based on epidemiological principles, but engineered around a nuanced understanding of the specific transitions in the spread of misinformation, which reveals the many indirect ways that one can intervene. Importantly, our model highlights the role of grassroots interventions, and the importance of programs that train science communicators. Furthermore, our model also reveals the specific place for "pre-bunking" and innovative STEM education approaches.

More important than any single intervention, we propose that "one size fits all" approaches are ineffective, and that interventions should be tailored to the individual needs of settings, with targeted goals in mind. This will require that the individual doing the communicating have intimate knowledge of the setting in which they operate. For example, approaching a group of individuals who are already deeply embedded in the misinformation ecosystem with classical STEM education tools will be a waste of effort. Similarly, an aggressive or persuasively pro-science message may not be necessary for those who simply want to understand the basics or have earnest questions about how complex phenomena work. It is our hope that our framework aids these efforts towards more nuanced and targeted messaging, that can undermine the process through which the public becomes misinformed.

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

Both authors conceived the idea, performed the analysis, and wrote the manuscript.

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Topical Analysis of Nuclear Experts' Perceptions of Publics, Nuclear Energy, and Sustainable Futures

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Nuclear energy experts consider commercial power from fission to be a strong contender to help mitigate the increasing effects of climate change, in part due to its low-to-no carbon emissions. Nevertheless, nuclear energy's history, including meltdowns such as Three Mile Island, Chernobyl, and Fukushima, and dumping in sacred Indigenous land such as Yucca Mountain, raises important concerns in public deliberation over nuclear power. These communicative dynamics are crucial to study because they inform larger conversations in communication scholarship about the role of experts in scientific controversies and the complicated nature of public trust in and engagement with science. Thus, this study explores the perspectives of experts and how they make sense of their own communicative practices through a topical analysis of semi-structured interviews with 12 nuclear scientists and engineers in the United States and Canada. Our analysis revealed four major *topoi*: (1) risk and safety, (2) government and policy, and (3) public education and engagement, and (4) cost, along which nuclear experts make sense of science-public boundaries and their role as scientists and scientist citizens. This paper extends our understanding and how scientists view themselves as communicative actors and the barriers and opportunities for how we can foster productive technical-public relationships around climate change solutions.

Keywords: energy rhetoric, nuclear energy, topoi, scientist citizens, climate change, monologue, dialogue

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INTRODUCTION

In our current age of environmental crises, there is a pressing need to foster relationships between technical and public actors to together establish sustainable futures. One area of scientific study aimed at exploring viable alternatives to fossil fuels is nuclear energy, which harnesses the unparalleled release of energy from splitting atoms. Trust in nuclear scientists and purveyors of nuclear power directly affects public opinion on subsequent acceptance of nuclear energy (Ho et al., 2019), making them key figures in nuclear energy deliberation. Nuclear energy, much like the larger, "wicked," interdisciplinary problem of climate change (Cagle and Tillery, 2015), is made up of seemingly disconnected "institutions, practices, and a dense network of representations and meanings" (Kinsella, 2005, p. 49). Wading into these complicated arenas is often not a priority for scientists, who may not have access to communication training or the incentives to seek out those resources. Consequently, science communicators often "speak of [science] more elegantly than the very scientists themselves" (Fahnestock, 1986, p. 331), leading to divides between scientists and the public not unlike the scientific controversies of climate change and the COVID-19 pandemic.

Scientists may be wary of public engagement because they do not want to be viewed negatively by other scientists or face harassment and backlash from the public (Waldman and Heikkinen, 2018). Some scientists fear the "Sagan effect," named after astrophysicist and *Cosmos* host Carl Sagan, which correlates an expert's amount of public interaction and media attention with less professional competence (Ecklund et al., 2012). Additionally, scientists may be penalized by both technical and public actors for seeming to cross the acceptable boundaries of science into politics (Walsh, 2010; Latour, 2014). Fortunately, research by Kotcher et al. (2017) suggests that some of these fears may be exaggerated, as their study found that scientists' credibility and trust in science was largely unaffected by public advocacy statements.

The study's one exception to this trend was the scientist who advocated for building more nuclear power plants (Kotcher et al., 2017). This scientist's perceived credibility did suffer when making advocacy statements, thereby demonstrating the fraught nature of public communication around nuclear energy and the various risks scientists take when engaging with public audiences on the topic (Kotcher et al., 2017). These perceived and potential risks of technical-public interactions dampen interest in public science communication and consequently hamper the most "promising candidates for bridging technical and public knowledge," scientists themselves (Pietrucci and Ceccarelli, 2019, p. 101). Pietrucci and Ceccarelli (2019) argue that scientists are the best bridges between the technical and public spheres because "they dwell in both" (p. 101). But, if technical experts, such as nuclear scientists, are fearful of such interactions, we may be "left with a dangerous gap between science and the public that can have disastrous results" (Pietrucci and Ceccarelli, 2019, p. 98).

These breakdowns between technical and public actors in our current moment could lead to inaction on environmental and health crises such as climate change and the COVID-19 pandemic, resulting in the loss of life, disproportionately across vulnerable and marginalized communities, and a failure to protect future generations and the planet (e.g., Sowards, 2012; Holifield et al., 2017; Reverby, 2021). Technical-public communication is thus integral to intervening in our various crises, especially environmental ones, because they center discussions of science, trust, expertise, and collaboration. Within the larger conversation about environmental crises, we focus on nuclear energy as a ripe arena for assessing public-technical dynamics and how scientists are making sense of their dual roles as scientists and science communicators. Simply put, nuclear scientists not valuing technical-public interactions can create barriers to conversation and collaboration that shut concerned publics out of energy deliberation.

For example, technical-public collaborations on nuclear energy might help overcome barriers to public participation, create regulations around nuclear waste, and leverage the potential benefits of nuclear energy while reducing its negative impacts. For example, research shows that nuclear energy could help combat the effects of climate change (Besley and Oh, 2013; Serp et al., 2017; Prăvălie and Bandoc, 2018), provide certain health and medical benefits (Kharecha and Hansen, 2013; Hacker et al., 2015), and contribute to global biodiversity conservation (Brook and Bradshaw, 2014). There are considerable drawbacks and concerns about nuclear energy, however, that necessitate public involvement and the incorporation of local, community needs with science. Evaluating the benefits and harms of nuclear energy with the expertise and experiences of both scientists and publics becomes more urgent as time passes and the consequences of the climate crisis loom ever larger.

This study thus joins a growing interdisciplinary interest in nuclear energy and nuclear experts. Many scholars who analyze nuclear rhetoric do so by highlighting public voices such as competing industries, anti-nuclear organizations, political groups, activists, and affected populations (e.g., Stoffle and Evans, 1988; Lynch, 2012; Goodin, 2013; Hynes, 2013; Thakur, 2013; Zhu et al., 2016). In their editorial introduction to a special issue of *Environmental Communication*, Ho and Kristiansen (2019) note that most studies of nuclear energy focus on media coverage of accidents and public opinion. Pointing to noticeable gaps in the literature, they call for more studies of nuclear energy that attend to long-term messaging, international comparative studies, and digital media's role in nuclear communication (Ho and Kristiansen, 2019). Missing from this list, but we feel necessary to add, is technical nuclear rhetoric, or discourse from within the technical sphere of nuclear energy.

Technical rhetoric in the nuclear energy industry has been a marginal area of study in communication, with notable exceptions (e.g., Kinsella, 1996, 1999; Endres et al., 2016; Summers et al., 2019). These studies have primarily been guided by ethnographic methods, making our methodology of interviews an opportunity to expand our understanding of how nuclear experts make sense of technical-public relationships and their careers in their own words. Scholars in other disciplines, such as sociology and policy studies, have begun engaging in such work (e.g., Shim et al., 2015; Harris et al., 2018; Saraç-Lesavre and Laurent, 2019; Schweitzer and Mix, 2021a,b). Schweitzer and Mix (2021a,b), for example, interviewed nuclear experts, advocates, and opponents in France, a country more familiar with nuclear power.

As a preliminary look into how nuclear scientists and engineers conceptualize public-technical interactions, this study performed a topical analysis of the personal perspectives of a small group of nuclear experts. In 2018, we performed semi-structured interviews with 12 nuclear scientists and engineers recruited via snowball sampling based on interest, availability, and expertise. All experts have obtained graduate degrees within a range of specific nuclear disciplines and with varying lengths of time participating in the nuclear industry (see **Table 1**). Questions (see **Appendix**) addressed the state of nuclear energy communication in North America. Interviews were conducted until saturation was reached regarding repeated themes and patterns. While this particular pool of individuals does not represent the views of all nuclear specialists, our topical analysis of these interviews reveals important areas for understanding the technical community's perspective on nuclear energy and public-technical interactions.

Topical analysis, which focuses on the appearance of *topoi,* or commonplace topics, reveals patterns and lines of argument. Topical analyses have previously been used to explore

TABLE 1 | Interviewee details.

Interviewee	Job description	Starting decade in the nuclear industry
1	Radiochemist	2010s
2	Nuclear physicist	2000s
3	Radiochemist	1990s
4	Nuclear engineer	1990s
5	Nuclear physicist	1990s
6	Nuclear engineer	1970s
7	Nuclear engineer	2010s
8	Nuclear engineer	2000s
9	Nuclear engineer	2000s
10	Nuclear physicist	1980s
11	Nuclear engineer	1960s
12	Nuclear engineer	2010s

environmental rhetoric in digital spaces and interviews (e.g., Ross, 2017; Cagle and Tillery, 2018; Tillery, 2018; Bloomfield and Tillery, 2019). Ross (2017) argued that *topoi* "appear operational as both generic, inventional topics and context-sensitive, argumentative heuristics" (p. 94). For example, nuclear scientists using terms such as "risk" may simultaneously be addressing broad categories of risk management, inherent risks in science, and specific risks from nuclear practices and accidents. *Topoi* can play an essential role in the process of "invention," through which ideas for argumentation, communication, and shared ground for collaboration emerge (Cagle and Tillery, 2018, p. 136).

In what follows, we offer a brief timeline of important moments in nuclear energy's history. Then, we describe the literature on public-technical relationships, the "scientist citizen," and dialogue that guides our analysis. Then, we interpret the interview data across four *topoi* that emerged during the interviews: (1) risk and safety, (2) government and policy, (3) public education and engagement, and (4) cost. We argue that these *topoi* manifested as inventional resources through which nuclear experts made sense both of their own roles as nuclear experts and of technical-public relationships. Together, these *topoi* provide insight into the rhetorical dynamics of nuclear energy from a technical perspective, albeit one that was variable and non-monolithic. We largely found that experts deploy features of both monologue and dialogue, which points toward barriers to technical-public engagement on nuclear but also potential opportunities. We conclude by considering future directions for research into nuclear energy communication and how these *topoi* might also constrain and inform other scientific topics.

IMPORTANT MOMENTS IN NUCLEAR ENERGY'S HISTORY

Controversies are rarely wholly novel; instead, they are re-emergences of "well-known paths of argument" that may become "dormant" but then "reappear" later (Goodnight, 2005, p. 27). In thinking of contemporary controversies over nuclear energy, it is useful to contextualize issues of "approach and avoidance, fear and hope, [and] risk and security" that have threaded through nuclear energy's history and informed our current moment (Goodnight, 2005, p. 26). In particular, nuclear energy's history tells a story of political and military priorities outranking public, local, and Indigenous concerns, in addition to long-standing issues with safety and risk management that help explain historical and contemporary skepticism toward nuclear energy.

A history of nuclear energy arguably starts with the discovery of uranium and radium in 1896 and 1902, respectively. The early twentieth century saw an explosion of interest in groundbreaking scientific discoveries using these materials, until it was discovered that they were highly toxic (Santos, 2021). In 1934, Irène Joliot-Curie and her husband Frédéric discovered artificial radioactivity, the fundamental science behind nuclear weapons. By the early 1940s, construction had started on the three primary locations for the development and construction of nuclear weapons: Los Alamos, New Mexico; Richland, Washington; and Oak Ridge, Tennessee (National Atomic Testing Museum, 2021).

These construction projects displaced Native Americans who had occupied the land for thousands of years. Many Native Americans continued to return to their sacred religious and cultural lands until the U.S. government installed physical barriers and armed security (National Atomic Testing Museum, 2021). A specific controversy over nuclear waste storage erupted when the Yucca Mountain Nuclear Waste Repository was established by the Nuclear Waste Policy Act of 1987 to serve as a disposal site for used fuel and other high-level radioactive wastes. In response, the Western Shoshone National Council issued land permits to anti-nuclear protestors at the Nevada Test Site and filed a federal lawsuit citing the 1893 Treaty of Ruby Valley that showed the land was never given to the US (Klenke, 2020). Although storing nuclear waste at Yucca Mountain is now "effectively off the table" (Klenke, 2020), the battle has been hard fought and illustrates the tensions between nuclear energy and Indigenous populations, lands, and sovereignty (Endres, 2009b).

In addition to displacing Native Americans and damaging Indigenous lands, nuclear energy was also used as a weapon of war. The first-ever nuclear weapon was detonated on July 7, 1945, and shortly thereafter, the Little Boy (August 6) and the Fat Man (August 9) were dropped on Hiroshima and Nagasaki, Japan, respectively, resulting in the country's surrender in World War II on August 14. The total number of casualties, injuries, and affected lives is not exactly known but is estimated to have taken the lives of upwards of hundreds of thousands of people (Tomonaga, 2019).

In 1953, then-President Eisenhower introduced the "Atoms for Peace" campaign aimed at quelling concerns about nuclear energy and committing the US to "peaceful" uses of the material, while the US and the Soviet Union increased their control and infrastructure of nuclear warheads (Kinsella et al., 2015). In 1954, Eisenhower signed the Atomic Energy Act that supported the development of atomic energy for peacetime uses, specifically the future of commercial nuclear power. The simultaneous development of wartime and peacetime uses of nuclear energy sent conflicting messages about its safety and functions.

Further complicating public support of nuclear energy was a history of accidents at nuclear power plants. One of the first accidents happened in 1950 when the Chalk River research reactor was mishandled, resulting in a meltdown and release of radioactive material into the environment (Lewis, 1953). In 1979, *Allen et al. vs. the United States of America* was filed by residents downwind from the Nevada Test Site, many of whom had developed cancers due to their proximity to the nuclear tests (National Atomic Testing Museum, 2021). 1979 was also the year that the Three Mile Island plant suffered a meltdown and channels for emergency communication failed, causing public trust in nuclear to be irreparably damaged (Farrell and Goodnight, 1981; Endres et al., 2016). One of the most famous nuclear meltdowns, the Chernobyl disaster, occurred in 1986 as a result of human error both in the operation and management of nuclear technology in the Soviet Union (Rich, 1986). Throughout the 1980s, the Cold War was at the front of everyone's minds (Gusterson, 1996), especially those running in the international nuclear arms race. These circumstances only strengthened the association of nuclear technology and nuclear professionals with militarization, weapons, and secrecy (Kinsella et al., 2015). In 2011, an earthquake resulting in a tsunami caused a meltdown in the Fukushima Daiichi nuclear power plant. Although the meltdown event did not result in any immediate deaths, the communication regarding the accident was contaminated (Kinsella, 2012; Endres et al., 2016), and public trust deteriorated with the reactor core (Kim et al., 2013; Tateno and Yokoyama, 2013; Besley and Oh, 2014; Endres et al., 2016).

The history of nuclear technology is riddled with controversies, corruption, lawsuits, and violated treaties, providing important context to public skepticism of nuclear power and the dynamics that influence potential public-technical collaboration on these topics. In order to build trust with a skeptical public and prevent further atrocities from occurring, it is imperative that the flow of information between the technical and public spheres include not only information from the technical to the public, but also participation and feedback from the public to the technical. Themes of colonialism, eminent domain, and Indigenous displacement are far too common and mostly unresolved as the industry moves forward without addressing past atrocities. If these rhetorical blockades can be broken down, there may be hope for technical-public collaboration on nuclear energy's future that involves the public as a key stakeholder and engages nuclear experts in the moral, reciprocal features of being bridges between technical and public arenas.

MONOLOGUE AND DIALOGUE IN INTERVIEWS WITH NUCLEAR EXPERTS

Following Bloomfield and Tillery's (2019) methodology, we first identified "recurring themes" in the interviewee responses and organized those under commonality and shared meaning (p. 25). Then, we analyzed those themes for constructions of public-technical relationships and their personal role as scientists. These interpretations are informed by scholarship on scientist citizens (Pietrucci and Ceccarelli, 2019), dialogue (Johannesen, 1974; Bloomfield, 2019a), and science-politics boundaries (e.g., Walsh, 2010; Latour, 2014) to examine how scientists make sense of their communicative practices. Within each *topos*, we first analyze evidence that experts engage a monologue and reinforce science-public boundaries. Then, we discuss evidence that the experts engage a scientist citizen identity and a dialogue approach to science-public boundaries.

"Scientist citizen" is a term that emphasizes the dual identity of scientists as simultaneous public and technical actors. Emphasizing this dual identity, Pietrucci and Ceccarelli (2019) argue that scientists have a "special responsibility" to engage in public-facing work rooted "in moral values (*arête*), goodwill (*eunoia*), and practical judgment (*phronesis*)" (pp. 101, 98). In other words, scientists' credibility is a matter not only of scientific expertise but also of their public evocation of morality, benevolence, and thoughtful action. In a different article, Ceccarelli (2020) elaborated that a scientist citizen's *arête* involves a commitment "to the virtue of honesty" and *phronesis* involves a sense of prudence and timing specific to particular contexts and situations (p. 242). *Eunoia* is often directly translated as "goodwill," but also means "approval, sympathy, and readiness to help" (de Romilly, 1958, p. 92). We thus locate qualities of honesty, virtue, prudence, readiness to help, and sympathy as characteristics of scientist citizens, which can foster opportunities for public-technical engagement.

By traversing the spheres, the scientist citizen persona calls into question what is traditionally viewed as appropriate scientific actions. Walsh (2010) calls this divide the "is/ought boundary," which denotes how scientists *should* normatively operate in the realm of knowledge, states of existence, and fact-gathering (i.e., "what *is* the severity and urgency of climate change?"), while political actors operate in the realm of action, policy, and deliberation (i.e., "what *ought* we to do about it?"). Latour (2014) framed this divide as "science-vs.-politics" (p. 147). Notions that science should only be concerned with communicating facts distinguishes technical and public stakeholders as having or not having knowledge, respectively, as opposed to respecting varying expertise and backgrounds as differently valuable (Endres, 2009a).

Focusing on a lack of knowledge evokes the information deficit model (IDM), which argues that filling a knowledge gap will increase public agreement with the topic at hand (Gross, 1994). Ultimately, studies have provided evidence that the IDM is an oversimplified model and that differences in knowledge are not solely responsible for lack of agreement between technical and public actors (Marteau et al., 2002; Bloomfield et al., 2020). Additionally, some studies argue that providing information that focuses on information gaps can create backfire effects, lead audiences to feel the information is personally irrelevant to them, and make conversations more difficult (Hart and Nisbet, 2012; Fernández, 2016; McFadden, 2016).

Based on the terminology of Johannesen (1974), we describe discourse that embraces the scientist citizen role, focuses on bridging science-public divides, and sees public audiences as equals as engaging in "dialogue." Alternatively, we describe discourse that focuses on information deficits, concretizes science-public divides, and views public audiences as inferior to scientists as engaging in "monologue." These two overarching terms organize our topical analysis to show how varied nuclear experts' attitudes are toward technical-public interactions and how monologue can stifle productive engagement and reify boundaries between scientists and the public. We now turn to our interviews with nuclear experts and show how attitudes of monologue and dialogue emerged across three of the *topoi*, risk and safety, government and policy, and public education and engagement, with the fourth *topos*, cost, dominated by monologue.

Risk and Safety

Risk and safety, collectively, was the most prominent *topos* expressed by nuclear experts, indicating a recognition of public concern over the risks of nuclear energy and radioactivity. It is often assumed that scientists and engineers perceive risk differently, guided by numbers, data, and statistics (quantitative risk), which is distinct from publics who largely conceptualize risk on a more personal and community level (qualitative risk). Consequently, it may be challenging for scientists and engineers to translate risks accurately due to the incompatibility of interests and frameworks from which experts and the public operate.

Monologue

Monologue in the risk and safety *topos* primarily appeared in devaluing the public's fears over nuclear risks and thereby treating public audiences as inferior conversation partners. For example, participant 1 noted, "people are afraid because they do not understand; people who understand embrace it." While this may be true for select instances in this expert's experiences, it is important to note that these perceptions over-emphasize knowledge as influencing acceptance of science (e.g., McFadden, 2016). Furthermore, this comment views nuclear fears as primarily coming from ignorance, undercutting the knowledge and rationality of those concerned about nuclear risks. A majority (eight) of the experts interviewed said that events like major nuclear accidents have significantly inflated the public's fear of radiation, inherently increasing public perceptions of the risk associated with nuclear power plants.

Statements from interviewees indicated that most felt the public's fears were not reasonable, thus downplaying the rationality of the public. Discussions of nuclear fears as irrational is called "radiophobia," which is a strategy to de-prioritize public concerns over nuclear energy used after the Chernobyl disaster (Novikau, 2017). Some of these comments indicate that interviewees believe that public fears can be blamed mostly on their own misunderstandings, instead of recognizing how the industry has helped to manifest those perceptions.

Many interviewed experts (nine) believe that nuclear energy is safer than most people think, which prevents agreement with technical experts. For example, participant 3 explained that as the "current [domestic] fleet of reactors is aging, [...] people are trying different reactor designs" that enhance safety, security, and efficiency. Participant 3 refers to new reactors being built with increased safety measures since the most recent accident at Fukushima Daiichi. Participant 7 thinks that nuclear "has the most strict regulatory requirements" compared to other energy options and that these advantages "should be communicated better" to ease public worries about safety and relative risks. In emphasizing communication simply as knowledge-transfer, these participants deploy a monologue and see public audiences at a knowledge deficit that increased communication can correct. It is important to note that a blanket call for communication is not in and of itself dialogue; dialogue is a specific type of communication that values everyone's perspectives. These comments, therefore, are more closely akin to a monologue that assumes people will eventually agree with the "right" perspective, the nuclear industry's perspective, with more information and dismisses disagreement with experts as ignorance of the topic.

Despite a focus on risk related to nuclear accidents, few interviewees addressed risks associated with storing nuclear waste. This is a notable absence because waste is a prominent topic, as previously mentioned, for Indigenous communities and marginalized populations. These responses suggest that this is not an issue at the forefront of experts' considerations of nuclear risk, thereby further marginalizing local populations that are dismissed by attitudes of nuclear colonialism in the US (Endres, 2012, p. 329).

Dialogue

The risk and safety *topos* also contained evidence of dialogue. In consideration of how risk affects everyone, participant 8 said that nuclear experts must have "respect for society, safety, and [society's] wishes for the types of risks they want to take." Deploying a sense of respect and goodwill (*eunoia*) toward the public, participant 8 centers the public's perception of risk and safety. Despite previously evoking a monologue perspective, participant 7 also recognized the unfortunate tendency for experts to ignore the public. Participant 7 noted, "people [in the nuclear industry] do not really have empathy for the public and dismiss them as uneducated" when attempting to address people's concerns about the risks and safety related to nuclear power. Participant 7 believes that instead of dismissing these concerns, they should be engaged with empathy, also demonstrating *eunoia* toward public audiences.

Many interviewees recognized various sources of fear as legitimate ones: infamous accidents, extensive atomic testing above and below sea level, and government mishandling of nuclear materials and projects around the world. Participant 6 recalls that "after Three Mile Island, the type of research we pursued changed" to prioritize the safety features that prevent such an event from happening again in the future. Instead of dismissing the public's fears, participant 6 engages in *phronesis*, or practical judgment on the proper direction of nuclear research based on evolving public concerns around risks.

Over half of the experts interviewed explicitly mentioned that no form of nuclear power is free of risk, thereby acknowledging that public fears are, at least in part, reasonable. These beliefs are similar to those recorded by Schweitzer and Mix (2021b) in France, who found nuclear experts believed that "'there is no such thing as zero risk' when talking about nuclear safety" (p. 9). In the words of participant 10, nuclear energy "should be a part of any energy solution," but "we should all be making rational decisions with the sum of all risks." This statement blends *phronesis* and *eunoia* in valuing public concerns and making decisions while considering various perspectives. While it is unclear whether nuclear waste and marginalized communities are included in this calculation, the general sentiment indicates that rational decisions should engage various forms of risks instead of dismissing them as unreasonable. Some interviewees perceive safety as a priority for the industry more than ever before, but as an area that can always use more attention.

Three of the interviewees shared personal experiences when talking about the risk associated with nuclear power. After Fukushima, participant 7 worked with communication experts in an "eye-opening experience" where they collaboratively gathered members of the public to talk about the state of the environment after the accident. This experience showed participant 7 first-hand the importance of framing risk to help ease concerns. Participant 7 recognized the different ways that publics might response to risk and said, "instead of saying 3% [of an area] is contaminated, say 97% is not contaminated" to emphasize where they do have control over contamination, rather than where they do not. This process is done with the hopes of engaging what will be the most effective communication with an audience that is likely under high stress and concerned for their own wellbeing. Recognizing these communicative differences frames participant 7 as aware of their role as communicators and the dynamics of communicating risk.

Participant 12 demonstrated an understanding of audience adaptation and the power of metaphor to communicate nuclear risks. In talking about nuclear energy as a tool that can be used to combat climate change, participant 12 noted, you "could chop down a tree with a pocket knife, but you'd probably like to use a saw." Of course, the risk of being hurt by a saw is much higher than that of a pocket knife, but both tools, each with their relative risks, can be used carefully and thoughtfully to get the job done. For participant 12, nuclear energy is a saw that is a better fit to cut down carbon emissions than other energy sources. This comment demonstrates attention to how to communicate energy choices to public audiences and also recognizes the inherent risks of nuclear energy and their hopes it can be a tool used for climate mitigation. Participant 2 expressed a similar hope that nuclear power may be adapted to meet the "needs [of] energy and environmental concern[s]" by making it safer.

Participant 11 also used a metaphor to compare added regulations for nuclear to vehicles: "if you have a parking brake and a foot brake on your car, do we need to add three more braking systems? No, but technically it would be safer." This participant used this metaphor to illustrate how additional regulations may lead to perceptions of safety but may instead be redundant and unnecessary, but in a way that does not necessarily "dumb down" the technical concept, but rather places it within a frame of reference likely familiar to public audiences. These interviewees are, in part, recognizing their roles as citizen scientists (Pietrucci and Ceccarelli, 2019) by considering audience adaptation and embracing a role as bridge-builders that communicate technical information to public audiences about risk and safety.

Although nuclear communication has proven to be a risky activity, participants were hopeful that the next generation of nuclear experts would improve public-technical relationships. In particular, participant 7 hopes that the nuclear community will learn more about the "environmental impacts of nuclear" technology when making risk assessments, and feels that as a materials and environmental scientist, "nuclear engineers do not [yet] understand the impacts" fully. Participant 8 thinks there will be "a lot of opportunity for independence [of] thought and creativity which hopefully does not come with repeating mistakes from the past," including downplaying risks. They continued by noting that there is a "lot of opportunity to change the culture of the nuclear industry" to be more open, honest, and transparent (*arête* and *eunoia*).

Participant 5 echoed concerns that nuclear communication has been fraught with issues of transparency and accuracy, noting that past statements from the industry framed nuclear reactors as "fool-proof." Drawing a connection to the Titanic being "unsinkable," participant 5 noted that "determining how to limit liability does not go well with "fool-proof" reactors." In other words, previous assertions of universal safety have been proven wrong, which reasonably inspires suspicion of contemporary claims of nuclear's safety. Instead of reiterating false claims of reactors being "fool-proof," participant 5 offers that nuclear communication should focus on translating the nuances that prevent nuclear energy from being labeled honestly as either "safe" or "unsafe." By advocating for truth, accuracy, and transparency, they echoed the scientist citizen's moral virtues (*arête*).

Six additional interviewees agreed with participant 5 that it is not public fears that have been the main problem for nuclear, but rather how nuclear relative risks and safety have been communicated. These comments shift blame from the publics' understanding of risk to the nuclear industry's lack of open, clear communication about them. By addressing known areas of uncertainty with compassion and the public's best interest in mind, these nuclear experts expressed an interest in building trust between the public and technical spheres.

Government and Policy

Another *topos* expressed by interviewees is the industry's dependence on government regulation and policy. The monologue and dialogue components of government and policy emerged in how experts made sense of the priorities of policy makers and legislators in relation to nuclear energy. As a result, monologue and dialogue reflect experts' reification or challenging of the science-vs.-politics divide.

Monologue

While cost emerged as a separate *topos*, issues of funding were also tied to experts' relationship with the government. Interviewee 3 explained that their "life is based on getting funding from mostly the government." Seven experts agreed, stating that their primary interaction with politics and policy is through aligning their proposals and interests with the political party in power. As one participant noted, there have been instances where Congress decreased "funding to certain projects where people have lost [working] relationships because of new sanctions regarding foreign relationships" (participant 1), only strengthening the expert's perception of a science-policy divide. These shifts in political administrations have marked effects on the ability of nuclear experts to do research and maintain valuable collaborations around the world. When these relationships and projects get disrupted, the government can be viewed as an enemy to science and to progress.

The interviewees unanimously lamented that the US has yet to provide a clear, consistent energy policy. Participant 10 stated that "we have no national energy policy," just a "mish-mosh of politics, greed, and dissociated energy costs." Participants generally described nuclear power as having to operate within a complex, politically charged sector of society that can be influenced by political power and greed. Evoking an inferior view of publics, participant 2 thinks that "there is not enough information for the public to have an opinion" either way on nuclear energy, which means political leaders find it hard to represent the public's priorities. This is not a concern to participant 2, however, as long as "those making decisions know how it works," thereby tacitly encouraging a dismissal of public concerns by politicians. Instead of making practical decisions with publics in mind, participant 2 rejects *phronesis* in favor of interfacing with political elite devoid of public participation. This interviewee thought that politicians were not necessarily fully rational actors either, noting that the "problem comes when we do not make decisions based on science and facts" and, alternatively, make decisions based on partisan goals. Noting that governments have been corrupted by both money and political loyalties (Cloud, 2020), participants separate themselves as above these concerns and see science as wholly rational when compared to politics, thereby deepening science-politics divides.

Dialogue

Although many interviewees had less than positive perceptions of government and politics, some interviewees embraced politics and saw it as integral to their career. For example, participant 5 describes their job as "correcting government officials in different countries who have made wrong statements" about nuclear power. Although "correcting" certainly implies a monologue approach to politicians and publics as inferior to scientists, the focus on engagement with politicians also reflects the *arête* of a scientist citizen. Pietrucci and Ceccarelli (2019) argued that when scientists fail to correct public officials, they wrongfully abdicate their responsibility to the truth and to the wellbeing of society. Through this perspective, participant 5 can be seen as evoking a scientist citizen identity where scientists view themselves as responsible for the accurate communication of their science and for intervening in public misconceptions.

Noting how "politics affect everything," participant 11 communicated how important it is for elected representatives to follow the views of their constituents and, therefore, how important communication of nuclear energy science is to both public audiences and policymakers. Without including the public, legislation becomes hierarchical and exclusive, resulting in the perpetuation of skepticism and fear. A few (three) of the interviewees explicitly mentioned that the public has limited trust in both the government and nuclear industry leaders, making them allies in the work to be more transparent and trustworthy (*arête*). Thus, participants argued that the nuclear industry and nuclear experts must work collaboratively with politicians. Instead of emphasizing a divide between politics and science, these interviewees embraced the linkages between them as integral to productive and ethical energy decision-making (*phronesis*). Unlike the *topos* of risk and safety, the *topos* of government and policy was dominated more by monologue than dialogue, but there were undercurrents of collaboration, *phronesis*, and *arête*.

Public Education and Engagement

Engaging and educating the public is another *topos* that emerged in interviewees' responses. As discussed in the risk and safety *topos*, discussions of knowledge can easily slide into a monologue framework, but discussions of engagement are more promising for dialogue. Under this *topos*, a monologue perspective often accompanied assumptions of ignorance, willful or otherwise, while a dialogue perspective accompanied empathy and attempts to incorporate public participation directly into the science. From both perspectives, the ultimate goals of public education and engagement center around doing what the interviewees believe is in the best interest of the public.

Monologue

Responses that evoked a monologue perspective echoed feelings of public ignorance and expressed what experts felt was undeserved scorn for their careers. Similarly, one nuclear expert in France claimed that lies that are "internalized by the public opinion ensure that almost everybody is extremely ignorant regarding the real situation of this industry" (Schweitzer and Mix, 2021b, p. 10). The lack of accurate information and the spread of what they refer to as lies makes them reticent to engage with the public about their careers, as expressed by participant 3 in our study who has felt people "look at [them] in a weird way for wearing a pro-nuclear shirt." Other participants reported that their early predecessors in the industry were often quick to shut down conversations that questioned the abilities of nuclear power when discussing nuclear with public audiences. Participant 10, for example, said they "do not bring up what [they] do at dinner parties," assuming they would be met with mixed and potentially even combative responses. Exhibiting what could be called radiophobia-phobia, this participant feared that they would be perceived as dismissive or elitist due to the actions of other nuclear experts, and therefore withdrew from engaging publicly with their careers. Participant 10 further characterized their reluctance to discuss their career in nuclear. They noted, that, in general, "scientists are well-trusted, but when it comes to nuclear there's mistrust."

Existing mistrust and also the perception of that mistrust can encourage nuclear experts to separate their careers from their public interactions, thereby contributing to further mistrust and secrecy. Instead of fostering a scientist citizen identity who builds bridges to the public, fears around public engagement can construct a science-citizen Rawlsian curtain that cleaves each identity from the other. The mistrust of nuclear energy and the subsequent lack of engagement by nuclear experts fearful of such mistrust can consequently create a self-fulfilling cycle that cuts off public engagement and participation and makes it less likely to occur.

Dialogue

Although participant 10 shared their fears of public engagement, they also were hopeful about future public engagement efforts. They noted, "this is a problem we already know how to solve. That's where rhetoric comes in," directly referencing the ways experts talk about nuclear energy. While only participant 10 used the term "rhetoric," the interviewees nearly collectively referenced the importance of communication in engaging the public around nuclear energy. Participant 8 noted that nuclear energy "has been an isolated field" that "should be more intertwined with other industries." They further argued that we must "train and motivate engineers [and scientists] to engage with the non-engineering part of nuclear: policy, education, risk, preparedness, and molding nuclear energy to fit with local cultures" (participant 8). Embracing the interdisciplinary and interconnected nature of nuclear, participant 8 forwarded the importance of dialogue and participation among various technical and public stakeholders, including educational spaces and local communities.

Participant 3 also highlighted the importance of being open to conversations, noting that it is important for experts to talk to non-experts "without being pompous" and without being dismissive of what they believe as "complete bologna." Participant 3's emphasis on not being "pompous" directly combats a monologue perspective of public audiences being inferior to nuclear experts. Instead, this view encourages a dialogue model of valuing participants as equal, or, at least, not as inferior. Participant 3, in part, evokes an IDM by focusing on explanation and one-way initial knowledge transfer, but tempers it with an emphasis on also providing opportunity for open discussions and active listening.

Participant 4 also pointed out problems with focusing on a lack of knowledge. They explained that there is a "perception of having to be a genius to understand nuclear" and some "people say 'we need more education'" to change this misconception. However, participant 4 emphasized that instead of more education, we need to "change the idea of that education" by "moving away from the specifics of nuclear safety" and toward how nuclear energy directly relates to and affects the public. Participant 4 thereby evokes *phronesis* in thinking about the specific, tailored needs of their audience and how education is not simply a matter of deficits and quantity, but also accommodation and quality.

Four participants discussed having personal experiences talking with people where their dialogue partner, even when expressing fear of nuclear or apathy on the topic, became more open to nuclear energy as an option. These participants view their roles, at least in part, as ambassadors of nuclear energy to the public, in which communication and building trust plays an integral role. Referring to the difficulties of playing this role, participant 9 asks, "how do we communicate with a wide variety of stakeholders about the value of nuclear and get buy-in so those stakeholders will pressure their legislators, the EPA, and the government to bring it to their communities?" Locating the solution at the level of communication and public engagement, participant 9 notes that public activism around nuclear is an essential component to the future of nuclear energy (*phronesis*).

Other interviewees echoed the importance of bridging technical and public communities through public outreach, with some directly addressing whether the goal of nuclear should be persuasion or engagement. For example, participant 8 engaged *eunoia* when they stated that nuclear energy's needs are "not about changing public opinion, but how do we open dialogue between the nuclear community and the public so the public can build trust" with nuclear experts. By encouraging the public to share their voice, this interviewee considers it a responsibility of the industry to engage the public sincerely and without overtly persuasive goals or with the predetermined goal of nuclear being the solution. To achieve this open dialogue, interviewees offered examples of public engagement events, training nuclear scientists and engineers to be more effective communicators ("teach people in the industry how to have that conversation"—participant 9), and taking to social media to spread their contributions and information about nuclear energy online.

Participant 9 said, "people in the nuclear industry love [nuclear technologies] and are natural advocates who need to know how to respond better to personal connections and stories." Seeing nuclear experts as both industry professionals but also as members of the public, participant 9 exemplifies the role of the scientist citizen. Furthermore, they strongly indicate that this is not the current way many nuclear experts engage with the public, but that it should be. Interviewees commented that newer generations of nuclear experts are more interested in public engagement and issues of diversity and equity, including the impact of nuclear on marginalized communities. Participant 2 argued that nuclear power is "not an all or nothing deal" and "everything plays its part for the greater good," linking nuclear energy, in their mind, as a tool for advocate for the public's wellbeing (*phronesis*).

Cost

While the three other *topoi* had evidence of monologue and dialogue, cost uniquely employed only monologue features. Seeing cost as a primary barrier to broad-scale nuclear adoption, participant 4 explained that "time is money. The cost is so high that companies are unwilling or unable to choose nuclear." Such a conceptualization, echoed by many interviewees, ignores the risks and impacts to marginalized communities and the moral dimensions of nuclear by reducing everything to a matter of money. The *topos* of cost, for many interviewees, displaced other concerns, functioning as a gatekeeper to more dialogue-based perspectives. Responses consequently evoked a neoliberal perspective where a concern for funding deflects not only environmental concerns but also the human element of nuclear energy's impacts.

Some interviewees discussed how waste accumulating at the end of the fuel cycle requires the management, transportation, and storage of high-level waste, which is expensive (participants 3, 5, and 7). Participant 10 thought that concerns about the costs of nuclear waste disposal were exaggerated and were uniquely targeted at nuclear energy: "There's a lot of concern about long-term waste disposal that plagues nuclear and somehow does not plague any other energy form." This interviewee refers to how any source of commercial energy production will produce waste, but concern about costs does not seem to be equally distributed to the waste produced by non-nuclear energy sources.

A few participants explained that many front-loaded costs in constructing new plants ultimately pay off in the long term, but do not create an attractive investment for many companies due to high short-term costs and painstaking regulatory processes. In addition to building new plants, there is also a high cost associated with both maintaining and decommissioning old plants. Furthermore, reactor designs are continuously being evaluated and adjusted to higher standards, which a few interviewees (participants 1, 2, and 3) noted makes old plants costly to maintain.

Five of the interviewees agreed that nuclear energy struggles explicitly to compete with fossil fuels by cost due to the relatively high regulation over nuclear compared to other sources of energy, making nuclear inherently more expensive by comparison. Participant 12 noted that if nuclear power became "significantly cheaper" than other clean energy options, it would "eliminate public opinion" from the decision-making process, because people will rationally choose the energy option that is the cheapest. Similarly, participant 11 said that nuclear energy does not "have a level [financial] playing field for producing power and electricity," but if it were level, "nuclear would probably win." Not only does this perspective reject *phronesis*, but it also reduces energy decision-making solely to a matter of markets and economic competition (Bloomfield, 2019b).

One potentially encouraging theme in the cost *topos* surfaced as five of the interviewees suggested that increased inclusion of nuclear energy would result in a significantly cleaner and more reliable energy portfolio. These statements about environmental benefits, however, came in the form of a positive side effect to choosing nuclear rather than a decision-making priority.

NUCLEAR ENERGY'S FUTURE

The four *topoi* of risk and safety, government and policy, public education and engagement, and cost emerged across interviews as inventional resources for making sense of public-technical relationships and interviewees' personal perceptions of their role and responsibilities as science communicators. Furthermore, these *topoi* serve as markers of key themes in nuclear rhetoric that inform perceptions of public-technical relationships. In other words, how nuclear experts negotiate these *topoi* configures potential collaborations or boundaries between public and technical actors on energy decisions. Framing nuclear energy through a monologue, for example, can close off considerations of public perceptions as valuable, legitimate, and reasonable, and further reifies technical spaces as the sole arenas of rationality. Alternatively, embracing dialogue fosters an attitude of scientists as citizens and public stakeholders as important and integral players in energy deliberation.

While this study focused on nuclear energy, we can preliminarily note that these *topoi* are also likely to emerge across other scientific topics. For example, interviewee concerns about how to communicate safety and risk while maintaining credibility are also rife in health communication regarding COVID-19. Additionally, scientists involved in climate change research are no strangers to the politicization of their science that affects grant funding as administrations change. Many interviewees exhibited features of both monologue and dialogue, even when discussing the same *topos*, which indicates that the tensions underlying nuclear energy rhetoric and may underlie other scientific topics as well.

Notably, unlike the other three *topoi*, the *topos* of cost only brought forth features of monologue. This is an important finding because it suggests that engaging nuclear experts on topics of cost may invite a monologue perspective that closes opportunities for dialogue. When money is on the line, it seemed difficult for experts to see nuclear through a dialogue frame, including those who previously used dialogue features in other responses. While shifting conversations into areas such as the economy may be productive strategies for scientific topics such as climate change (Elliott, 2014; Bloomfield, 2019a), this strategy appears to be more fraught in nuclear energy. Instead, we propose that attempts to engage in collaboration with nuclear experts may avoid issues of cost and start from alternative grounds to ward off potentially defensive turns to monologue.

This analysis demonstrates that there are substantial barriers to technical-public collaboration rooted in experts' perceptions and attitudes. These barriers, however, also point to opportunities for fostering more public-technical collaboration and including public voices and the moral concerns of the scientist citizen in nuclear decision-making. As some interviewees noted, individuals who comprise the nuclear energy industry today are not those who built the bombs. As opposed to an interest in weaponry, our youngest interviewee became a nuclear scientist primarily for environmental reasons because they are "very concerned about climate change." As the industry changes, the dynamic of age and shifting generational perspectives are essential to consider. Centering new voices in the field who are more openly critical about nuclear, for example, could serve as an exemplar for the field to embrace vulnerability and honesty (*arête*) and value public participation in nuclear energy (*phronesis*) without fears of violating boundaries or the "proper" role of scientists and technical experts. Elevating these perspectives will come, in part, from creating opportunities for public-technical interactions, changing scientific curriculum to include public communication skills, and reducing barriers to experts acting as scientist citizens.

Additionally, the nuclear industry must actively include and address the concerns raised by those in opposition to nuclear energy. The values and cultures of marginalized communities such as Indigenous populations should be recognized and respected, unlike the environmental decision-making of past and current projects. To assist in the process of connecting the industry to public stakeholders energy communicators should explore opportunities to provide a platform for nuclear experts' voices and public voices to be shared and valued in decision-making. This paper is a preliminary step to understanding nuclear experts' conceptualization of technical-public interactions around nuclear energy, and we encourage more work on nuclear energy and other scientific topics along the lines of how to foster scientist citizens and public-technical relationships.

In the unfolding nuclear debate, we hope that deliberations may take the form of dialogue as opposed to monologue. Based on these interviews, striving for dialogue will be tempered by foundational attitudes of monologue underlying many interviewees' responses. The impending consequences of climate change on people and the planet are the most pressing problems of our time. The role that nuclear energy plays in our environmental story is still being written, but we believe that a more sustainable future will be achieved with collaboration and dialogue between stakeholders across public and technical arenas.

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 Institutional Review Board, UNLV. The participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

HP performed the interviews and drafted the paper. EB and HP edited the paper. All authors contributed to the article and approved the submitted version.

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APPENDIX

Interview Questions

1. What is your role in the nuclear field, and what led you to this point?
2. Why is nuclear energy important to you?
3. What obstacles do you see the nuclear energy industry facing, and what do you foresee the nuclear energy industry will face in the future?
4. How do you think the public views nuclear energy? *Follow-ups:* Do you think those perceptions are a problem/why? How do you think we could change the perceptions of nuclear energy?
5. Have there been instances in your career where the political discourse about nuclear energy has affected your work or the work of people you know? *Follow-ups:* How do you respond in those situations, if at all?
6. Are there any specific public misconceptions that have impacted your work or the work of people you know? *Follow-ups:* How do you respond in those situations, if at all?
7. What effect do you think the next generation/incoming generations of nuclear scientists and engineers will have on the nuclear energy industry?
8. What is the most important thing you want people to know about nuclear energy?

frontiers in Communication

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How Does Strategic Communication Shape Transdisciplinary Collaboration? A Focus on Definitions, Audience, Expertise, and Ethical Praxis

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Transdisciplinary collaboration offers great potential for meaningfully addressing complex problems related to climate change and social inequities. Communication shapes transdisciplinary collaboration in myriad ways, and interdisciplinary and rhetorical approaches to communication can help identify these influences as well as strategies to transform inequitable communication patterns. In this paper, we share results from an engaged and ethnographic research project focused on strategic communication in a large-scale transdisciplinary collaboration to develop environmental-DNA (eDNA) science for coastal resilience. In this context, definitions of eDNA, perspectives about communication, and constructions of audience and expertise shape the ways in which collaborators co-produce knowledge across disciplines and with diverse partners. Identifying relationships among strategic communication, knowledge co-production, and power enables the development of strategic collaborative practices, including asking questions as a means to identify and negotiate differences in definitions of eDNA and using participatory methods and anti-oppressive data management platforms for ethical praxis.

Keywords: strategic communication, rhetoric, transdisciplinary collaboration, epistemic authority, environmental DNA (eDNA), ethics

INTRODUCTION

Complex problems at the nexus of ecological, social, cultural, technological, and economic concerns require diverse approaches to collaboration (Blythe et al., 2008; Brown et al., 2010). There are several factors that intensify the complexity that occurs at this nexus, including the influence of context and local histories, cross-scale interactions, and diverse perspectives about the nature of any particular problem or solution. For example, climate change is occurring in dramatically different ways depending on the sociocultural and ecological conditions of a place. The context specificity of climate change can make efforts to adapt strategies from one place to another difficult if not impossible. In an effort to tailor national-scale solutions to regional coastal environments, Leslie et al. (2015) argue for "strategic approaches, targeted to the needs and strengths of specific regions" (p. 5,982) that pay close attention to cross-scale interactions and social constructions. Collaborative approaches strengthen abilities to pay attention to how social, political, economic, and institutional factors interact with local ecological conditions. In addition to encouraging more bottom up and inclusive approaches to climate change adaptation, it is important to consider how dominant understandings of spatial and temporal scales are themselves constructed (McGreavy et al., 2021). What one collaborator may define as a pressing and urgent issue that invites a technical solution, another may identify as an issue linked to a longer-term colonial history that requires a different kind of "solution" entirely. The influence of cross-scale interactions as well as multiple constructions of problems, space, and time amplifies the need for individuals to engage in more relational forms of collaboration (Whyte, 2021).

Addressing complex problems like climate change through collaborative, science-based approaches can build capacities to understand the multiple dimensions of an issue and produce knowledge(s) that support action. Finding ways to bring diverse forms of knowledge together in knowledge co-production processes is a key commitment in these types of efforts (Tengö et al., 2014). Interdisciplinary and rhetorical approaches to strategic communication can lend insights about how to both study and shape such processes (Blythe et al., 2008; Herndl and Cutlip, 2013; Druschke, 2014; Graham et al., 2017; Suldovsky et al., 2018). Further, interdisciplinary scholarship on strategic communication calls attention to the myriad ways in which communication shapes information sharing, meaning making, and the formation of social difference and power (Holtzhausen and Zerfass, 2015; Heide et al., 2018; Ihlen, 2020). Finally, bringing interdisciplinary and rhetorical perspectives to strategic communication can also inform engaged praxis, emphasizing the value of listening and shared learning for ethical and inclusive transdisciplinary collaborations (Druschke and McGreavy, 2016; McGreavy et al., 2018; Suldovsky et al., 2018).

In this paper, we share insights and practices from an engaged and ethnographic study that focuses on how strategic communication shapes a large-scale transdisciplinary collaboration. The Maine-eDNA Project focuses on resilience to climate change and interconnected challenges, such as shifting livelihoods, harmful algal blooms, and changing species distributions in coastal ecosystems. This multi-institution project uses environmental-DNA (hereafter eDNA) science to address information needs associated with ecological changes in the Gulf of Maine. The Gulf is warming faster than many other areas of the earth's oceans (Pershing et al., 2015) and climate change is already having widespread impacts on coastal livelihoods and ecosystems (Maine Climate Council, 2021; Olson, 2021; Stoll et al., 2021). We start by introducing interdisciplinary and rhetorical approaches to strategic communication. We then describe the context and methodology for this work and share results from a series of semi-formal interviews (n = 15) and ongoing participant observations of project meetings (August 2020 through September 2021). Our qualitative results identify strategic communication patterns within this project, including how participants negotiate definitions and construct audiences and expertise in ways that both reinforce and challenge dominant approaches to science. We conclude by discussing the implications of our research for collaborative praxis. We highlight the importance of posing questions to promote reflexivity and using knowledge mapping and anti-oppressive data management to guide knowledge co-production. We also emphasize the value of centering questions about and as ethics to meaningfully address connections among language, knowledge, and power.

Strategic Communication and Transdisciplinary Collaborations

Within literature on transdisciplinary collaboration, scholars have identified how interdisciplinary and rhetorically-informed approaches to strategic communication can produce applicable knowledge about science-based collaborations (Druschke and McGreavy, 2016; McGreavy et al., 2018; Werder et al., 2018; Ihlen, 2020). Strategic communication serves "as a transdisciplinary, holistic, and inclusive field of knowledge," (Heide et al., 2018, p. 452) and can be understood as an umbrella term that weaves across multiple communication fields. These fields include public relations, rhetoric and technical, corporate, organizational, and management communication and each demonstrates nuanced yet important differences in what strategic communication means in theory and practice (Lock et al., 2020). Similarly, transdisciplinarity has diverse meanings; here we define it as the commitment to produce knowledge about complex problems in ways that build capacity to address them (Jahn et al., 2012). Knowledge co-production names the process through which transdisciplinarity emerges, with two main foci: (1) the communication practices that connect multiple forms of knowledge about a problem (Tengö et al., 2014; Norström et al., 2020); and (2) the guiding assumption that the ways in which we produce knowledge form social orders, such as identities, organizations, and discourses (Jasanoff, 2004; TallBear, 2013). Here we summarize three primary orientations to strategic communication that have influenced our work, including how we conceptualize strategic communication; key communication processes that matter in collaboration; and how constructing audiences and expertise connects with power.

Interdisciplinarity, Rhetoric, and Strategic Communication

First, in contrast with approaches that would position strategic communication as a singular and linear process of information sharing, an interdisciplinary and rhetorical orientation to strategic communication emphasizes a multidimensional approach. Strategic communication includes techniques that are deliberate, purposive, and goal-oriented (Hallahan et al., 2007; Rus, 2014) and yet also practice-based, relational, and collaboratively-constructed (Holtzhausen and Zerfass, 2015; Heide et al., 2018; Ihlen, 2020). Consistent with this orientation, Holtzhausen and Zerfass (2015) identify a series of focal points for strategic communication, including attending to communication as both pragmatic and constitutive and focusing on processes of meaning making and audience constructions. Their approach points to the value of pairing strategic communication with engaged methodology in ways that allow communities of practitioners to develop a situated understanding of what strategic communication means (Holtzhausen and Zerfass, 2015).

In a call to connect rhetoric, science communication, and strategic communication, Ihlen (2020) demonstrates how working across disciplines and with communities of practitioners can also help "alert us to how knowledge is generated and socially constructed through communication" (p. 165). In this case, Ihlen (2020) focuses on the timely issue of vaccine hesitancy and how strategic communication can help trace how audiences and credibility are both constructed. Understanding audience constructions and who is seen to have credible knowledge creates the foundation for attending to how communication also constitutes power between people and within organizations (Blythe et al., 2008). For example, in their rhetorically-oriented critical action research, Blythe et al. (2008) found that asking questions about audience constructions allowed their team to understand power differences that shaped community negotiations of scientific and technical knowledge about an environmental remediation project. Similarly, Heide et al. (2018) argue for a more explicit focus on power in analyses of strategic communication "where taken-for-granted ideas, such as the notion of organizational goals, are examined and questioned" (p. 466). In his analysis of the taken-for-granted term "environment" Ross (2013) describes how this "seemingly innocuous word... carries multiple complex meanings dependent largely on audience interpretation and understanding, suggesting that rhetors should carefully choose their phrasing when attempting to motivate an audience to action in relation to environment-related communication" (p. 93). Thus, in addition to emphasizing the practical and technical elements of strategic communication, a rhetorical approach also highlights the constitutive or relational nature of all communication and the need to pay attention to the connections between language, knowledge, and power, especially in the context of science.

Asking Questions About Definitions

Relatedly, and as a second orientation that guides our study, asking questions about how key concepts are defined lends specificity to the focus on communication, knowledge, and power (Walsh, 2017). Focusing on definitions can help illustrate which ideas are considered important, shared, or contested within a communication situation (McGee, 1999). This is particularly important in collaborative approaches to science, as definitions can become commonplaces that collaborators come back to repeatedly to create and negotiate meanings (Blythe et al., 2008; Walsh, 2017). In this context, an approach like knowledge mapping can foster collaborative discussions by posing questions to help guide these negotiations (Wilson and Herndl, 2007; Graham et al., 2017). Scholars have also drawn from stasis theory to attend to how definitions shape arguments about contentious science issues. Stasis theory helps analyze how "sticking points" in arguments tend to center around definitions, as well as matters of fact, value, cause-effect, and action (Fahnestock and Secor, 1988; Walsh, 2017). In the case of climate change communication, definitions can serve as *both* commonplace and stasis, where "[Scientists] may indeed come to stasis and wrangle back and forth over whether a particular dip in the global temperature record should be defined as anomalous, for instance" (Walsh, 2017, p. 5). This pattern can create challenges in a collaboration because "If people are invoking the same term to imply differing definitions, then the task of reaching *agreed upon* stases becomes all the more difficult" (Blythe et al., 2008; p. 290, emphasis added). Thus, paying attention to and asking questions about definitions can point to repeated patterns, or touchstones, as well as sticking points that shape collaborations.

That definitions are subject to revision or debate also demonstrates their contingency (McGee, 1999; Lynch, 2011). Arguments about definitions can help participants find definitions best suited to establishing a context for their work (Schiappa, 1993). Debates over how a community uses particular words provide opportunities to strengthen knowledge co-production, increase understanding, and overcome conflicting interests or values in pursuit of collaboration (Schiappa, 2003). The practice of introducing and establishing definitions illustrates how rhetoric can be understood as the power to define, or the process through which definition comes to matter for how groups construct knowledge and authority (Zarefsky, 1998). The relationship between definition and power is shaped through collective negotiations that establish a basis for definitions and may also be collectively contested and justified over time (Clarke, 2005). Further, reflexive negotiation of contested definitions can help establish the purpose a term is expected to serve in a particular dialogic setting or science-based context (Lynch, 2011). For example, when Lynch (2011) works through the complex definitions that shape arguments about stem cell research, he highlights how contestations signal "that a given issue or object deserves attention: It should be selected and made a figure against the backdrop of other objects, issues, and actions" (p. 151). In contrast to perceptions that arguments about definitions detract from effective science communication, this perspective points to the value of argumentation about definitions, especially for research that intends to shape policy making.

Constructing Audiences for Science

Third and finally, there remains a need to consider relationships between communication, especially focused on negotiating definitions, and constructions of audience and expertise. This is particularly important in light of both the persistence of the information deficit model in science communication and the potential, yet still limited, value of message-centric communication (Cagle and Tillery, 2015; Suldovsky, 2016). Connections between perceptions of communication, audience, and expertise construct and reinforce the relative power of different forms of knowledge, also known as epistemic authority, in collaborations (Bucchi, 2008; Suldovsky et al., 2018; Ihlen, 2020). As Suldovsky et al. (2018) describe, such a focus "demonstrates the importance of attending to specific discursive influences on perceptions about epistemic authority and subsequent stakeholder engagement" (p. 501). Interconnections between perceptions of communication and researchers' worldviews constitute a key discursive influence within science, especially in contexts that privilege post-positivist approaches. Post-positivism is a research paradigm often associated with dominant approaches to science that is based largely on a worldview that assumes a singular reality that exists independent of communication (Lincoln and Guba, 1985). This assumption reinforces belief in an objective observer who, by using empirical methods, has both the ability and the authority to describe that reality accurately *to* audiences (Druschke, 2014). These logics of objectivity and expertise thus reinforce a linear diffusion-based model of communication (Suldovsky et al., 2018).

In our orientation, "audience" serves as a broad term that encompasses a set of related constructs that are often used in studies of collaboration, including stakeholder, decision maker, partner, end user, client, and so forth. Though there are multiple communication processes that construct audiences and expertise, we build from the above discussion of definitions to consider the related practices of naming and framing, all of which serve as rhetorical strategies whereby language is a process of material and symbolic action (Burke, 1966). Naming refers to the practice of articulating symbols and material entities, like naming some groups "decision makers," "lay publics," or "researchers," in ways that draw on and reinforce specific meanings and power relations. For example, McGreavy et al. (2021) explain how naming practices that emphasize decision makers as key audiences for the knowledge that a collaboration produces can shape the focus and direction of a project. When collaborations involve diverse groups with differences in social standing and power, such as between state agencies and Tribal Nations or between academic institutions and local communities, the ways in which audiences are named can reinforce, as well as challenge, colonial, or otherwise unequal power dynamics (Stuckey and Murphy, 2001; Endres, 2009). Framing is a related and broader strategy in which some aspects of reality are emphasized while others are not, a process that Burke (1966) also refers to as "terministic screens" (p. 45). In our use, framing refers to the communication processes through which some forms of knowledge and expertise are emphasized while others are not. For example, the use of metaphors, analogies, and related tropes that compare one thing to another are common framing techniques that can privilege some meanings associated with knowledge and expertise over others. Orienting in this way recognizes, as Burke (1966) famously remarked, "Even if any terminology is a *reflection* of reality, by its very nature as a terminology it must be a *selection* of reality; and to this extent it must also function as a *deflection* of reality" (p. 54). Thus, a focus on definitions, naming, and framing is not simply a matter of paying attention to the symbols we use to communicate but also those that are not included within discourse. This approach allows for a multidimensional and yet specific focus that can help guide analyses of what can otherwise feel like ambiguous relationships between communication, knowledge, and power.

Approaching strategic communication as a multidimensional process that attends to constructions of, interconnections between, and exclusions within definitions, audiences, and expertise provides a way of making sense of some of the complexity in collaboration. Further, this orientation points toward praxis commitments, which we define as emergent and problem-oriented practices (Ono and Sloop, 1992), that can help collaborators shape these constructions in more intentional, inclusive, and equitable ways (Blythe et al., 2008). As part of these commitments, an emphasis on knowledge co-production can invite attention to the specific practices through which multiple forms of knowledge are combined to shape emerging social orders (Jasanoff, 2004). Focusing on knowledge co-production also raises questions about how science *should* be conducted to promote more just and anticolonial social orders that can emerge within academic organizations and institutions of science (Van Kerkhoff and Lebel, 2006; TallBear, 2013). Along these lines, Suldovsky et al. (2018) recommend that collaborators should have early and ongoing conversations that focus explicitly on whose knowledge is prioritized to begin to identify and negotiate epistemic authority on scientific projects. As part of this process, demonstrated reflexivity, or open active reflection as part of a social process within teams or collaborative settings, can help create a space for clarifying key concepts (Thompson, 2009; Popa et al., 2015; Ihlen, 2020; Norström et al., 2020). It is also important to take time to figure out where each participant is coming from and how to co-construct definitions in ways that are "interesting, useful, and consequential for all" (Druschke, 2014, p. 5). Further, finding time to build trusting relationships (Endres et al., 2008), identify just ways of engaging with minoritized communities (Chen et al., 2012), and create equitable incentives for participation (Burke et al., 2016) can help collaborators develop consequential approaches to equity within a project.

RESEARCH QUESTION

In addition to the inherent complexity in the problems that many science-based transdisciplinary projects engage, large-scale collaborations also involve complex participation experiences, particularly when differences in power and issues of equity are foregrounded. Despite numerous studies that have produced important insights about how communication influences transdisciplinary collaborations, there remains a need to more fully develop an engaged approach that uses research-informed insights about communication to shape collaborative praxis.

Our **research question** thus asks: How does strategic communication shape transdisciplinary collaborations? More specifically, we describe how participants describe and negotiate definitions of eDNA, audiences, and expertise. We also provide examples of how we draw from research insights to inform strategic communication praxis and how an engaged research approach can make a difference in transdisciplinary collaborations.

An Ethnographic and Engaged Methodology

We pose this research question in the context of the Maine-eDNA Project, a 5-year $20 million National Science Foundation

(NSF) EPSCoR Research Infrastructure Investment Track 1 grant. The project's formal mission is to make Maine "the DNA Coast" and a leader in environmental DNA-based partnerships to support the resilience of coastal marine and freshwater ecosystems (https://umaine.edu/edna/). The project intends to take a transdisciplinary approach to develop eDNA science to build capacity to address complex problems, such as harmful algae blooms and fisheries declines. The project involves more than 100 participants including faculty, graduate, and undergraduate students, postdocs, and staff from nine partner institutions. Together, we are focused on building capacities for eDNA data collection; workforce development; and diverse partnerships across academic institutions, Wabanaki Tribal Nations, state and municipal governments, businesses, and non-profit organizations.

Environmental DNA is a relatively new application of genetic technologies to environmental monitoring and research and has experienced considerable growth in recent years (e.g., Ficetola et al., 2008; Bohmann et al., 2014; Deiner et al., 2017; Huerlimann et al., 2020; Veilleux et al., 2021). As such, definitions and applications are still in flux among both academic researchers and communities of practitioners. Indeed, this applies to the concept of eDNA itself. For example, it is common to use the term to refer both to the material studied and the technologies used to study it, leading to an almost tautological framing of "use of eDNA to study eDNA." There is also variation among practitioners in what organismal sources and approaches they consider to be subsumed within eDNA based on already-established fields with overlapping subject matter, such as "DNA barcoding" and "microbiomes." We explore the significance of this diversity of definitions in more depth in the next section.

We use an ethnographic and engaged methodology that draws from mixed methods data collection (Creswell, 2014) and a participatory modeling technique known as knowledge mapping (Wilson and Herndl, 2007; Graham et al., 2017). Our ethnographic methodology defines how we conduct ongoing observations in diverse organizational settings to observe how communication shapes this transdisciplinary collaboration through time (Rai, 2016; Lindlof and Taylor, 2017). When paired with an ethnographic methodology, an engaged research design can bring situated social knowledge to bear on addressing differences in perspective and power-related tensions that inherently shape efforts to link knowledge with action (Trickett and Espino, 2004; Van Kerkhoff and Lebel, 2006). This methodology involves showing up; observing; and, when permission is granted, audio recording diverse project meetings, including those of research and administrative leadership teams as well as project-wide annual meetings. In addition to methodological commitments to deep listening and paying attention to communication practices over an extended period of time, we also use a dialogic process of checking in to situate ourselves in this work and refine insights through time (Madison, 2006). Checking in supports our ability to share emerging insights back with teams and projects leaders to help shape collaborative praxis, which we do through both formal reports and presentations as well as informal invited updates.

This methodology also includes the method of conducting semi-formal interviews ($n = 15$) using key informant and purposive techniques to invite participation (Lindlof and Taylor, 2017). These techniques allowed us to identify potential interview participants based on diverse positionalities in the project, including roles as faculty, students, and administrators; discipline; gender; race and ethnicity; and institutional affiliation. Interviews lasted an average of 73 min (range of 37–93 min) and were recorded and transcribed. Our iterative approach to thematic analysis involved multiple rounds of coding and triangulation (Corbin and Strauss, 2008).

Defining and Negotiating Meanings: eDNA as...

The following quote aptly summarizes how different and sometimes competing definitions of a concept shape collaboration: "What does eDNA mean? That's the...$20 million question." Asking what eDNA means is a valuable question because definitions feed into ongoing rhetorical negotiations around shared understandings of a situation as well as coordinated and policy-oriented action (Lynch, 2011; Walsh, 2017). For example, TallBear (2013) examines how a dominant and singular definition of DNA as gene "leaves us with an impoverished understanding of DNA" (p. 71), where definitions of DNA that draw from multiple forms of knowledge and perspectives (i.e., social, cultural, political, economic, etc.) would enrich what DNA comes to mean in any setting. In addition to limiting diversity, negotiations around definitions can also establish and reinforce power inequities, as some definitions align with dominant meanings and others fall outside the norm (Zarefsky, 1998; Clarke, 2005; Blythe et al., 2008). In this section we begin by tracing four primary ways in which participants in the Maine eDNA Project define "eDNA," including as a material entity, a tool or technology, an approach to science, and as a communication process. For each definition, we consider some of the associated meanings and how these patterns relate to power.

Material Entity

Many participants define eDNA as a material entity, the genetic material that is collected and analyzed to produce an understanding of patterns and processes in the natural environment. Highlighting the material nature of eDNA, one participant says: "eDNA, to me, is DNA that is within the environment. So that can be water, it can be in soil, it can be in the air, it can be in feces. So feces can be a vector for environmental DNA, like a tool for it to travel." Despite the clear material definition that this description implies, within this orientation there are also distinct nuances, especially related to assumptions about where eDNA is located. These differences are partially connected to a researcher's scale of observation and disciplinary training. Attention to scale influences differences in whether eDNA is defined as genetic material found in the external environment of the organism or that are still within an intact organism. At a broader geographic scale, participants define eDNA as genetic material that was shed from organisms typically too large or mobile to themselves be collected in an environmental sample such as from air, water, snow, or sediment. At a finer and organism-focused scale, some participants define eDNA as also including genetic material that is still located within the bodies of living organisms that are collected in environmental samples. Of this distinction, one participant situates themselves in the following way: "Some people call that [genetic material within organisms] eDNA as well. I do not. I kind of restrict my definition of eDNA to what's found out in the external environment. I would call that other example something different." Importantly, this participant is not suggesting that the other definition is wrong but is instead marking the difference between definitions that are circulating on the project. Another speaks to the need to attend to the constructed boundary between macro and micro scales when they say "There's just so many shared techniques and I think it helps get peoples' heads a little bit into the idea that we shouldn't be having this artificial boundary between macro- and microorganisms." These latter two quotes point to another key pattern that has important implications for negotiating definitions within the project. As we describe more fully below, while participants describe their own definition of eDNA, they also acknowledge the "artificial" or constructed differences and the need for dialogue to continue to learn across those differences.

Creating spaces for dialogue, such as in the use of knowledge maps (Wilson and Herndl, 2007; Graham et al., 2017), can help identify the multiplicity of definitions and also how one definition can blur into another, such as how definitions of eDNA intersect with definitions of scale. However, mapping out different definitions also needs to consider the sets of meanings that guide how these definitions come to make sense in the first place (Lynch, 2011; Walsh, 2017), and especially how meanings connect with research paradigms, or the respective ontologies and epistemologies. The material definition of eDNA relies on and reinforces ontological assumptions about the nature of reality and epistemological assumptions about what constitutes knowledge. For example, the first quote above locates eDNA in the environment in ways that assume spatial relationships where the environment is composed of constituent parts, like air, water, soil, and so forth that can be measured and distinguished from the organisms within it. In this part-to-whole formation, material definitions mobilize binaries between parts of the environment as well as binaries that separate samples/organism, observer/observed, and interiority/exteriority. The concept of parts connecting into wholes is based on a systems ontology which is a common paradigm for post-positivist approaches to ecosystem and resilience-focused research (Walker and Cooper, 2011).

There is also an assumed temporality to environmental measurements, such that sampling for eDNA in the environment or within an organism can tell us something about the present in ways that connect with the past and potential futures. The logics that link eDNA as a material entity with how eDNA serves as evidence for present, past, and future conditions constructs a linear and singular temporality (Adam, 1998). Defining eDNA as a *reflection* of the past *deflects* the multiple definitions for what eDNA data could come to mean, including the multiple temporalities that *could be* constructed through eDNA (Burke, 1966). For example, a sample of water showing presence or absence of alewife chronologically reflects contemporaneous or past fish presence but is almost always perceived by those invested in the fish as evidence for possible recovery outcomes. In these future-oriented perspectives, cultural revitalization or Indigenous kinship-based relations to alewife serve as secondary considerations to recovery goals, if these considerations are included at all. Likewise, detection of harmful algae blooms might be interpreted through the lens of an impending shellfish closure. In this sense, while the processes that produce eDNA are largely contemporary or historical, the motivations for eDNA are often future looking, and orient to particular futures that run the risk of reinforcing existing and unequal power relations. This example helps show how definitions are consequential for how they deflect or foreclose multiple and Indigenous forms of time that are not based on linear sequences but instead attunements to place, space, community, ecology, Land, and myriad other forms of relationality (Liboiron, 2021; McGreavy et al., 2021). Further, material definitions of eDNA rely on a set of meanings that connect with post-positivist research paradigms. This attention to paradigms, and the relative dominance of some paradigms over others, can enhance efforts to grapple with connections between definitions and power, as we more fully describe in the next section.

Tool, Technology, and Technical Process

Definitions that emphasize eDNA as a tool or technology focus on the technical process of taking samples of genetic material organisms leave in the environment and then studying these samples to better understand ecosystems. Where the material definition approaches eDNA as a thing or object, the technical definition emphasizes the practical details of going out into an environment, collecting samples, and processing and screening those samples to see what species are present. In these practices, participants focus on developing and applying assays that either characterize diverse biological assemblages (e.g., eDNA metabarcoding), or detect and quantify particular taxa of interest [e.g., Quantitative Polymerase Chain Reaction (qPCR)]. The relative foci define the component tools within eDNA as technology, as well what individuals perceive to be the strengths and limitations of the technology. Similar to the influence of constructs of scale in the material definitions, these technical practices, and who uses them to study eDNA at a specific scale, fold back into constructs for where eDNA as a material entity is located, and diverse attunements of scale, space, community, etc. This pattern begins to show how definitions on the project do not necessarily have clear boundaries. Instead, definitions overlap and blur together such that meanings sometimes align and other times contradict. The multiplicity of definitions and the ambiguity involved in what definitions are relevant in any particular context can shape science-based deliberations in myriad ways (Walsh, 2017).

Consistent with the pattern noted above where researchers identify how definitions are constructed, in this technical orientation to defining eDNA some participants note a need to be careful about how such a focus can "lock out people." As critiques of technical solutions point out, technical definitions can reinforce assumptions about the nature of problems, whose knowledge counts, and how the world works in ways that can amplify power disparities and ignore the range of potential consequences of proposed solutions (Plec and Pettenger, 2012; Kuntsman and Rattle, 2019). The following participant describes how a technical definition of eDNA could contribute to these kinds of exclusions and power asymmetries:

> *You can imagine a scenario with a grant like this where the people in control of the technological measure side of the DNA things get to dictate how they get used. None of us know enough about how the things actually work or where they serve a technological performative control over the knowledge of things. So I guess I worry about that.*

The concern expressed here emphasizes individual agency and control, where having access to the technical knowledge of how to sample and what types of tools are required to address what types of questions privileges some forms of knowledge over others. The criticism of technological dominance in shaping project knowledge takes on an even greater significance when we move from concerns about individual agency to consideration of institutional power, and especially how academic institutions and dominant approaches to science intersect with colonialism (Whitt, 2009). One participant describes how "Technology-based data points can mobilize through colony institutions and artifact knowledge to disabuse Indigenous people or remove lands." This point calls attention to how approaching eDNA as "data" that can be collected through sampling technology is in fact a social-material construction that aligns with a particular worldview. Further, this participant points to how dominant approaches to science intersects with colonialism, as dominant science continues to be organized by assumptions about who can and should have access to land and water as Resources (Liboiron, 2021). A technical definition of eDNA emphasizes individual agency to collect eDNA as a material entity in ways that can reinforce anthropocentric, neoliberal, and colonial assumptions about who has the ability and the right to collect data and for what purposes, in this case the purpose of producing scientific knowledge to guide management. To begin to address this issue, a recent initiative by Local Contexts (localcontexts.org) shifts individual-level management of biocultural data to a collaborative approach through the creation and application of Biocultural (BC) Labels and Notices on data. As Liggins et al. (2021) describe, the BC labels signal "the right of Indigenous communities to define the use of information, collections, and data (including DSI) generated from biodiversity and genetic resources associated with their traditional lands or water" (p. 2,478). In this approach, Indigenous communities work with researchers to address management, cultural rights, and responsibilities for eDNA data and work to actively define how data and related eco-cultural knowledge should be described, shared, and archived and we return to this effort in the concluding section.

Science and Forensics

Definitions of eDNA as a science often combine the focus on eDNA as a material entity with the technological process to describe the kinds of questions and new knowledge that can be produced within this approach. The goal for knowledge tends to focus on producing new understanding about ecosystem processes over larger temporal and spatial scales than previous methods allow. This orientation also emphasizes methodological innovations, especially for the efficiency of data collection and the spatial and temporal extent of sampling. Further, the goal for eDNA as science prioritizes policy applications or technical solutions, and in particular, to address questions related to climate change. Mobilizing the definition of eDNA as genetic material left in the environment, this participant shows how this definition connects with their approach to science: "I define [eDNA] as the genetic signatures that organisms leave behind in their environment. And by capturing a sample of water and interrogating that water to find out what DNA is in it we can say something about who has been in the environment in recent time." The use of the term "interrogation" signals a related set of meanings for how eDNA is often defined as a *forensic* science. Approaching eDNA as a forensic science invites crime-based metaphors for characterizing ecological processes and events. This definition of eDNA frequently references popular television and crime shows, which further intensifies the link between eDNA, forensics, and crime. One participant offers an extended illustration of how they use crime scene analogies to explain eDNA to public audiences:

> *We went by and saw this school of fish and our first suspect was [a specific species] and then DNA came back and exonerated [this species]. Now we're trying to figure out: Who was it? Who was the culprit? And we think it's [an entirely different species]. So it's like a crime scene investigation.*

The value or potential utility of using crime scene analogies like this one differ based on the imagined audiences. For the participant communicating with a public audience, connecting with crime scenes provides a commonplace of understanding that could motivate a shared interest in the topic. In other cases, this approach is beneficial for helping natural resource managers conceptualize "how to handle" the samples they collect or the data they receive from the project. When communicating with donors, some participants note the importance of attention-getting tactics like comparing eDNA to a crime scene because they have experienced donors having "Very [. . .] short attention spans," and "so you need to hook them in really quickly." While participants value these kinds of comparisons, this approach also requires simplifying the complex problems of climate change and other environmental challenges into binary frames of innocent-guilty or problem-solution. The crime scene analogy may also be off-putting or threatening to those who have experienced biased, colonial, or state-based law enforcement. For example, clam harvesters face the threat of criminalization through environmental regulations related to water quality. If they dig in an area that has been closed due to fecal contamination or harmful algae blooms they can be prosecuted. Consequently, while this project seeks to use eDNA to strengthen local communities' capacities to more accurately detect and reduce the negative impacts of these types of closures, explaining the methodology through crime-based analogies may intensify some stakeholders' legitimate concerns that these tools will be used to reinforce unequal power.

Interestingly, although forensic and crime scene analogies were used extensively early in the project, the onset of the COVID-19 pandemic shifted many conversations toward a more clinical analogy involving comparisons between eDNA science and detection of SARS-CoV-2 and its variants. This includes drawing on common molecular tools (PCR), the importance of controlling false positive and false negative tests, the limits of detection of assays, and real cross applications like the detection of SARS-CoV-2 in sewage water. Still, this clinical science analogy tends toward binary frames and the comparison runs the risk of reducing the kinds of complexities that climate change and many other environmental challenges present. Likewise, both the crime scene and clinical framings rely on the assumption that there is a singular reality that can be accurately observed and measured through the collection of material evidence, again reinforcing post-positivist approaches to science.

Communication and Social Construction

In addition to the above patterns, some participants also describe eDNA as a communication process. The following quote provides an illustrative example of how talking about definitions constitutes eDNA in this way:

> *Part of it is, it's asking for definitions… When terms come up like that, I was like, "When you say "sample," what do you mean?" That just opens it up to dialogue. Then, people question "Oh, okay. I was thinking about it this way and you're thinking about it that way. Let's see where we can go. I understand what you're saying now." I think trying to highlight when we need to define terms so [that] we can tease out where we might have differences.*

This characterization demonstrates how some participants recognize that definitions matter because they shape differences and also because the dialogic process itself actively constitutes what "eDNA" becomes. Not only does this orientation add to the diversity of ways in which eDNA is defined, awareness that some participants define eDNA as a communication process can help challenge dominant or singular assumptions about what eDNA *really* means (Lynch, 2011) and encourage reflexive constructions of shared definitions or agreed-upon stases (Blythe et al., 2008). This orientation is consistent with the reflexivity we note above when researchers recognize how definitions of eDNA are socially constructed. The recognition that eDNA is a communication process also aligns with embodied performances of communication, where researchers describe perceptions of communication that align with dominant patterns in science-based collaborations that emphasize a linear information flow. And yet, at the same time, they describe and demonstrate a more multidimensional embodied understanding of communication as well. Recognizing this pattern helps build capacity within our engaged research approach to strategically connect with and find ways to amplify these perspectives to challenge patterns of dominance and promote greater diversity in perspectives and equity in participation within the collaboration.

As this analysis helps show, definitions are not mutually exclusive. Defining eDNA as a material entity is not incommensurate with defining it as a tool, technology, science and/or communication process. Instead, tracing different definitions helps demonstrate that when collaborators define eDNA, they are not necessarily approaching this concept in the same way. Inattention to differences in definition can set collaborators up for getting "stuck" (i.e., negative stasis) in ongoing deliberations about what a project should focus on and what it comes to mean (Blythe et al., 2008; Walsh, 2017). More importantly, a lack of reflexive attention to these differences can also reinforce power disparities when some definitions are emphasized or prioritized more than others (Popa et al., 2015). While the critical perspectives about the intersection of technical definitions and colonialism and that emphasize the social construction of eDNA are not widely shared within the project, these perspectives are still present. Identifying the presence of these perspectives can help engaged researchers be ready to amplify these perspectives and promote reflexive attention to how eDNA is always more than any single definition and how language, knowledge, and power shape collaborations in complex ways. Where a focus on definitions helps identify important differences in meanings that constitute a project, layering definitions with how participants define communication, audiences, and expertise directs attention to how definitional work can help identify and challenge unequal power, especially for defining who participates in a project and in what ways.

Constructing Communication, Audiences, and Expertise for eDNA

The following quote frames the relative importance of attending to how communication, audiences, and expertise are defined on a project and how these definitions feed into one another. One participant sums this up by saying: "It starts with knowing who you're talking to, right?" We appreciate this sentiment and extend it by noting that in addition to knowing who one is talking to it is equally important to attend to how audiences are defined in the first place and how implicit definitions of communication, audience, and expertise are co-constituted in ways that shape relative power within collaboration (Ihlen, 2020).

Consistent with previous research on communication within transdisciplinary collaborations, participants often describe an information-centric and linear approach to communication similar to the sender-receiver or diffusion model of communication (Bucchi, 2008; Suldovsky et al., 2018). Communication is characterized as a "two-way" or reciprocal flow of information through verbal speech or media, such as writing and e-mail. One of the main objectives in this model of communication is effective messaging, tailored outreach, and getting past "jargon" to describe scientific information in simple and accessible terms. The emphasis on information sharing tends to center the role of researchers or administrators as communicators who have a message they want to convey. Further, the goal frequently focuses on promoting mutual understanding of the project but where the terms for understanding, and especially as they relate to dominant paradigms, are not necessarily open for negotiation. The following quote represents this broad pattern:

> *I would define communication as an understanding of the content that's being communicated between both parties or all parties present. And I think the key there is understanding. And I think good communication is often, is very difficult to achieve because when you work in interdisciplinary projects, people feel more comfortable using words or terminology, so jargon, that others don't understand.*

Echoing this sentiment for audiences not directly involved in the collaboration, participants emphasize the value of describing the science in as simple terms as possible in ways that avoid getting into the details. Many argue that it is important to explain basic processes, such as collecting and analyzing eDNA, and focusing on the questions those scientific processes can help answer. Taking the time to explain the science was important for connecting with audiences, even if it "might not be scientifically the most accurate" or even if "[Identified audiences] probably still won't understand completely."

As demonstrated in the quote above, "jargon" as a frame often connects with linear or diffusion approaches to communication, where jargon is assumed to get in the way of effectively conveying information. The frame "jargon" can be deployed in distinctly uneven ways, where some forms of language or knowledges are deemed jargon and others that are equally technical are not. Further, calling some terms jargon makes assumptions that the knowledge associated with those terms should be accessible to others. As TallBear (2013) argues:

> …[Academic scientists] often refer to social theory as 'jargon,' as if they should readily understand what it has taken me and other social scientists and humanists years to master. I do not assume I should readily grasp all of the language used and data introduced in a technical presentation about the genome diversity of oak-tree populations in Northern California. (p. 122)

TallBear (2013) instead suggests that "We need precise languages to talk about precise ideas that have derived from specific histories of work, from the development of theories and methods" (p. 122). In this approach, the challenge in communicating across disciplines and with partners is not in getting past jargon but in how we define and produce knowledge about eDNA in ways that allow diverse meanings to connect on their own terms and within their respective meaning systems. Such a process would create opportunities for identifying and challenging dominant paradigms that set the terms for knowledge and understanding in the first place.

Despite the unsurprising presence of message-based, linear, and diffusion-oriented perceptions about communication (Suldovsky, 2016), we also regularly observe other definitions of communication circulating as well. Like definitions of eDNA, definitions of communication are diverse, overlapping, and contradictory, and the following quote provides a representative example: "I mean I'm being a biologist here and thinking about senders and receivers and signals and things of that nature. But it's not just a sender and a receiver. It needs to be both directions for communication to occur, otherwise it's just signaling. People are just sending stuff one way, it's not really communication. Communication requires reciprocal information transfer." On one level, this perspective aligns with a diffusion model of communication. Like jargon, the concepts of senders, receivers, signals, and so forth imply a linear transfer of information. Yet, on another level, the perspective also begins to show how it would be overly reductive to indicate that linear definitions of communication were the only meanings circulating.

There are two distinct patterns that we have noticed consistently. First, the frequent emphasis on reciprocity points toward a more dynamic and relational orientation to communication than an information-centric approach would imply. Reciprocity as a relational commitment works to transform the more linear meanings associated with information transfer. And where this quote makes a nod to a more relational approach, many others linked ideas of reciprocity with commitments to dialogue and listening, as seen here: "And for me…that communication starting as early as possible and listening and learning as early as possible is pretty critical to the overall success of the project. It may take a while and it may require extra effort, but it's been invaluable." Second, when the participant situates themselves as a biologist, as in "I mean I'm being a biologist here," they *perform* a reflexive orientation to communication (Thompson, 2009; Popa et al., 2015), one that positions themselves as a communicator and where they are trying to define communication in more expansive terms than the discourses of their disciplinary training may allow. This demonstrated reflexivity becomes a means through which more diverse definitions of communication can become articulated, both in terms of the overt definitions (i.e., stating what communication means) and the embodied and relational performances of communication.

These diverse perspectives about communication and audience layer with constructions of expertise in ways that open up and constrain possibilities for collaboration. Participants frequently describe how they reserve technical terms or formal science associated with eDNA for scientific audiences. Instead of focusing on the technical and scientific aspects of the work, participants describe how they center research or application-focused questions in their communication with "non-scientific" audiences. As one participant explains, "I think it's really about the questions. So we walk them through the range of questions that can be identified." Using a similar question-focused communication strategy, the following participant helps show the constitutive relationship between questions and audience constructions, which we quote at length because the perspective is uniquely illustrative:

> *Yeah, if you're talking to a mussel farmer, you say "Do you wish you knew when the seed set was coming in in advance so you knew when to get your ropes in the water?" I'm trying to think from [a biologist's] perspective. If you're talking to a lobster fisherman,*

> *then you want to say "Don't you want to figure out where those Stage 2 larvae are going, and are they eating Calanus finmarchicus [a species of zooplankton]? Are they following them out to sea? Is that why we are not seeing them around here?" Or [one non-profit fisheries leader] was really excited thinking about looking for [a shellfish species] off of Downeast using eDNA because that fishery has been closed for a little while, I think, and they think the stocks are rebounding. And there's not a concerted effort to go out there and survey them with trawling. And knowing that those trawling surveys are destructive in the first place. "Isn't there a non-destructive way that we can sample and figure out what the standing stock looks like?"*

Asking questions becomes a relational process that positions audiences in terms of their roles and relative interests in eDNA topics and reinforces material and tool or technology-based definitions of eDNA. This approach reinforces specific definitions of eDNA, in this case as a material entity or tool and technology. It also defines audiences in terms of the eventual applications of these tools and not in terms of the specific knowledge they would contribute or the ways in which they may define eDNA or issues of environmental change. However, this perspective also demonstrates reflexivity in how this participant imagines what specific audiences would want to know about the kinds of questions that, in this case, lobster fishermen, would ask. Asking questions paired with reflexive consideration of audience interests can promote connections across differences in knowledge, as project researchers work to describe their science in more relatable terms and in ways that start with and center audience questions. Thus, a focus on questions—where questions come from, who is asking questions of whom, and how questions can disrupt or challenge patterns of dominance in definitions, communication, and expertise—emerges as significant communication strategy within transdisciplinary collaborations.

CONCLUSION: ENGAGED PRAXIS FOR MORE STRATEGIC COMMUNICATION

This research contributes insights about how a focus on definitions, audience, and expertise can produce knowledge about some of the complex and multidimensional ways that strategic communication shapes collaboration. Further, this focus lends specificity to identifying and potentially challenging unequal power within science-based transdisciplinary collaborations. In the Maine-eDNA project, participants described multiple definitions of eDNA, including as a material entity, tool or technology, science, and communication process and each of these definitions connects with different meanings related to spatial and temporal scales as well as ontologies and epistemologies, where systems ontologies and post-positivist research paradigms were frequently articulated. Definitions of eDNA layer with definitions of communication, audiences, and expertise in ways that align with previous research that demonstrates the dominance of linear and diffusion-based models of communication and the relative epistemic authority of post-positivism in science-based contexts (Bucchi, 2008; Suldovsky et al., 2018). However, we also observe important differences as compared with previous scholarship, especially in terms of the diversity of definitions and consistent performances of both reflexive and relational approaches to communication.

What accounts for these differences and, more importantly, how do these patterns shape transdisciplinary collaboration? There is no single explanation. As we hope to have shown, communication influences collaboration in ways that exceed any single perspective or ability to observe and describe. There are also contextual details that matter and that shape the ways in which we might compare one collaboration to another. For example, many researchers on this project have been involved in related large-scale transdisciplinary collaborations, some of which were also funded by NSF, and they reflect on what they have learned from those previous experiences, and especially from communication challenges. Another contextual factor is the relatively new nature of eDNA research itself, where definitions are not as entrenched as in more established fields and where the lack of shared and singular disciplinary agreements may invite reflexivity as team members work toward situating their own perspectives about eDNA.

However, this research helps identify opportunities to more carefully and critically attend to how specific communication practices shape knowledge co-production for more diverse and equitable transdisciplinary outcomes. We conclude here by highlighting three ways in which this engaged approach to strategic communication is shaping collaboration, including question-focused strategies that promote reflexivity, using knowledge mapping to identify and negotiate differences in definitions, and using questions about/as ethics for identifying and shifting relationships between language, knowledge, and power.

Pose Questions to Create Spaces for Reflexive Attention to Rhetorical Constructions of Definitions and Knowledge

Our engaged and ethnographic approach to strategic communication in this science-based context centers a strategy of continuously posing questions. A shared and consistent focus on addressing questions together helps promote active consideration of how core concepts, like definitions of eDNA, are rhetorically constructed and reflexive awareness about the multiple ways in which eDNA can be defined. Questions thus function as a type of genre, an identifiable space of social action within the collaboration (Miller, 1984), that promotes specific types of interactions, such as the consideration of how one's own perspective relates to or differs from another. The practice of asking questions together occurs in myriad ways, including most notably in the context of conducting the interviews described above. In addition to helping us gather evidence to address our research questions, posing interview questions about definitions, communication, the type of knowledge that someone brings to a project, and experiences with collaboration creates a space for more actively considering the diversity of possible perspectives and how something like a definition is socially constructed. The reflexive space that interview questions create is evident in many of the quotes throughout the analysis.

Taking a question-focused approach also served as a main objective for the formation of a working group focused on communication and collaboration. This group, which involved all of the co-authors on this paper as well as other collaborators, met on a monthly basis for two years. Unlike other teams on the project, such as those that focus on project administration or biophysical research, this working group intended to create a space to address shared questions, engage in open-ended dialogue, and consider and discuss what we were learning from the interviews. The diverse participation in this group helped to foster recursive consideration of questions and insights throughout the project, and we observed many instances where conversations we had in this working group were then taken up in other project meetings.

Use Knowledge Mapping for Question-Focused Knowledge Co-production

We brought the above commitment to asking questions to a knowledge mapping approach to create space to talk about different definitions of eDNA and the knowledge we each contribute to the project. Drawing from previous work on how knowledge mapping creates spaces for rhetorical constructions and negotiations across difference (Wilson and Herndl, 2007; Graham et al., 2017), we noticed how the embodied activity of working together on knowledge maps created opportunities for participants to visualize and create linkages between multiple definitions of eDNA. Knowledge mapping provided space to consider different perceptions about eDNA and fostered discussions about how a transdisciplinary approach invites us to consider ethical issues associated with linking knowledge with action. Occurring in parallel with interviews, both efforts coalesced into a consistent focus on what an ethics of eDNA and, more broadly, an ethics of transdisciplinary collaboration would mean.

Center Questions About/As Ethics as a Strategy to Address Language, Knowledge, and Power

The practice of asking questions created space for focused discussions about ethics, and what an ethics of eDNA would mean for this project and for emerging eDNA science more broadly. The frame about/as ethics refers to the two distinct orientations to how we understand the practice of asking ethics-focused questions. First, project dialogue *about* ethics sought to identify ethical research commitments that included but also transcended formal research regulation in the Institutional Review Board (IRB) and Institutional Animal Care and Use Committee (IACUC). In the context of a transdisciplinary collaboration, there are myriad ethical issues that are related to the under-specified and yet crucially important considerations of mutual beneficence and justice (Lynch, 2019). For example, some of the research efforts on the project include citizen science and partnerships with Natural Resources Departments in Wabanaki Tribal Nations where ethical issues related to data management and ownership intersect with questions about how eDNA is defined and whose knowledge is prioritized. The graduate student-led pilot project on Biocultural (BC) Labels with Local Contexts and ENRICH (https://www.enrich-hub.org/) mentioned in the analysis above seeks to amplify relational and reflexive commitments to communication. In addition to setting up a platform to actively challenge dominant definitions of eDNA, this effort creates further opportunity to ask questions such as: who or what form of knowledge counts and what are alternative ways of defining eDNA? Further given the complexities in communication and across differences and in relative power, what are our responsibilities to each other and within this place?

Related to these latter questions, we also approach ethics *as* a commitment to centering questions in the project as a whole, a commitment which includes but goes well-beyond ethics as a prescribed set of principles. Active participation in our engaged research serves as one example of this project-wide commitment and the questions we ask in the context of this engaged approach have intensified the more deliberate and extensive focus on an ethics of eDNA in the project. For example, as part of our focus on definitions, one of our interview questions asked about the kinds of visual images participants use to communicate about eDNA and this question created an opportunity for a participant to raise a concern about the ethical implications of using the double helix as a visual image in light of the relationship between DNA research, colonialism, and eugenics (Whitt, 2009). Sharing this and related insights in multiple project meetings promoted project-wide efforts to use questions about/as ethics to intentionally grapple with the intersections between language, knowledge, and power, which coalesced in a series of presentations in project meetings; a half-day ethics workshop that invited speakers with diverse perspectives about Indigenous ethics, applied biomedical ethics, and environmental ethics; and incorporating a consistent focus on ethics in the two graduate courses on the project.

In closing, when paired with an engaged and ethnographic methodology, an interdisciplinary and rhetorical approach to strategic communication can help study patterns and shape collaborative praxis. In large transdisciplinary collaborations, such as the Maine eDNA Project, the myriad ways in which communication shapes knowledge co-production processes can, at first, seem overwhelming and impossible to meaningfully address. As critiques of the diffusion model help show (Bucchi, 2008; Suldovsky et al., 2018), it is not desirable nor arguably even possible to control communication within science-based collaborations. However, attention to definitions, perceptions of communication, audience, and expertise can help identify the types of questions that can be paired with specific techniques, such as using knowledge mapping and anti-oppressive data management platforms, to foster a shared commitment to strategic communication as ethical praxis.

DATA AVAILABILITY STATEMENT

The datasets presented in this article are not readily available because they are IRB-protected qualitative data.

Requests to access the datasets should be directed to bridie.mcgreavy@maine.edu.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by University of Maine Office of Research Compliance, Institutional Review Board for the Protection of Human Subjects (IRB). The patients/participants provided their verbal informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

BM led the writing and co-led the research design, data collection, and qualitative analysis. KH contributed to all aspects of the writing and co-led the qualitative analysis. JS-M contributed to the data collection. JS-M, JR-M, MTK, and DR contributed to the writing, research design, and qualitative analysis. HL co-led the research design, data collection, qualitative analysis, and contributed to the writing. MTK, HL, BM, and DR obtained funding for the research (#OIA-1849227). All authors contributed to the article and approved the submitted version.

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Acknowledging and Supplanting White Supremacy Culture in Science Communication and STEM: The Role of Science Communication Trainers

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Racism remains a root cause of underrepresentation of Black, Indigenous, and Latinx scholars across STEM. It also contributes to a lack of diversity in science communication, the types of science stories that are told, and the communities science communicators seek to engage. Racism is omnipresent in STEM, from education to research to science communication (SciComm), because STEM institutions operate within a culture systematically privileging Whiteness, i.e., a White supremacy culture (WSC), that dictates the norms and practices that most in these fields heedlessly accept and replicate. In this Perspective, we acknowledge the ways in which SciComm and SciComm training perpetuate WSC and examine how SciComm trainers can use their power to dismantle it. SciComm trainers pioneer new methods of sharing ideas and influence the culture of STEM, so are uniquely situated to bring about systemic change to address these problems in SciComm, STEM, and society, starting with four core themes for action: (1) Authentic Interrogation, Acknowledgment, and Accountability; (2) Representation; (3) Culturally Responsive Practice; and (4) Inclusion. We also describe our current work, which builds upon the Key Traits of Inclusive SciComm identified by leaders in the field, to co-create a framework to guide authentic, culturally competent, and inclusive SciComm. The draft framework integrates the Key Traits across spheres of influence (e.g., self, interpersonal, community, institution, society: politics and culture), with the ultimate goal of using SciComm to supplant WSC across these spheres of influence, with new co-created norms centering minoritized scholars, science communicators, and audiences in STEM.

Keywords: White supremacy culture, science communication training, cultural norms, equity, inclusion

INTRODUCTION

Racism is a root cause of underrepresentation of Black, Indigenous, and Latinx scholars across STEM. It also contributes to a lack of diversity in science communication, the types of science stories that are told, and the communities who are engaged. Racism is omnipresent in STEM, from education to research to science communication (SciComm), because STEM institutions[1] operate

[1]STEM institutions refers to the STEM enterprise collectively, including higher education, non-profit research and educational organizations, government research labs and agencies, and corporate STEM research institutions.

within a system that advantages White people, termed by Jones and Okun in a 2001 article, White Supremacy Culture (WSC) (Jones and Okun, 2001).

Jones and Okun identified 15 characteristics of WSC, including perfectionism, paternalism, power hoarding, worship of the written word, sense of urgency, belief in one right way, and defensiveness (see **Table 1**). WSC is embedded in the design of our institutions. It dictates the norms and practices that most in these fields heedlessly accept and replicate. Due to its pervasive nature, WSC is difficult for many to see and to process, thereby making it equally as difficult to address.

Our purpose in describing WSC in STEM institutions and SciComm is to name it so we can see it and change it (Bryant et al., 2021). Suggesting that WSC harms minoritized scholars in STEM may cause some to respond defensively or express disbelief (Handley et al., 2015; Bryant et al., 2021). Rather than dismissing the suggestion, we argue that important questions to consider are:

- *Who does WSC in STEM harm, and how are they harmed ?*
- *What is the role of SciComm in perpetuating and dismantling WSC in STEM?*
- *Who is responsible for designing and implementing solutions?*

Here we offer our responses to these questions, with the following intentions: We write from the perspective of science communication trainers, complicit in a system that causes harm, with a desire to work for change from within our community of professionals. We encourage you to reflect on your own answers; to lean into these questions to determine what actions you can take to create a better, stronger culture in STEM; and if any feelings of discomfort, anger, or defensiveness arise, to acknowledge and reflect on your experiences in STEM and SciComm that shape your perspectives.

Who Does WSC in STEM Harm, and How Are They Harmed?

Underrepresented scholars in STEM are speaking about the ways they are harmed by WSC in STEM *via* social media (#BlackIn, as described by Ortega, 2021); affinity, empowerment and advocacy groups (500 Women Scientists, 2016; Academics for Black Survival Wellness, 2020); presentations (Baxter, 2021); and film (Cheney and Shattuck, 2020). These personal narratives illustrate trends reported in publications documenting disproportionate barriers and lost opportunities for Black scholars in STEM (Lee, 2020; McGee, 2020; Easley, 2021). WSC places the burden on underrepresented individuals to prove a causal relationship between the hostile environment in STEM and the demographics of STEM institutions. The most common tropes are that an individual's attitude, aptitude, or interests determine whether they succeed in STEM (Henry, 2010). However, the environment—the *culture* of STEM—remains uninterrogated. We argue that the correct order of operations is to first interrogate the role of WSC in STEM for determining the demographics of STEM institutions. Only once STEM leaders whose actions perpetuate WSC, relinquish their gatekeeping role determining who is considered a scientist, can we begin to consider the role of attitude, aptitude, and interests.

What Is the Role of SciComm in Perpetuating and Dismantling WSC in STEM?

The most conspicuous way SciComm trainers and practitioners of SciComm (collectively, SciCommers[2]) perpetuate WSC is by disproportionately training, elevating, and amplifying White scientists and their research (Dawson, 2018; Dudo et al., 2021). While improving access to training and elevating and amplifying the voices of underrepresented scientists is one part of the solution, we also need new models, frameworks, and cultural change in SciComm and STEM in order for STEM to truly be an authentic multicultural enterprise.

SciComm trainers have a history of being cultural change-agents. They pioneer new methods of sharing ideas and influence the culture of STEM, so are uniquely situated to bring about systemic change. SciCommers are contributing to a shift in the culture of science by placing increased value on the critical roles of outreach and engagement (Christopherson et al., 2018). The next frontier is cultural change needed to dismantle WSC in STEM.

Who Is Responsible for Designing and Implementing Solutions?

In the remainder of the article, we will draw on the literature, the reported experiences of our colleagues, and our own experiences as scientists and SciCommers to document the fingerprints of WSC in the culture of STEM institutions, the harm caused by it, and foundations for doing better. Below, we suggest four key themes for immediate action, and describe our current work, to co-create a framework to help guide authentic, culturally competent, and inclusive SciComm. The draft framework integrates Canfield and Menezes (2020)'s Key Traits of Inclusive SciComm across multiple spheres of influence (e.g., self, interpersonal, community, institution, society: politics and culture) (**Figure 1**), with the ultimate goal of using SciComm to supplant WSC across these levels of influence with new co-created norms centering minoritized scholars, science communicators, and audiences in STEM.

WSC in STEM and SciComm

Does WSC Exist in STEM?

Most (if not all) of the WSC characteristics described by Jones and Okun (2001) are valued as essential for success in our field (see **Table 1**). White supremacist norms are prevalent in college admissions and hiring, awarding funding, determining who gets published and who has access to what is published, which communities and audiences are prioritized for communications, and who has a say in what is studied and why (Stevens et al., 2021; Taffe and Gilpin, 2021). Accordingly, institutional and systemic change is needed to mitigate the WSC characteristics woven into the fabric of our STEM institutions and standards of practice.

[2]Unless otherwise noted, we are using the term SciCommers to refer to SciComm professionals collectively, including trainers, practitioners, researchers and evaluators. Within this perspective, we also identify specific action items for SciComm trainers.

TABLE 1 | List of White Supremacy Culture characteristics identified by Jones and Okun (2001) and examples of how these show up in STEM fields.

Characteristics of White Supremacy Culture (adapted from Jones and Okun, 2001)	Descriptions of the characteristic	Consequences of the characteristic for scientists, the scientific enterprise, and/or SciComm
Defensiveness	White people spend energy defending against charges of racism instead of examining how racism is actually happening.	Results in leaders of STEM institutions focusing their attention on addressing individual or small-scale instances of racism, while ignoring or reinforcing systemic biases in the institutions and practices of science.
	Energy in the organization is spent ensuring that feelings are not hurt, or working around defensive people.	Creates reluctance to work with students or colleagues if they question WSC in science.
Either/or thinking	Results in trying to simplify complex things.	Encourages single-factor explanations, ignoring complexities of systems/processes and leading to oversimplified science.
Fear of open conflict	Emphasis on false politeness, oblivious to offense; insisting on politeness as terms for conversation or negotiation.	Leads to insincerity in interactions; mistrust among scientists and between scientists and public audiences.
Individualism/I'm the only one	The belief that if something is going to get done right, "I" am the one to do it; a belief that if the outcome is celebrated, I should be the one to take credit (even if others were involved).	Reduces collaboration, increases competition, and cultivates the belief that science and science communication is done by "superstars" acting alone.
	Desire for individual recognition and credit.	Reinforced by institutional rewards for being a single author or senior author. Leads to a small number of people getting most of the credit, forgetting that science is built upon the work of others; also associated with overestimating one's own scientific knowledge or competence.
Objectivity	Impatience with any thinking that does not appear "logical."	Ignores human propensity for System 1 thinking.
	The belief that emotions are inherently destructive, irrational, and should not play a role in decision-making or group process.	Makes science inaccessible; Ignores the science indicating that emotions are inherent and necessary in human decision-making.
Only one right way	The belief there is one right way to do things and once people are introduced to the right way, they will see the light and adopt it.	Generates deficit model communication and a tendency to blame audiences for failure to understand.
Paternalism	Those with power often don't think it is important or necessary to understand the viewpoint or experience of those for whom they are making decisions.	Leads to science communication that is perceived as tone-deaf, insensitive, or irrelevant by audiences with significantly different experiences from the leadership. Leads to alienating scientists, science communicators, and audiences whose experiences differ from the dominant narrative. Loss of creativity and talent from science and science communication.
Perfectionism	Making a mistake is confused with being a mistake, doing wrong with being wrong.	Leads to reluctance to engage in SciComm if scientists are concerned that their research may not meet high standards or if they are concerned that they will make mistakes in their SciComm.
	Little appreciation expressed among people for the work that others are doing. Appreciation that is expressed usually directed to those who get most of the credit anyway.	Selectively encourages those who have received extensive validation from the scientific enterprise to seek out SciComm training because they are less likely to feel that their mistakes will be seen as shortcomings, while discouraging others.
Power hoarding	Power is viewed as a zero-sum game; only few people can have it, it cannot be shared. Those with power assume they have the best interests of the organization at heart and discount other viewpoints.	Introduces secondary agendas to maintain the status-quo. Reinforces the myth of meritocracy. Gatekeepers play an outsized role in determining what ideas are elevated.
Quantity over quality/progress is bigger, more	Downplays the monetary and non-monetary costs of bigger/more. Ignores ways in which people may be exploited, excluded, or underserved.	Causes scientists to focus on their own agendas and needs rather than the audience's issues and needs.
	Values product over process, productivity over engagement.	Prioritizes of research and publications; devaluing of public outreach or community-based projects.
	Discomfort with emotion and feelings.	Feeds the stereotype that scientists are cold, impersonal, and distant.
Right to comfort	The belief that those with power have a right to emotional and psychological comfort.	Makes a person the problem, causing scapegoating and gaslighting. Denies experiences and emotions of scientists and science communicators.
Sense of urgency	Pressure to quickly produce highly visible results.	Sacrifices relationship-building in favor of action, including relationships between researchers and diverse communities or stakeholders.
Worship of the written word	The organization only values highly cited publications, and does not value other ways in which information gets shared.	Reinforces the publish or perish mentality. Networks, collaborations, activities, and outputs are only valued if they are connected to established practices or traditional formats.

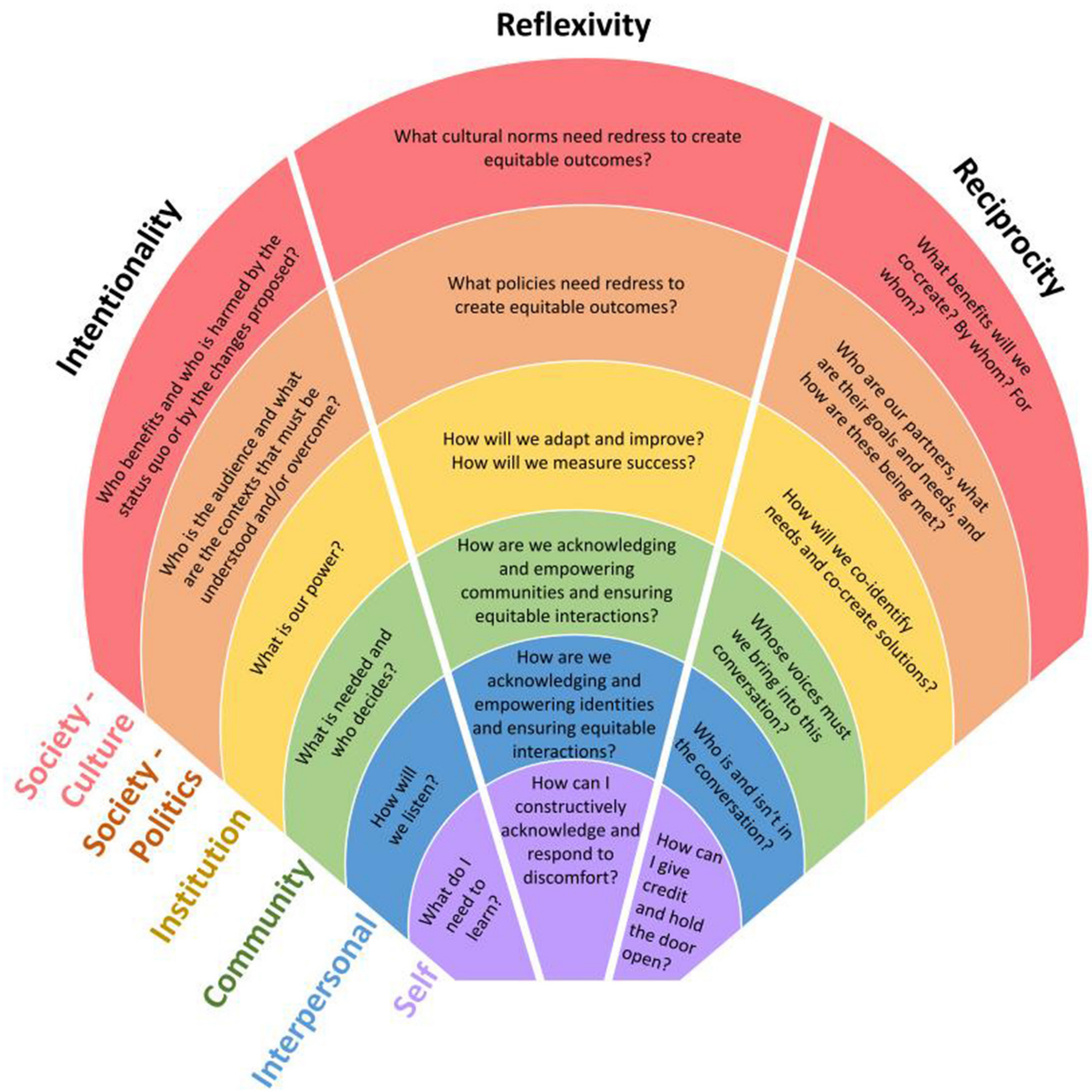

FIGURE 1 | Concept for co-creating a framework to guide authentic, culturally competent, and inclusive SciComm. In this figure, spheres of influence are represented as arcs of color, from self at center, to society-culture at the outer ring. The arcs are divided into three sections, each representing one of three traits of inclusive science communication (intentionality, reflexivity, and reciprocity) as marked at the top of each section. Each intersection of a sphere of influence and trait of Inclusive SciComm contains a question. Each question is a prompt to consider, for developing inclusive science communication trainings, workshops, and interactions. The draft prompts here are still in development and are intended as representative examples.

How Does WSC Persist in STEM?

Some argue that science is neutral, objective, and even "colorblind." These suggestions fail to explain persistent disparities in STEM (**Table 2**). Biases are frequently invisible to dominant groups who do not experience them personally (Henry, 2010). Dominant groups hold most leadership roles in STEM; accordingly, the biases in STEM are frequently invisible to those in power, leadership, and decision-making roles.

Racial disparities in STEM are the most visible evidence and most urgent reminder of racism and WSC in STEM Institutions. Cultural norms, values, beliefs, and standards give institutional power to White scientists, and enable them to maintain power and advantages over minitorized groups.

Biased standards of practice in STEM are inherited, not affirmatively chosen, co-produced, or inclusively designed. They persist when cultural dynamics designed to center a White norm (Lee, 2020; McGee, 2020) interact with cognitive biases in hiring and advancement (Linos and Reinhard, 2015); they create a sleight of hand that the dominant culture has branded "merit" (Markovits, 2019). WSC invisibly ensures White majority scientists who protect the status quo continue to hold most decision-making and power-holding roles in STEM (Johnson and Howsam, 2020; McGee, 2020; Gee and Hicken, 2021). Such practices permeate institutional design; they benefit few and harm many. Although these norms harm people regardless of identity, people who are Black, Indigenous, Latinx, and other minoritized identities are harmed most.

STEM institutions persistently fail to account for the influences of WSC on STEM research and institutional culture. This error is caused by a disproportionate focus on intentional acts of racism [i.e., Explicitly holding Black, Indigenous, Latinx, and minoritized researchers and scholars to a different stsandard from White academics for hiring and funding decisions (e.g., Lewis, 2020; Rucks-Ahidiana, 2021)]; unintentional acts of racism [hiring choices based on subjective categories like "fit" (e.g., Milkman et al., 2015)]; and other biases perpetuated by individuals within organizations. By unquestioningly accepting institutional standards of practice, we uphold structures that are intended to be neutral but unintentionally perpetuate and accentuate bias (e.g., Hoppe et al., 2019; Stevens et al., 2021; Taffe and Gilpin, 2021)[3].

When considering institutions, we focus on intent (such as scientific rigor or objectivity) and ignore the evidence that systems designed by White scientists favor White scientists. For example, per Hoppe et al. (2019), majority White review panels direct funding to topics disproportionately preferred by White applicants. Accordingly, NIH grant applications with White PIs are 1.7 times more likely to be funded than applications with Black PIs, and this gap has persisted unchanged for nearly a decade (Hoppe et al., 2019; Taffe and Gilpin, 2021). We amplify this bias by using grants and manuscripts as criteria for hiring and promotion (Stevens et al., 2021; Taffe and Gilpin, 2021) and as a basis for merit pay bonuses (Harvard University, 2021).

What Is the Role of Scicomm?

Patterns and practices of SciComm have set the stage for a series of myths about science and scientists that perpetuate WSC. The cultural ideology of science as unbiased truth generates the notion of what author Chimamanda Ngozi Adichie refers to as a "single story" (Adichie, 2009). SciComm around that "single story" typically represents a White-centered narrative of science as objective truth and a benevolent force. SciComm can also amplify the *myths of meritocracy* and *solitary genius*, by telling stories focused on innovative protagonists who single-handedly make novel discoveries and earn esteem within the academy. This ignores the realities that advancement results from a mix of effort, abilities, and social factors (McNamee, 2014), and science is a team effort (Wuchty et al., 2007); most research is achieved *via* contributions from students, staff, and collaborators, whose efforts often accrue to a single senior scientist (Clark, 2017). SciCommers also disproportionately amplify science by White researchers (Dawson, 2018), which unintentionally reinforces the *power of normal* (Fuentes, 2014) enjoyed by White scientists, and creates associations between whiteness and authority, accomplishment, and skill (Dutt, 2018). These false ideas tilt science toward the WSC characteristics of perfectionism, individualism, defensiveness, and the idea that there is only one right way, prioritizing a focus on "inadequacies" while giving credit to those who are already centered.

[3]We also acknowledge that these issues intersect with and can be amplified by perspective, positionality, and cognitive biases; however, here in this manuscript we are focusing specifically on the role of WSC.

DISCUSSION

How We Create Change

We call upon SciComm trainers to be models for mitigating WSC in SciComm, STEM, and society, starting with four core themes for action: (1) Authentic Interrogation, Acknowledgment, and Accountability; (2) Representation; (3) Culturally Responsive Practice; and (4) Inclusion. In considering these themes, we must also consider how we match actions within each of our spheres of influence, from self, to interpersonal, to community, to institution, to society: politics and culture.

This work must start with awareness; opening our eyes to the issues and acknowledging the ways we collectively contribute to and perpetuate them. *Authentic Interrogation, Acknowledgment, and Accountability* requires SciCommers to explicitly articulate the ways in which STEM and SciComm have been used as systems of oppression, upholding WSC. Beyond confronting the ways in which the scientific enterprise and field of SciComm have maintained WSC, SciCommers can reflexively examine their own work to identify ways in which their organizations and practices in particular have been complicit in perpetuating it. This includes acknowledging both current and past harms before attempting to move forward. In addition to interrogating and acknowledging WSC traits and myths when they are visible in our work, we can begin to create systems of accountability, which should be formalized over time as we become more adept at recognizing the problems.

Prioritizing *Representation* provides another avenue for dismantling WSC in STEM and SciComm. Scientists of color continue to be underrepresented. Similarly, SciComm content commonly focuses on issues not of concern to marginalized communities (Dawson, 2018). Communicators must proactively showcase work done by scientists of color. Not only is it crucial to convey (in all forms of media) the diversity of scientists, it is also important to examine the narratives or myths that are being conveyed in the process. Additionally, we need to showcase topics and issues in science that will benefit and advance knowledge in diverse communities. SciComm trainers, specifically, can call out the importance of diverse representation in their trainings, and they can also model it by ensuring that all examples and exercises they include in their curricula represent scientists with a wide range of identities and backgrounds.

Representation also includes thinking about who is visible. Scientists who communicate regularly or whose work is featured more with public audiences tend to be more visible within and beyond the scientific enterprise. This visibility can bring a number of additional benefits, including more citations and greater likelihood of earning awards and recognition, which validate their efforts, and ultimately increase their funding opportunities. These types of recognitions perpetuate the cycle of people with more privilege having greater access to the opportunities, resources, and platforms to do more SciComm.

TABLE 2 | Common perceptions about inequality in STEM institutions (a) can be evaluated *via* associated expectations (b). However, persistent disparities in STEM (c) suggesting that STEM institutions are not "colorblind," and that racism in STEM is a systemic cultural problem.

(a) If this is true	(b) Then we expect	(c) But the reality is
STEM Institutions are "colorblind."	Demographics of STEM institutions would reflect the demographics of the general population. Funding and pay would not correlate with race.	Black scientists are underrepresented in STEM careers, as are Latinx and Indigenous scientists (Fry et al., 2021). White scientists benefit from a funding advantage (Hoppe et al., 2019; Stevens et al., 2021; Taffe and Gilpin, 2021) and a pay advantage (Li and Koedel, 2017; Fry et al., 2021).
Racism in STEM primarily occurs via discrete, isolated instances of discriminatory behaviors. In other words, racism is perpetuated by a few "bad apples."	Taking action to resolve isolated incidents of racism would result in diverse, equitable STEM institutions.	Persistent racial disparities have not changed much over time (Taffe and Gilpin, 2021).

Lastly, representation applies not only to whose work is being communicated about, but also to communicators themselves. SciComm trainers have a role to play in diversifying the pool of science communicators. Trainers can do this by prioritizing trainings for Black, Indigenous, and Latinx researchers and reducing barriers to participation, for example by finding ways to reduce or eliminate costs and scheduling trainings at times and places that are convenient to scientists of color. In addition to reducing logistical barriers to participation, trainers can break down psychological barriers by ensuring that the training is as inclusive as possible. The 500 Women Scientists Guide to Inclusive Science Meetings (Pendergrass et al., 2019) is a good starting place, and the Inclusive SciComm community has assembled additional resources on this topic (see "Conference and Meeting Planning") (Inclusive SciComm, 2020). Furthermore, trainers must demand that the field of SciComm training itself become more diverse, which will facilitate broader representation in trainees and in the scientists whose stories are told. Again, this can be done by intentionally reducing barriers to entry into the field.

The next strategy includes shifting to a more *Culturally Responsive SciComm Practice*. Culture is how we make sense of the world and greatly influences how we see it, how we try to understand it, and how we communicate with each other. Cultural responsiveness involves considering how to incorporate the many aspects that an audience brings with them to a learning experience and further demonstrating how diversity is valued. This includes placing value on cultural competency, the ability to understand, honor, appreciate, and respect the values, beliefs, attitudes, and behaviors of those from cultures different from our own (Roberts, 1990; DeAngelis, 2015). Further, the cultural contexts in which someone learns affects how they interpret the content shared with them (Guild, 1994; Futterman, 2015; Lynch, 2016; Pusey, 2018). As such, SciComm experiences should prioritize diverse representation (as mentioned above), and also different ways of knowing, experiences, and understanding that will allow audiences to find and value their own voices, histories, and cultures. In order to do this, SciCommers must know their audiences - this is necessary scaffolding for effective communication with any group. Knowing your audience also involves understanding where their interests lie and what matters most to them, by asking. Though the deficit model still persists in many science communication spheres, it is now time for us to transition toward something that is more engaging: two-way communication, a dialog where SciCommers and audiences can both be heard (Trench, 2008; Dudo et al., 2021). To be successful at cultural responsiveness, SciCommers need to evaluate the cultural contexts through which we present our content, and incorporate methods of engagement that can accommodate various belief systems and cultural perspectives.

The prior themes feed into the final one of *Inclusivity*, which can be achieved by creating a climate for diversity. We need to work collectively to improve the current climate by reducing attitudes of hostility and competition that are pervasive among STEM fields, including SciComm. We must also decrease the sense of exclusion that is felt by marginalized communities. Creating authentic inclusion will lead to a more positive climate and contribute to increased sense of belonging and visibility. As Verna Meyers said, "Diversity is being invited to the party; inclusion is being asked to dance," (per Cho, 2016). This will also include actions such as (but not limited to) authentic collaboration and co-creation with marginalized communities that includes a seat at the table with equal weight as other members; actively challenging and dismantling the oppressive systems in place, particularly when you can speak from a position of power, privilege, or status; and always holding ourselves and others accountable for actively and continually progressing in this work. As articulated by Canfield and Menezes (2020), *inclusive* SciComm is characterized by three Key Traits. The first is *intentionality*, the intentional consideration of our audiences, how "science" is defined, and how marginalized identities are, and have been, represented and supported. Second is *reciprocity,* interactions between science communicators and audiences that address past and present inequities through equal partnerships marked by co-creation and recognition of the assets and varied forms of expertise communities bring with them. *Reflexivity* is the third key trait and describes the continuous, critical, and systematic reflection on the communicators' and audiences' personal identities, practices, and outcomes, coupled with adaptation as needed to redress inequitable interactions. We will further explore how these Key Traits can be incorporated in this work below.

Next Steps

Incorporating authentic interrogation, acknowledgment, and accountability, increasing representation, creating a culturally responsive practice, and furthering inclusion will require creating, testing, and applying new approaches and new frameworks in SciComm. Transcending WSC will also require making changes across levels of societal influence, ranging from individual, at the most proximal, to societal-cultural, at the broadest. Our team has begun building a framework based on applying the Key Traits of Inclusive SciComm (Canfield and Menezes, 2020) across levels of societal influence, that is intended to guide authentic, culturally competent, and inclusive SciComm. The goal is to use SciComm to supplant WSC in science and society with new co-created norms centering minoritized scholars, SciCommers, and audiences in STEM.

The framework crosses the three Key Traits (intentionality, reciprocity, and reflexivity) with six levels of influence (individual, interpersonal, community, organizational or institutional, societal-policy, and societal-cultural). At each intersection of a Key Trait and level of influence, we articulate questions that SciCommers can ask themselves and considerations to be aware of to help them assess the extent to which their practice aligns with the themes for actions (**Figure 1**). Creating the framework is an iterative process. In October of 2021, our team led a brainstorming and collaboration session with participants at the Inclusive SciComm symposium to study the problem of WSC in SciComm and STEM, consider the value of the framework as a possible solution, and iterate on how to improve it (Callwood et al., 2022). We anticipate continued co-creation with SciCommers in the future, to ensure that the framework is as useful as possible to those who aim to dismantle WSC through SciComm and SciComm training.

We welcome collaboration and feedback on this work in progress: we see this work as ongoing, iterative, interactive, and open-source. We also hope other collaborations are exploring avenues for mitigating WSC in SciComm. Just as SciCommers have shifted the culture of STEM already, we know SciComm can continue to lead on dismantling WSC in STEM.

We are grateful to all of our teachers from whom we are continuing to learn, and who inspire us in this ongoing work. We are particularly inspired by and learning from new resources and perspectives on inequality in STEM and what we can do about it (#BlackInSciComm, 2020; Canfield et al., 2020; Lee, 2020; McGee, 2020; Baxter, 2021; Easley, 2021). We hope that SciCommers will join us to work on the framework we are developing, and/or to develop additional liberating strategies that work to dismantle WSC in science and in society, while creating and maintaining a climate for diversity.

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

KC and MW conceived the original concept for and wrote the original draft of this manuscript. KC, MW, TT, and RH wrote, reviewed, and edited the manuscript. All authors contributed to the article and approved the submitted version.

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Defining a Flexible Notion of "Good" STEM Writing Across Contexts: Lessons Learned From a Cross-Institutional Conversation

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We respond to a surging interest in science communication training for graduate scientists by advocating for a focus on rhetorically informed approaches to STEM writing and its assessment. We argue that STEM communication initiatives would benefit by shifting from a strategic focus on products to a flexible understanding of writing as a practice worthy of attention and study. To do that, we use our experience across two universities and two distinct programmatic contexts to train STEM graduate students in writing and communication. We draw from cross-disciplinary conversations to identify four facets of "good" STEM writing: (1) connecting to the big picture; (2) explaining science; (3) adhering to genre conventions; and (4) choosing context-appropriate language. We then describe our ongoing conversations across contexts to develop and implement flexible rubrics that capture and foster conversations around "good" writing. In doing so, we argue for a notion of writing rubrics as boundary objects, capable of fostering cross-disciplinary, integrative conversations and collaborations that strengthen student writing, shift STEM students toward a rhetorically informed sense of "good" writing, and offer that kinds of assessment data that make for persuasive evidence of the power of writing-centric approaches for STEM administrators and funders.

Keywords: STEM, science communication, rhetoric graduate student training, collaborate

INTRODUCTION

Scientists and educators increasingly recognize the demand for improved STEM (science, technology, engineering, and math) training in communication, including writing, and its importance for facilitating wider dissemination of research results, improved policy outcomes, and richer engagement with public audiences (Fischhoff, 2013; Kuehne and Olden, 2015). This paper discusses two separate but complementary programs at Northwestern University and the University of Rhode Island that responded to that call. Each developed focused training programs and related tools, including the rubrics discussed here, to equip STEM graduate students to communicate their science to broad audiences. Central to the philosophy of each program is to situate STEM writing and its assessment as a social, contextual, iterative, and public practice.

This authorship team—faculty and staff collaborating across different institutional, disciplinary, and programmatic contexts—had to grapple with defining a flexible notion of "good" writing applicable across a variety of STEM disciplines, taught to STEM faculty, practiced by STEM students, and ultimately supported by STEM administrators and funding agencies. Because we were in communication throughout that process, we share our experiences in this collaborative piece to build on continued calls for the development of STEM writing and communication skills as part of the education and professionalization of STEM undergraduate and graduate students (Fuhrmann et al., 2011; Denecke et al., 2017). We use the terms writing and communication here to encompass all modes of building, sharing, and reinforcing knowledge. We use rhetoric, a term often politically loaded, in reference to the ancient tradition of communication with purpose for an audience within a specific set of circumstances. Rhetorical moves refer to the intentional decisions a writer or speaker makes in order to meet the needs of those circumstances most effectively.

Here we draw from interdisciplinary literatures in science, science communication, and writing studies. We define four facets of effective communication that we argue constitute a flexible and capacious definition of "good" STEM writing across a range of genres and audiences: (1) connecting to the big picture; (2) explaining science; (3) adhering to genre conventions; and (4) choosing context-appropriate language. We then describe our work to capture these facets of "good" STEM writing in the development of two rubrics that support different contextually situated training programs designed to support STEM writers. In doing so, we build from a flexible understanding of writing rubrics (Henningsen et al., 2010; Nolen et al., 2011), conceiving of writing rubrics that formalize the expectations and definitions of good STEM writing as boundary objects: "a rhetorical construct that can foster cooperation and communication among the diverse members of heterogeneous working groups" (Wilson and Herndl, 2007). Here, writing rubrics that articulate teaching and learning goals for STEM students are an opportunity to span communities and build bridges between diverse stakeholders interested and invested in science communication outcomes. We argue that the development and implementation of writing rubrics can facilitate conversations across disciplines about good STEM writing. This process can foster collective investment in and understanding of STEM writing practices, while offering a valuable opportunity to generate data on the impacts of programs in increasingly competitive funding environments in higher education.

We deploy rubrics as rhetorical boundary objects (Wilson and Herndl, 2007) to connect knowledge-making in science with good STEM writing practice and pedagogy to develop locally situated thinking at our two institutions. This approach helped us leverage outside perspectives and empirical evidence to create resilient and flexible resources and instruments to meet local needs as part of a recursive assessment loop (Rutz and Lauer-Glebov, 2005). Our focus on writing as a practice not a product and on rubrics as a shared articulation of learning goals and essential rhetorical moves allowed us to accommodate the broader shift from a deficit model to a contextual model (Gross, 1994; Perrault, n.d). It also allowed us to emphasize rhetoric as a critical component in science communication (Gross, 1994; Druschke and McGreavy, 2016) and the importance of a user-centered paradigm for designing effective communication artifacts (Rothwell and Cloud, 2017).

We began working together several years ago as cross-institutional collaborators looking for tools to facilitate shared approaches to the training and assessment of STEM writing. While our processes and products have converged and diverged through the years, the shared development of these rubrics enabled nuanced conversations about what defines good STEM writing across our many disciplines, encouraging us to clarify to ourselves and each other which rhetorical approaches and goals were specific to our individual program aims and which were broader, more universal element of good practice. We found that developing these tools was a profoundly helpful opportunity to open cross-disciplinary dialogue on the key ingredients of "good" writing and how those ingredients might be taught, explicated, and assessed. This is especially important in light of recent research highlighting the lack of consensus on what constitutes good science communication and the ability of current training programs to improve students' capacity in these areas (Rubega et al., 2021).

Of course, once a rubric is created, there are next steps to test its reliability and validity in the field, particularly as an instrument to assess skill-gain among students. We acknowledge this process is not yet complete for our tools. However, we are not advocating here for the broad adoption of our specific instruments. Rather, we want to shed light on their development, including discussions about the diverse but often siloed literatures that informed them, and their deployment for assessment as important conceptual steps in developing a shared understanding across faculty and students of good STEM writing, its best practices, and eventually its meaningful assessment. In particular, we hope to contribute to the conversation facilitating a shift toward science communication as a messy, iterative practice, bringing the insights of writing studies and rhetorical studies to bear on broad science communication initiatives and training in ways that can inform guiding principles implemented at the local level.

OUR PROGRAMMATIC CONTEXTS

Northwestern University's program, *Skills and Careers in Science Writing*, is a partnership between two academic units: Science in Society, a community-engaged research center, and Medill, a world-renowned journalism school. This semester-long graduate-level course is for STEM doctoral students across all disciplines including microbiology, materials science, environmental engineering and developmental psychology. The course is led by journalism faculty and practicing writing professionals to cover best practices in writing, public science communication, and science reporting including principles of structure, narrative, and voice. Students produce an original magazine-style article about their own research. Critically discussing lay audience-friendly science stories also enables students to recognize and grapple with the immense shift of moving from traditional academic writing to an accessible style (Crossley et al., 2014). The course also focuses on science writing career pathways, and provides exposure to science communication and journalism professionals given the likelihood many STEM PhDs will pursue non-academic careers (Cyranoski et al., 2011; Powell, 2012).

University of Rhode Island's (URI) program, SciWrite, focuses on equipping science graduate students to move between academic and public-facing writing in two ways: (1) layering rhetorical training into graduate student curricula and (2) training faculty to support writing pedagogy in classrooms and laboratories. SciWrite is a cross-disciplinary training program funded by the National Science Foundation for STEM graduate students and faculty at URI and was collaboratively developed by faculty from Writing and Rhetoric, Nutrition and Food Sciences, and Natural Resources Science. The 2-year program includes internships and workshops alongside a four-course sequence where students gain a rhetorical foundation for writing through a series of academic and public writing projects. Full programmatic and assessment details are offered elsewhere (Druschke et al., 2018, n.d; Harrington et al., 2021).

INTERDISCIPLINARY AND INTER-INSTITUTIONAL COLLABORATION

Our programs initially developed independently. But our joint discussions about assessment helped us realize that rubrics were productive mechanisms for helping us push back against the widespread notion of writing (and communication more broadly) as strategic endpoint and for reframing the idea of writing as an intentional, situated, and messy practice. Particularly when integrated into multi-modal assessment portfolios, we argue that rubrics can serve three separate but interrelated purposes: (1) assessing STEM writing with flexible and locally-informed instruments; (2) empowering STEM faculty to engage more heartily with a rhetorical approach to writing training; and (3) communicating with students about important aspects of rhetorically savvy writing. Rather than treating rubrics—and the good writing they are meant to assess—as static, stringent structures, both programs deployed rubrics as unique opportunities for dialogue and collaboration with diverse faculty tasked with teaching (and grading) trainee writing.

During rubric development, we considered interdisciplinary sources such as impact measures in science communication and engagement (Coppola, 1999; Bucchi, 2013; Fischhoff, 2013; Denecke et al., 2017; of Sciences, Engineering, and Medicine et al., 2017), specialist assessment work being done in engineering undergraduate writing (Boettger, 2010), researcher oral presentations (Dunbar et al., 2006), and public science communication rubrics (Mercer-Mapstone and Kuchel, 2017; Murdock, n.d) as well as best practices in writing assessment (Rutz and Lauer-Glebov, 2005; Huot and O'Neill, 2009; Adler-Kassner and O'Neill, 2010). This diverse list of sources points to the disjointed and siloed nature of discussions taking place in science writing, science communication, rhetoric, and teaching and learning practices more broadly. Drawing from these various disciplines allowed us to map their commonalities and begin to stitch together a shared framework with four distinct, but overlapping features.

Connecting to the Big Picture

Good writers and communicators position themselves in the wider discourse; draw from existing understandings; make a compelling, structured articulation of their goals, purpose or main point; and vary their deployment of these elements depending on purpose and intended audience. This facet builds from perspectives present in writing studies since at least John Swales' Create a Research Space (CARS) model (Swales, 1981, 1984, 1990) with its emphasis on establishing a territory. This contextualizing is picked up in popular scicomm trainings like the Compass message box (Compass Science Communication Inc., 2017), and the SciWrite@URI program relied on it extensively in their training program (Druschke et al., 2018, n.d; Harrington et al., 2021).

Explaining Science

Good writers and communicators understand the highly academic ways scientists conventionally describe their research to peers, and identify how these are likely to be difficult or unfamiliar for novice readers. This facet includes understanding how the organization and technical detail provided in an explanation are critical components for effective science communication. Understanding these hurdles requires that communicators grapple with the specific challenges for communicating to novices (Wolfe and Mienko, 2007; Rottman et al., 2012) and the subject-specific vocabulary, or jargon, which impedes communication between science to non-scientists (Bullock et al., 2019). Bullock et al. found the presence of jargon impairs people's ability to process scientific information, and suggests that the use of jargon undermines efforts to inform and persuade the public (Bullock et al., 2019). At the same time, jargon serves an important function within specific discourse communities discourse communities (Porter, 1986), peer groups accustomed to specific ways of exchanging information. It is essential that good STEM writers recognize jargon as a community-specific vocabulary and make conscious choices about when and how to include it to explain complex scientific concepts to a variety of audiences with accuracy and clarity.

Adhering to Genre Conventions

Good writers and communicators understand and can appropriately navigate genre-specific expectations, which vary community to community and piece to piece. Both programs emphasize the importance of genre, but teach different genres to students, and the two program's rubrics reflect these genre-specific differences.

Choosing Context-Appropriate Language

Good writers and communicators have a solid grasp of the rhetorical moves at their disposal, such as style, tone, and register, as well as grammar, semantic and linguistic complexity, and scientific conventions such as hedging and citations. Importantly, this facet includes but moves well beyond word choice. This facet is most directly aligned with other quantifications of contextually good writing (Crossley et al., 2014) and broader discourse around stylistics and language (Pinker, 2015; Zinsser, 2016).

IMPLEMENTING RUBRICS AS CONTEXTUALLY SITUATED TOOLS

While our collective conversations coalesced around these shared facets of good writing, the rubrics we developed to articulate them were structured to our unique programmatic goals and needs. For example, the "genre conventions" our programs were designed to address were vastly different. So, while our shared goal was to articulate and teach these conventions, the ways in which our rubrics could reflect that would differ substantially.

Northwestern's program focuses specifically on lay-friendly magazine writing and science storytelling approaches (Leslie et al., 2013; Dahlstrom, 2014), and therefore this rubric deliberately defines some narrative conventions (Zinsser, 2016; Hart, n.d) which connect with research on recall and processing of narrative elements (Speer et al., 2009; Zak, 2015), as well as metaphors and analogies (Wolff and Gentner, 2011).

For example, the Science in Society rubric defined "Relevance (shows how this work is connected to real world experience in meaningful ways and why it matters)" as "Clearly defines the context and/or application of this work"; Reader perspective and real world connections meaningfully articulate the purpose/promise of this work. "Order and Structure (builds scaffolded scientific explanations)" was articulated as, "Effectively connect to reader's context and prior knowledge; Well structured and scaffolded explanations building bridges from existing understanding; Clearly walks through steps of processes and explains phenomena in a logical and coherent order; Consistently and clearly builds bridges from existing knowledge." (See **Supplementary Material** for more information).

URI's SciWrite, on the other hand, reinforces the idea of STEM writing as a rhetorical act in and among specific discourse communities (Penrose and Katz, 2010; Kuhn, 2012), and encompasses a range of formats including visual representation. Perhaps uniquely, this rubric is intended to span both academic- and public-facing artifacts in order to reinforce the public as a valuable partner in larger conversations about science (Collins and Evans, 2002; Rowe and Frewer, 2005) and citizen science (Druschke and Seltzer, 2012; Shirk et al., 2012; Bonney et al., 2016). This rubric is therefore made up of 12 categories divided into subsections, some of which apply to all artifacts, and some of which are specific to certain modalities and formats. In both cases, the role of genre conventions is central, but how this is articulated is in conversation with broader programmatic goals and models.

In the SciWrite rubric, the category "Is the text appropriate for the target audience?" is articulated as, "The text consistently incorporates appropriate definitions and explanations of all key terms and concepts that makes the research/text fully comprehensible, accessible, and engaging to the primary intended audience." For the category, "Is there an appropriate depth of content given genre and subject matter?" "The text includes a sufficient depth of content about the subject matter for the genre and primary intended audience." And the category, "Does the text demonstrate its significance in a wider context, and build on the existing knowledge base by using literary elements appropriate to the genre (e.g., analogies, metaphors, similes, visual examples, case studies, etc.) to support deeper levels of understanding of complex ideas and phenomena?" was defined as, "The text explicitly demonstrates its significance in a wider context, and consistently builds on the existing knowledge base by using highly effective literary elements appropriate to the genre to support deeper levels of understanding of complex ideas and phenomena." (See **Supplementary Material** for more information).

As we mentioned above, this paper is not intended to report a validated instrument, but to call out how our processes and ultimate products converge and diverge in important ways. This transparency is intended to contribute to wider conversations about how science communication and writing programs should be developed, delivered and evaluated. We are certainly not done, and hope that sharing our process of developing rubrics as boundary objects within our own programs—and with each other across programs—helps others see how to incorporate rhetoric into STEM communication training conversations going forward.

MOVING FORWARD TOWARD "GOOD" STEM WRITING

As we well know, assessment is essential to STEM writing training and teaching. Well-structured, meaningful assessment also offers datasets and analyses that can be used to argue for funding and build a sustainable enterprise for this vital professional training. Such metrics are increasingly necessary to support and advocate for sustainable, rhetorically-informed and writing-focused practice within higher education (Rutz and Lauer-Glebov, 2005; Adler-Kassner and O'Neill, 2010).

In particular, embedded, rhetorically grounded frameworks provide a unique opportunity to create deeper interdisciplinary conversations about the values and definitions of good writing—and they make disciplinary and genre conventions and practices visible. Including colleagues from a range of fields in this process is one step toward making those nebulous, frustrating guidelines for science writing more explicit.

We believe that conversations about the practice and pedagogy of good STEM writing vitally contribute to conversations about science and scientist training. A meta-analysis of over 700,000 biomedical journal abstracts over the past 150 years clearly demonstrates the readability of scientific abstracts is decreasing over time, and Rubega et al. (2021)

recently demonstrated that current science communication training programs provide little evidence of improved practice (Pontus et al., 2017). Even further, the need for scientists to communicate across genres and audiences seems particularly apparent in a cultural moment of political division and policy-making challenges where cynicism and science-skepticism (Charney, 2003) inform highly-motivated interpretations of science and research (Washburn and Skitka, 2018). The need for cross-disciplinary conversations about good and great science writing, dissemination, and public engagement—and how to convey and assess these goals—has never been more obvious or more necessary.

AUTHOR CONTRIBUTIONS

SG, JM-A, CD, and IL organized the data and results. SG and JM-A wrote the first draft of the manuscript and revised the manuscript after receiving feedback from the rest of the authors. All authors contributed to the conception and design of the study, manuscript revision, read, and approved the submitted version.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fcomm.2022.767557/full#supplementary-material

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