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Emerging Technologies for Invasive Insects: The Role of Engagement

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Abstract

Emerging technologies have the potential to offer new applications for managing invasive insects. While scientific and technological advancements are vital to realizing this potential, the successful development and use of these applications will also largely depend on community and stakeholder engagement. To contribute to a relevant and rigorous envisioning of engagement for emerging technologies for invasive insects (ETII), we begin by reviewing key insights on engagement from three scholarly fields: invasive species management, responsible research and innovation, and ecological risk assessment. Across these fields we glean best practices for engagement for ETII: 1) pursue engagement across decision phases and sectors; 2) select context-appropriate participants and methods; and 3) recognize and navigate engagement-related tensions. We illustrate these best practices by describing an ongoing project that uses engagement to inform risk assessment and broader decision making on biotechnologies being developed to address the Spotted-wing Drosophila (*Drosophila suzukii*) invasive fruit fly. We describe completed and planned engagement activities designed to identify and prioritize potential adverse effects, benefits, management actions, and research actions of the proposed genetically engineered sterile male, gene drive, and RNAi biotechnologies. In the face of broadening calls for engagement on emerging technologies, this article provides theoretical and empirical insights that can guide future engagement for ETII.

Keywords: responsible research and innovation, ecological risk assessment, invasive species management, community and stakeholder engagement, *Drosophila suzukii*

Emerging technologies provide a host of new potential tools for managing invasive insects and other invasive species. As made clear by the case studies discussed in this special issue and broader interest by the invasive species community (e.g., Martinez et al. 2018), emerging technologies hold the possibility of creating new and better approaches for addressing some of the most problematic invasive insects. The potential for novel management tools increases optimism that existing management challenges and failures may yet be overcome—that we are not, for example, necessarily stuck with a choice between increasing damage from a growing number of invasive insects or dramatic increases in pesticide use. Yet the history of promissory rhetoric surrounding novel technologies (Borup et al. 2006, Selin 2008, Lucivero et al. 2011) should give pause and encourage a thoughtful reflection on the factors that need to align to realize such beneficial outcomes and avoid harmful ones.

While the literature exploring governance and societal issues surrounding emerging technologies for pests and invasive species continues to grow (Delborne et al. 2018c; Kofler et al. 2018, Medina 2018), there are three challenges that are particularly germane to our discussion of emerging technologies for invasive insects (ETII): 1) the complexity of emerging technologies, which creates uncertainty about their potential adverse effects and benefits; 2) the values-laden nature of ETII-related related decision making; and 3) the integration of stakeholders' and communities' perspectives and preferences in governance and management decisions.

First, complexity and uncertainty are unavoidable in the scientific studies and decision making surrounding ETII. Many of the potential ETII applications insert novel traits into invasive insects and, as a result, understandings of how such changes will reverberate through ecosystems are faced with significant uncertainty (Simon et al. 2018). Determining what types of studies and what

level of certainty is needed to adequately inform risk assessments and broader decision making will be essential topics for emerging technologies—and answers to these questions will be influenced by such factors as one's risk tolerance, disciplinary training, values, and worldview (Thompson 2003, Myhr 2010).

Second, decisions concerning whether, where, and how to use ETII are unavoidably values-laden (Thompson 2018). The importance of recognizing and navigating values is realized in invasive species management (Estévez et al. 2015, Shackleton et al. 2019b) and emerging technology governance scholarship (Sarewitz 2011, Rudenko et al. 2018). Values-laden decisions related to ETII include not only which invasive insects are most problematic and worth addressing, but also the severity of nontarget impacts deemed acceptable; under what conditions ETII should be used; who should be involved in decision making; how costs should be distributed; and who is responsible for any emergent consequences. Scientific evidence informs such decisions, but decision making surrounding ETII always reflects value-based choices and must find productive ways to navigate the potential lack of consensus arising from diverse worldviews and associated values and preferences (Courtier-Orgogozo et al. 2017, Burall 2018).

Third, because of the novelty, power, uncertainty, and values-laden nature of many of these ETII, stakeholders and relevant communities need to play important roles in decision making. Communities represent those who live near a potential ETII application and stakeholders refer to people who have a personal or professional interest in the ETII, including those from industry, nongovernmental organizations (NGOs), and agricultural groups (National Academies of Sciences, Engineering, and Medicine 2016). Stakeholders and communities are needed in decision making because: 1) they have knowledge on the social and ecological contexts surrounding ETII; 2) they are essential for ensuring that decision making is both transparent and based on robust consent; and 3) they are essential for achieving mutual learning and trust (Dietz and Stern 2008, National Academies of Sciences, Engineering, and Medicine 2016). For example, potential applications seen as forced upon people or deployed without adequate contributions from relevant groups can cause significant harm and societal backlash (Resnik 2018).

One important potential means for addressing these challenges is engagement. Engagement, however, can have many competing and sometimes contradictory meanings, so exactly *how* it is defined and enacted is essential to its potential success (Reed et al. 2018). Engagement can mean everything from persuasion campaigns seeking to justify an already-made decision, to performing a brief consultation to inform part of a decision, to fostering two-way dialog with stakeholders to jointly frame and inform decisions (Rowe and Frewer 2005). Given the contextual nature of decisions about what type of engagement is appropriate in a particular instance, establishing clarity concerning the goals of and methods for engagement will be essential for the ETII field. As a starting definition, we follow the National Academies of Science, Engineering, and Medicine (NASEM) gene drive report's definition of engagement as 'seeking and facilitating the sharing and exchange of knowledge, perspectives, and preferences between or among groups who often have differences in expertise, power, and values' (NASEM 2016, p. 131). This type of engagement that incorporates a diversity of 'knowledge, perspectives, and preferences' will be essential for ETII to avoid problematic pitfalls and to realize its full potential (Stirling et al. 2018).

We believe that engagement can help foster responsible decision making for emerging technologies to address invasive insects, especially if it is well designed and draws upon the insights from the variety of existing literatures on engagement. We begin by reviewing three areas of scholarship that inform engagement best practices for emerging technologies for invasive insects: invasive species management, responsible research and innovation, and ecological risk assessment. Drawing upon this literature, we develop three best practices for engagement for ETII: 1) pursue engagement across decision phases and sectors; 2) select context-appropriate participants and methods; and 3) recognize and navigate engagement-related tensions. Alongside these three best practices we explore the case study of an engagement project for ETII that involves examining three emerging biotechnologies (genetically engineered sterile males, gene drive, and RNAi) to address the Spotted-wing Drosophila, *Drosophila suzukii* (Matsumura), invasive insect pest. To help inform future risk assessments and broader decision making for these emerging biotechnologies, we designed a host of engagement activities to identify and prioritize their potential adverse effects, benefits, management actions, and research actions. Together, the best practices and case study provide key considerations for the design of engagement activities for ETII.

Engagement Scholarship to Inform ETII

Engagement and Invasive Species Management

Invasive species management scholarship has long addressed the importance of engaging with communities and stakeholders, but much of the effort has consisted of trying to understand the behavior that facilitates the spread of invasive species and how it can be prevented (Clout and Williams 2009). The importance of engagement is broadening, however, as the significance of the social dimensions of invasive species management becomes more clear (Schüttler et al. 2011, Shackleton et al. 2019b). For example, societal values are unavoidable in deciding whether the change caused by a non-native species is considered harmful, as opposed to inconsequential (Sagoff 2009, Hattingh 2010). They are also present in a host of other decisions influencing invasive species management, such as the desired state of nature, when management is worthwhile, desired management priorities, and what nontarget consequences from management actions are acceptable (Larson et al. 2011, Buckley and Han 2014, Estévez et al. 2015, Kokotovich and Andow 2017, Kueffer and Kull 2017). In addition, there is a greater recognition of the problems that can emerge in invasive species management when adequate engagement does not take place (Estévez et al. 2015, Novoa et al. 2016, Crowley et al. 2019).

To navigate these societal values there is a broadening array of literature that explores the importance of engagement across many aspects of invasive species management, including: understanding stakeholder and community perceptions and priorities concerning invasive species and invasive species management actions (Kleitou et al. 2019, Wald et al. 2019); understanding and navigating conflict (Crowley et al. 2019); conducting citizen science (Grason et al. 2018, Mannino and Balistreri 2018); and co-designing management actions (Novoa et al. 2016). This literature makes a strong argument for incorporating community and stakeholder knowledge, values, and worldviews into invasive species management. Given that ETII will be part of invasive species management, it is important to acknowledge and build upon these existing insights on engagement in decision making concerning ETII.

Engagement and Responsible Research and Innovation

While invasive species management is one area of scholarship that offers insights on engagement for ETII, another area of scholarship that explores engagement in the context of emerging technologies is Responsible Research and Innovation (RRI; Owen et al. 2012, Stilgoe et al. 2013, Macnaghten et al. 2014). RRI is useful in this context because it provides a conceptual lens for considering what engagement can mean and how to approach it. Central to RRI is that governance, in addition to analyzing the potential adverse and beneficial impacts of a novel innovation, should also question the very purpose of the application and the processes used to make decisions. Stilgoe et al. (2013) articulate three categories of governance questions: product (e.g., What are the risks and benefits? How are they distributed? What don't we know?); process (e.g., Who is in control? Who is taking part? How are risks and benefits defined and measured?); and purpose (e.g., Why is it being done? What are the alternatives? Are the motivations transparent and in the public interest?).

To address these three lines of questioning, the RRI literature proposes four dimensions of responsible research and innovation: anticipation, reflexivity, inclusion, and responsiveness (Stilgoe et al. 2013, Macnaghten 2016). Each of these dimensions provides guidance on how to design engagement to address product, process, and purpose questions. *Anticipation* calls attention to the need for engagement to take place in an upstream way—early enough for the results to impact research and development and the ultimate form a technology takes. It highlights the limitations of engagement that takes place once a product is fully developed and ready to be deployed, as the vast amount of resources and time already spent will make additional changes more difficult than if these engagement-produced insights were available earlier. Instead, engagement that is anticipatory in nature can identify and reflect on the potential undesirable and desirable paths of a technology and can envision ways of achieving those that are desirable. For example, they can be used to envision the types of potential technological applications that are best situated to address key problems stakeholders are facing. The importance of anticipation has been regularly recognized in the technology governance literature, more broadly (Wilsdon and Willis 2004, Karinen and Guston 2010).

Reflexivity highlights that engagement must incorporate ways of 'holding a mirror to one's own activities, commitments, and assumptions', (Stilgoe et al. 2013) and recognizes that how we frame a problem, the knowledge we see as relevant for decision making, and how we define a desirable solution are not universally held. The assumptions underlying these decisions are influenced by worldview, disciplinary training, and lived experience. Engagement that fosters reflexivity helps both recognize key assumptions and explore their implications, to ultimately result in better informed and improved decision making. Such reflexivity can be achieved using a variety of methods (Fisher et al. 2006, Schuurbiers 2011). The importance of *inclusion* emerges naturally from the discussion of reflexivity. Who is involved and how they are involved are essential components of engagement, as they are central to what perspectives and insights will be raised. An easy way to ensure that certain perspectives or disciplines do not enter into decision making is to exclude them from engagement processes. As a result, questions of who to include and how are fraught with power dynamics and require careful scrutiny (Oudheusden 2014, Long and Blok 2017). Proper design of engagement exercises can help ensure engagement processes achieve their goals (Rowe and Frewer 2005). Finally, *responsiveness* is a call for both decision makers and those designing engagement exercises to find ways for decision making to become more responsive to engagement. Considerations that support responsiveness include designing engagement to occur at the right time with the right scope to contribute to a particular decision context, and helping decision makers realize the value of engagement.

In addition to preventing potentially harmful research and innovation, RRI can also help identify and advance particularly beneficial applications of a technology by fostering inclusive and reflexive discussions about potential technological futures. The growing field of RRI, and its attention to anticipation, reflexivity, inclusion, and responsiveness, is well suited to help inform the decision making surrounding the novel research and innovation required for ETII.

Engagement and Ecological Risk Assessment

Finally, to take a more detailed look at what engagement could look like in a specific arena of ETII decision making, we examine the role of engagement in ecological risk assessment. Ecological risk assessment is an analytical framework used to synthesize science to inform decision making (EPA 1998, Andow et al. 2008). In the context of ETII, ecological risk assessment will serve as a key process for analyzing the potential adverse effects that may result from a potential emerging biotechnology application (National Academies of Sciences, Engineering, and Medicine 2016). Ecological risk assessment is generally thought of as having four stages: problem formulation, exposure analysis, effects analysis, and risk characterization (EPA 1998). Problem formulation is the stage where the scope and scale of the assessment is determined, including identifying the potential stressor(s), valued ecological entities, potential adverse effects, and analysis plan. Exposure analysis examines whether and how the valued ecological entities will come into contact with the stressor(s), and effects analysis determines the potential for and type of effects that can be expected as a result of that exposure. Risk characterization summarizes risk assessment findings for the decision context.

While risk assessment is sometimes popularly understood as being an objective endeavor outside of values, risk experts from academia, government, and industry have all identified and grappled with the important role of value judgments within risk assessment (EPA 1998, Thompson 2003, Raybould 2007, National Research Council 2009, Nelson et al. 2009); factors such as one's worldview, lived experience, and disciplinary training influence the choices made during risk assessments (Jensen et al. 2003, Thompson 2003, Kokotovich 2014). For example, at the most basic level, it is impossible to explore all potential adverse effects and risk pathways from a novel technology, so some prioritization must be made concerning which to study and how thoroughly. Problem formulation, with its explicit focus on defining the scope and scale of the risk assessment is the most obvious location of value-judgments, which include:

- Protection goals—What components of an ecosystem are most important to protect?
- Defining harm—What changes to those valued ecosystem components constitute harm?
- Scope and scale—What temporal and spatial scale will be assessed?
- Navigating uncertainty—When is enough known to adequately characterize risks?

These decisions combine both empirical components (e.g., Where is a product likely to be deployed? How does it function? What is the ecological context?) and value judgments (e.g., What is valued in an ecosystem? What quantity and quality of evidence is convincing?).

Further within the analysis stage of the risk assessment process lies another set of less obvious values-based decisions. These can be understood as epistemic value-judgments, or decisions within science that people may disagree upon based on their disciplinary training or worldview (Elliott 2012). Examples of where these may come up in the analysis stage include:

- Study design—What lab, semifield, and field studies need to be conducted to adequately analyze a particular risk pathway?
- Species selection—Should local or surrogate species be used in studies?
- Extrapolation—What uncertainty factors are needed to compensate for a particular extrapolation?

People differ in their views of where these value judgments exist within risk assessment and how to navigate them, but the fact that they exist is rarely disputed. A prevalent view—one that we build upon here—is that the breadth of unavoidable value judgments within risk assessment necessitates some type of engagement with stakeholders, communities, and decision makers (Stern and Fineberg 1996, Nelson et al. 2007, Hayes et al. 2018, Stirling et al. 2018). A minority view is that value judgments are contained to problem formulation and regulatory mandates and contexts are all that is needed to decide upon them. Such a view does not see a role for engagement in risk assessment (e.g., Kuntz 2012).

While the need for engagement is largely agreed upon, there exist divergences concerning: 1) who exactly should be included; 2) what stages of risk assessment they should be involved with; and 3) what questions they should address within each stage they are involved with. Some argue for engagement that is limited in participation and scope—for example, a small group of risk managers or decision makers informing key judgments within the problem formulation process; or, also limited, bringing together a more expansive group of experts to ensure that many disciplinary perspectives are included in problem formulation (e.g., Roberts et al. 2017). Others conceive engagement more broadly, as relevant throughout the risk assessment process. Hartley and Kokotovich (2018) argue that engagement should involve the right representation and expertise at each stage of the risk assessment process. For example, while the analysis stage of risk assessment requires substantial expertise, there are usually expert stakeholders available who hold such expertise. These expert stakeholders, with their diverse worldviews and disciplinary training, can be engaged to help recognize and reflect on key judgments and assumptions within the analysis stage of risk assessment. Alternatively, the questions grappled with in the problem formulation stage are well suited for input from a broader set of stakeholders and communities (Hartley and Kokotovich 2018).

Incorporating engagement into risk assessment can therefore be seen as a way to bring together the right group of people to discuss the decisions inherent to the risk assessment process that depend upon value judgments. Benefits from this type of engagement in risk assessment include: 1) risk assessments are more likely to be relevant and trusted if the value judgments are contextually appropriate; 2) risk assessments are likely to be substantively improved if more assumptions are seen and scrutinized by a wider set of experts and stakeholders (Glicken 2000, Kellett et al. 2007). The centrality of risk assessment to decision making related to ETII requires careful consideration for how to design risk assessment and the role of engagement within it.

Engagement Best Practices for ETII

Included in these three areas of scholarship is a variety of guidance on how to design engagement, whether for invasive species management (Novoa et al. 2018, Shackleton et al. 2019a), responsible research and innovation (Hartley et al. 2016, Groves 2017), or ecological risk assessment (Nelson and Banker 2007, Dana et al. 2014). To help inform engagement for ETII, we synthesize insights from across these literatures and apply them to the contemporary context facing ETII to identify three best practices for engagement surrounding ETII. These best practices are: 1) pursue engagement across decision phases and sectors; 2) select context-appropriate participants and methods; and 3) recognize and navigate engagement-related tensions. To help animate these best practices we present them alongside a case study of an ongoing project involving engagement on emerging biotechnologies for the invasive insect pest *Drosophila suzukii* (Spotted-wing Drosophila, SWD). SWD is a particularly problematic agricultural pest, and a variety of emerging biotechnology applications have been proposed and are in development to help manage it. The ongoing project seeks to inform future risk assessments and the broader governance of these novel potential applications by conducting engagement using a variety of methods. After providing an introduction to SWD, we present the ETII engagement best practices and describe how they have influenced the SWD engagement project.

Introduction to SWD Engagement Project

SWD is an invasive pest of soft skinned fruit crops native to eastern Asia that has dramatically expanded its global range in the last decade (Asplen et al. 2015). SWD was initially detected on the west coast of the United States in 2008 and roughly simultaneously in Italy and Spain (Asplen et al. 2015). Following these initial detections, SWD subsequently expanded its range into the rest of the United States, Canada, Mexico, Europe, and South America. The genetic variability among SWD populations in the United States and Europe suggests that they are the result of multiple, likely recurring, invasion events (Adrion et al. 2014, Fraimout et al. 2017; Lavrinienko et al. 2017). SWD has a large host range, including both crop and noncrop hosts (Kenis et al. 2016, Elsensohn and Loeb 2018). The most significantly affected crop hosts are high value berries, including cherries, blueberries, blackberries, raspberries, and strawberries. Direct crop loss potential in the United States alone has been estimated at nearly $800 million annually (Bolda et al. 2010, NC State Extension 2012).

Fresh market and whole frozen fruit purchasers routinely reject fruit that has any signs of SWD infestation (Farnsworth et al. 2017), which has led to highly conservative preventative management practices. SWD management is highly reliant on pesticides (Diepenbrock et al. 2016) and this has led to a dramatic increase in pesticide use in susceptible crops (Diepenbrock et al. 2017). SWD populations are largest during late summer and fall, so crops harvested during these times of year are at high risk of infestation. Pesticide efficacy is negatively impacted by rainfall, and growers of high-risk crops in areas with frequent rainfall routinely experience SWD infestation despite increased pesticide use. In these scenarios, some growers have eliminated production of SWD susceptible crops.

Emerging Technologies for SWD Management

Given the problematic nature of SWD, there is an interest in utilizing emerging biotechnologies for SWD population suppression, replacement, or elimination. Recent efforts have focused on three particular applications: genetically engineered sterile males, gene drive, and RNAi yeast.

First, genetically engineered sterile males are being developed for potential use in sterile insect technique (SIT) programs. While the use of genetic engineering to sterilize insects is novel, SIT programs using

chemicals or radiation for insect sterilization have been employed to locally eradicate invasions of other internally feeding fly pests of fruit crops including the Mediterranean fruit fly (*Ceratitis capitata*), Oriental fruit fly (*Bactrocera dorsalis*), and Caribbean fruit fly (*Anastrepha suspensa*). Efforts to develop radiation-based methods for SIT for SWD are underway (Lanouette et al. 2017). Genetically engineered sterile strains of SWD have also been developed and are being evaluated in the laboratory (Scott et al. 2018). The most common mechanism to produce genetically sterile strains involves an antibiotic-mediated promoter which results in the death of female embryos (Thomas et al. 2000). Genetically engineered sterile strains intended for use in SIT are considered self-limiting, meaning that they are not designed to spread and persist in the environment, thus requiring multiple, recurring releases in response to population pressure, similar to conventional SIT programs.

Second, gene drive systems, which are intended to move a trait through a population using biased inheritance (NASEM 2016), have generated substantial interest for a number of insects including SWD (Buchman et al. 2018). In SWD, this preferential inheritance could be utilized to potentially push a trait that would cause local SWD populations to crash (lethal) or to make females unable to lay eggs in ripening fruit (nonlethal). Gene drive systems are being developed in SWD containing lethal (Buchman et al. 2018) and nonlethal (Li and Scott 2016) traits. Gene drive systems were initially envisioned to be self-sustaining—meaning they would continue to spread once released—but there is also significant interest in developing self-limiting gene drive mechanisms (Noble et al. 2019). The first U.S. survey of public attitudes about gene drives in agricultural pests identified limiting mechanisms as the most significant determinant of support (Jones et al. 2019).

Finally, using RNA interference (RNAi) expressed in SWD food resources to interfere with gene transcription is also being developed for applications in SWD management (Murphy et al. 2016, Taning et al. 2016). Flies would be exposed to RNAi through ingestion, with effects ranging from reduced life span, to reduced fitness or fecundity. In this management tactic, the flies themselves would not be genetically engineered, but the RNAi delivery system would be genetic engineered. The proposed RNAi delivery vehicle is engineered brewer's yeast, *Saccharomyces cerevisiae*. Yeast is a common component of insect diets and can be spread by them to other environments. Therefore, the genetically engineered component of an RNAi system would need to be species-specific and self-limiting (Lam and Howell 2015, Madden et al. 2017).

Engagement for Potential SWD Emerging Biotechnologies

These three proposed emerging biotechnologies for managing SWD are still under development, and research is still being conducted to understand the potential beneficial and detrimental effects from their possible use. Currently, no decisions have been made about whether or how to use them. The host of risk assessment and governance-related decisions soon to be facing these technologies makes the current moment well situated for engagement. As part of a larger USDA project studying SWD and its management, we are designing and conducting an engagement project to inform the future risk assessments and governance decisions of these proposed emerging biotechnologies. Focus groups and interviews were conducted to identify the most important potential adverse effects, potential benefits, potential management actions, and potential research actions for each proposed biotechnology, and a survey is being conducted to prioritize these items. We further describe this engagement alongside our presentation of best practices for engagement for ETII.

Engagement Best Practice 1: Pursue Engagement Across Decision Phases and Sectors

Each potential ETII application will involve many types of decisions across different contexts, and there is a role for well-designed engagement to play in all of them. The first best practice is to pursue engagement across decision phases and sectors. Here, we identify five decision phases (problem framing; research and development; risk assessment; regulatory review; and deployment, management, and monitoring) and four sectors (government; industry; NGOs; and academia) that engagement can be pursued within. Engagement will necessarily look different in each decision phase and sector. In examining the differences across these contexts, we elucidate some of the opportunities and challenges that exist for engagement for ETII.

Engagement Across Decision Phases

While regulatory decisions concerning whether or not to allow the release of a technology often receive the most attention, there are a host of different decisions that take place before and after regulatory decisions that also influence whether and how a technology is developed and deployed. Envisioning and designing engagement for these different decision phases, or decision contexts, can help ensure engagement for ETII fulfills its potential and stays relevant to decision making (Burgess et al. 2018, Delborne et al. 2018a). Five potential decision phases for ETII with corresponding example questions to inform engagement are identified in Table 1.

First, engagement on problem framing is important for ensuring the invasive insect issue under consideration is well understood from a variety of perspectives. In addition to arriving at a robust understanding of the ecological and social context of the invasive insect, the strengths and weaknesses of existing management options as well as potential emerging technology and nonemerging technology management actions should all be explored (Nelson et al. 2009). Second, once the potential need for an ETII has been established, further engagement can take place to inform research and development on that technology. Engagement participants can help identify desirable and undesirable attributes of the potential application to inform product development in an upstream manner (e.g., Buchthal et al. 2019). This engagement can also address what attributes need to be realized and potential adverse effects avoided for the technology to be better than alternative management options.

Third, once a potential ETII application has been developed to the point where safety testing can begin, more focused engagement can take place to inform the risk assessment process (see *Engagement and Ecological Risk Assessment*). This can occur in conjunction with a regulatory body that is undertaking a risk assessment on the ETII application, or it can be undertaken by those in academia or other sectors who wish to help advance risk assessment knowledge on the particular application. This engagement will look different for the problem formulation stage and for the analysis stage of risk assessment (see *Engagement and Ecological Risk Assessment*). Fourth, engagement can also be utilized once an ETII application is fully developed and submitted to a regulatory agency for review. This engagement can help ensure that the regulatory process for an ETII application is transparent and trusted by encouraging a variety of relevant stakeholders and communities to weigh in on what should be considered in the review and how the review should be completed (Kuzma 2018). It can also grapple with and inform where and how testing should be completed (Adelman et al. 2017). Finally, the deployment, management, and monitoring of an ETII application that has achieved regulatory approval can also benefit from engagement. In particular, engaging with communities and stakeholders can help

Table 1. Decision phases and example questions to inform ETII engagement

Decision phase	Example questions to inform engagement
Problem framing	• What are the social and ecological components of the invasive insect issue? • What are the strengths and weaknesses of current management options? • What are possible novel non-emerging technology management options? • What are possible novel emerging technology management options? • Who/what is likely to benefit and be harmed by these different options?
Research and development	• What are the desirable and undesirable attributes of the potential ETII application? • What potential beneficial attributes need to be realized and potential adverse effects avoided for the ETII application to be better than alternative management options?
Risk assessment	• Problem formulation stage: What are the ETII risk assessment's protection goals, most important potential adverse effects, and scope and scale? • Analysis stage: What assumptions and design choices should be made in scientific studies and the characterization of risk?
Regulatory review	• What questions should inform the regulatory review for the ETII? • What studies are needed to answer these questions? • What standards of evidence should apply? • Where, how, and by whom should testing be completed? • What process should be used for arriving at a decision?
Deployment, management and monitoring	• Where and under what conditions should the ETII be used (or not used)? • What monitoring and management plans should accompany the use of the ETII and who is responsible for them?

Table 2. Potential ETII engagement goals by sector

Sector	Potential ETII engagement goals
Government	• Fund ETII research that fulfills societal need and pursues the public good • Recognize relevant social, environmental and technical issues surrounding ETII • Ensure that ETII risk assessments and regulatory decisions are rigorous and informed by societal values • Ensure ETII regulatory decisions do not cause undue harm
Industry	• Identify key problems surrounding invasive insects well suited for ETII investment • Identify desired ETII product attributes • Avoid developing a ETII product that causes significant harm and backlash • Prevent sunk costs from developing undesirable ETII product
NGOs (those not aligned with industry goals)	• Foster reflections on problem framing and potential management actions including those using ETII and those not using ETII • Ensure that values, worldviews, and disciplines informing ETII decisions are determined by reflexive, inclusive deliberation by all relevant stakeholders • Ensure marginalized perspectives are included in decision making • Determine ways to stop harmful technology and support beneficial technology
Academia	*All potential engagement goals listed above*

ensure an appropriate deployment of the technology, including where and how the application should be used and how management decisions should be revisited with novel monitoring data (Plummer et al. 2013, Baltzegar et al. 2018, Bruce and Bruce 2019).

Engagement Across Sectors

Another noteworthy aspect of the ETII engagement context is the different goals that exist across sectors involved with ETII (Table 2). Organizations situated in different sectors are likely to seek varying outcomes from engagement due to their differing legal mandates, missions, and values. For example, organizations in industry doing product development are likely to pursue different goals for engagement than governmental bodies responsible for regulation. It is important to consider this sector-based context both when designing engagement and when analyzing or critiquing engagement activities. While engagement organizers may often seek to address the goals across multiple sectors and while organizations or individuals themselves may not fit neatly into just one sector, it is important to grapple with how these differing goals impact engagement.

First, the government sector may be interested in engagement concerning ETII to help identify research priorities, inform risk assessments, and recognize relevant social, environmental, and technical issues (EPA 1998, Invasive Species Advisory Committee 2017). What form government sector engagement activities take will also be influenced by existing legal mandates and leadership priorities (Dietz and Stern 2008). For industry, there are a variety of engagement goals that may align with their priorities. While using stakeholder engagement to help identify investment opportunities, select product attributes, and market products is not new, there is also a growing interest in broadening the considerations influencing industry through, for example, incorporating insights from RRI (Blok et al. 2015). Engagement in industry is not without its challenges.

A variety of scholarship is helping to understand and grapple with such challenges, including how the speed of product development conflicts with the time needed for engagement, the disincentive for transparency given intellectual property issues, and concern about the loss of investment by opening decisions to engagement (Blok et al. 2015, Noorman et al. 2017, Bruce and Bruce 2019).

NGOs may hold goals such as reflecting on what constitutes the public good concerning ETII, how to protect the environment from harm related to ETII, how to include indigenous and marginalized peoples in decision making, and how to pursue responsible innovation on ETII (Helliwell et al. 2017, Keystone Policy Center 2019). While there are many NGOs, like trade associations, developed to pursue the interests of industry, for this conversation NGOs refer to groups pursuing social, environmental, and cultural well-being. Finally, within academia lies the greatest flexibility and diversity concerning the objectives for engagement. Given the makeup of the contemporary research university, there may be parts of an academic institution that share ETII engagement goals with all other sectors. For example, those in molecular biology and business fields may hold similar goals to industry, those in environmental science and public policy may hold goals similar to government, and those in the social sciences and humanities may hold goals similar to NGOs. The reality is much more complex, however, since these categories are just broad characterizations and since academics' priorities are shaped my more than just their discipline. As a result, one could certainly find molecular biologists who share the engagement goals listed for NGOs and those in the humanities working towards industry engagement goals.

As a result of the differences across sectors, there are tensions between their engagement goals (Noorman et al. 2017). One should be aware of which goals are motivating an engagement process and their limitations. For example, the goal of fostering reflection on problem framing and the host of management actions that could be relevant for an invasive insect is a very different outcome than trying to select desired attributes of an ETII application. Both goals may be needed in different contexts and at different times, but they are fundamentally different. Furthermore, if all the engagement on an ETII aligns with the goals of a single sector, it may be a sign that a particular sector has become too dominant in the ETII decision space and a broader set of engagement goals are needed. Acknowledging these differences across sectors should not be seen as providing an excuse for certain sectors to sidestep their responsibility to ask challenging questions by assuming it is the role of another sector. Rather, it is to emphasize the importance of these differences and to help encourage critical reflection on the factors that impact engagement.

SWD Engagement Project

As researchers with this SWD engagement project, we faced the following context concerning decision phase and sector. First, the three potential emerging biotechnology applications that we focused on were all in the research and development phase. In addition, given our place within the academic sector, we wanted to conduct research that helped recognize and reflect upon value judgments informing decision making but that had relevance across sectors. We decided, therefore, to focus on informing the continuing research and development phase and the problem formulation stage of risk assessment. We decided to use engagement to identify and prioritize potential adverse effects, potential benefits, potential research actions, and potential management actions for each of the biotechnologies. Since informing the value judgments within the problem formulation step of risk assessment (such as selecting potential adverse effects to study) with well-designed engagement is essential to its success and robustness, this research would be useful to those in any sector conducting risk assessment (Elliott 2019). Also, learning which potential benefits from a biotechnology and which potential management and research actions accompanying a technology were most important to those involved with SWD would be insightful for broader decision making about these biotechnologies.

Engagement Best Practice 2: Select Context-Appropriate Participants and Methods

Context-Appropriate Participants

The novel and potentially powerful nature of ETII applications are likely to lead to notable interest in ETII decision making and engagement activities. As a result of this and the consequence of deciding who is included in engagement, the selection of participants for engagement is one of the most important design choices. Another best practice, then, is to select context-appropriate participants. The decision phase, sector, and engagement goals surrounding the ETII in question will vary and influence who is a context-appropriate participant. Questions to inform the selection of appropriate participants include:

- Who are the interested and affected parties surrounding the ETII?
- Who are the indigenous peoples or other groups who have special ties to, or legal rights to inform decision making for, the potential use site?
- Who has the necessary type of expertise required for each decision phase?
- Who are the groups that need to be engaged to navigate or potentially address conflict?
- Who has a willingness to participate in good faith?

These questions highlight a variety of important considerations for selecting appropriate participants. First, participants should have a personal or professional stake or interest in the ETII issue (National Academies of Sciences, Engineering, and Medicine 2016). Second, indigenous peoples potentially impacted by an ETII should be included in engagement. Indigenous peoples are important to include in such engagement activities because of their legal rights and historical exclusion (Whyte 2011, Maldonado et al. 2016, Barnhill-Dilling and Delborne 2019), in addition to the fact they have been recognized by the United Nations Convention on Biological Diversity as particularly relevant to issues of free, prior, and informed consent around emerging technologies such as gene drives (Wit 2019). Third, engagement for different decision phases and sectors will require participants with varying levels of expertise in topics relating to ETII. For example, while potential participants may need a higher level of expertise to participate in engagement for the analysis stage of risk assessment, they would not need that level of expertise to participate in the problem formulation stage (Hartley and Kokotovich 2018). One needs to recognize the different levels of expertise required across decision phases (Fig. 1) and find appropriate participants for that situation. Finally, when facing potentially conflictual topics, it is important to consider who needs to be in the room to foster productive conversations that can help better understand and navigate such conflict. Not including a key group in a conflictual situation will limit what can be achieved.

Based on these criteria, there are seven types of people we highlight as important potential participants for ETII engagement:

1) *Stakeholders*—People who have a personal or professional interest in the ETII, including those from industry, NGOs, and agricultural groups;

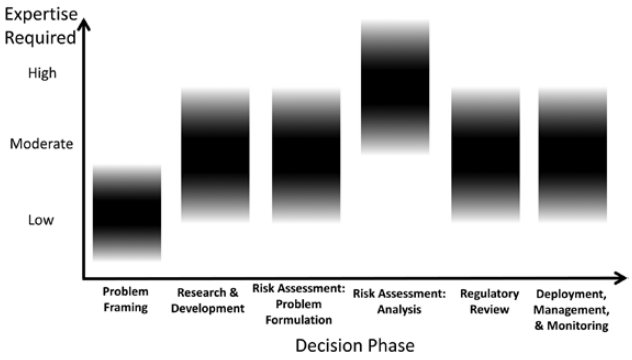

Fig. 1. Levels of expertise required in each decision phase. Risk assessment is divided into two parts—analysis refers to all components of risk assessment after problem formulation. This figure indicates that engagement can be designed for any decision phase, but requires identifying individuals with the appropriate level of expertise. The level of expertise required for each decision phase will vary based on the ETII in consideration and should be considered on a case-by-case basis.

2) *Expert stakeholders*—Stakeholders who hold significant expertise relevant to a decision phase;
3) *Indigenous community members*—Indigenous peoples who live near and are potentially impacted by an ETII application;
4) *Indigenous experts*—Indigenous peoples who hold significant expertise relevant to a decision phase;
5) *Community members*—Individuals who live near and are potentially impacted by an ETII application (may overlap with indigenous community members);
6) *Experts*—Academics or other public sector experts (e.g., researchers at state or federal agencies) committed to the public good. These are distinguished from expert stakeholders who promote the interests of a particular group;
7) *Decision makers*—Individuals in government who have some sort of decision making authority over the ETII in question, including, for example, those involved with regulation or project funding related to ETII.

Context-Appropriate Methods

There are a host of different methods that can be utilized when designing engagement for ETII, including, but not limited to: surveys, interviews, focus groups, town hall meetings, and workshops (Rowe and Frewer 2005). To select the appropriate methods for engagement for a particular decision context, the following factors should be considered: the objectives of the engagement; the type of interaction, if any, desired among participants; and available resources (Table 3).

One set of objectives for engagement that should be considered in the selection of methods is the potential to foster deliberation, mutual understanding, and reflexivity (Fishkin and Laslett 2008). This objective is especially important to conflictual situations. Engagement is most impactful when participants have the opportunity to hear from and learn from others as opposed to merely stating their own opinion. Methods that promote sharing and deliberation can help those who hold different views come to a better understanding of each other and why they think the way they do (Bull et al. 2008). Well facilitated deliberation that supports mutual understanding can help prevent polarization and the righteous dismissal of those who hold different worldviews (Bächtiger et al. 2018). In addition, interaction with those who hold different worldviews can help one better see and reflect upon their own worldview and the assumptions it is based upon. If one is only asked to vote on particular management options, this type of deeper interaction cannot take place. This is not to say, however, that there will never be instances where a survey or interview will be the right method for a particular situation. One needs to match the method to the context.

Table 3. Example methods organized by degree of interaction and resources required

Method	Interaction among participants	Resources required
Survey	None	Low (Online, targeted participation) High (Broad participation and representative)
Interview	None	Low (Phone or online)
Focus group	Moderate	Moderate
Workshop	High	High
Town hall meeting	Moderate	Moderate

SWD Engagement Project

We designed engagement that utilized multiple methods with different participants to achieve our goal of identifying and prioritizing potential adverse effects, potential benefits, and potential research and management actions for proposed emerging biotechnologies to manage SWD.

First, to create a broad list of potential adverse effects, benefits, research actions, and management actions for these emerging biotechnologies, we wanted to foster more in-depth conversations with those who held relevant knowledge and experience. In February 2017, we held three focus groups with a variety of experts and expert stakeholders who were knowledgeable about SWD, impacts on agriculture from SWD, or emerging biotechnologies, including: researchers, individuals from fruit grower groups, and individuals from fruit commodity groups. Focus groups contained between 5 and 7 people each and a total of 19 people participated. For each of the emerging technologies considered, focus group participants were provided with a description of the technology being proposed, and then they engaged in a conversation to identify possible beneficial and detrimental outcomes from that technology. We then wanted the list of outcomes for each technology from the focus groups to be reviewed for completeness. To do so we conducted individual phone interviews with five experts and expert stakeholders in September 2017 where they were provided with the focus group findings and reported what they thought was missing.

Following the focus groups and interviews, we analyzed the complete list of potential outcomes and transformed them into a list of potential adverse effects, potential benefits, potential management actions, and potential research actions (see Table 4 for a list of examples for the gene drive technology). A literature review on risk assessment problem formulation for such emerging technologies (e.g., David et al. 2013, Roberts et al. 2017) was also completed at this time to ensure the lists were complete.

The next step of our project is to conduct a survey in fall 2019 to prioritize the lists of potential adverse effects, benefits, research actions, and management actions. This will help inform what potential adverse effects are most important to study in future risk assessments, which potential benefits are seen as most vital, and which management and research actions are most important. A survey methodology more easily allows for a much broader set of participants who are involved with SWD and these emerging biotechnologies. This survey will be administered online to a variety of

Table 4. Example potential adverse effects, benefits, management actions, and research actions for the gene drive emerging technology

Example potential adverse effects	
Entity	*Attribute*
SWD—native populations	Species extinction [Spread of gene drive to SWD native range]
Non-SWD pests	Population size increase [Ecosystem dynamics influenced by complete or partial elimination of SWD]
Growers	Loss of organic certification to growers using or exposed to gene drive technology [Detection of residue from gene drive organisms on crops]
Growers	Domestic sales decrease [consumer reaction to the use of gene drive]
Example potential benefits	
Entity	*Attribute*
SWD—pest populations	Population size decrease [From deployment of gene drive technology]
Beneficial insects (e.g., natural enemies, pollinators)	Population size, Pollination rates, predation and parasitism rates increase [Decrease in pesticides used to manage SWD because of gene drive technology is successfully controlling SWD]
Humans	Overall health increase [Decrease in pesticide usage]
Growers	Revenue increase [Long-term pest management costs decreased]
Example potential management actions	
Further reduce conflicts of interest in safety testing between groups such as companies doing product development, scientists, end users, and regulators	
Establish predetermined liability and responsibility for any realized adverse effects	
Establish and fund an effective monitoring plan	
Increase the number and quality of open and transparent deliberations with stakeholders to inform governance decisions	
Example potential research actions	
Establish a reversibility option for the gene drive application—for example, creating the ability to stop the gene drive if something were to go wrong	
Establish a gene drive that is locally limited—for example, one that only works for a predetermined, limited number of generations or within a given geographic area	

Potential pathways for adverse effects and benefits included in brackets for clarity. The examples provided in this table are but a subset of what emerged through the project activities and are meant to serve as examples of the types of topics covered.

stakeholders, expert stakeholders, experts, and decision makers, including: growers, academics, regulators, NGOs, individuals from commodity groups, and individuals from industry.

Engagement Best Practice 3: Recognize and Navigate Tensions

Designing and conducting engagement for ETII, as well as for other emerging technologies, requires a healthy relationship to tension—that is, a healthy relationship to conflicting ideas and competing priorities. Many of the most important design decisions for engagement are not 'check box' items where there is a single obvious right way to complete them. These decisions require careful consideration of context and the weighing of competing priorities. Furthermore, recognizing the tensions that are present with engagement can help ensure that they are well navigated, instead of wishing they were not present and ignoring them. The final best practice is to recognize and navigate tensions within engagement.

Many important tensions exist with respect to engagement (Delgado et al. 2011, Blok et al. 2015, Sonck et al. 2017, Braun and Könninger 2018). In the *Engagement Best Practice 1: Pursue Engagement Across Decision Phases and Sectors* and *Engagement Best Practice 2: Select Context-Appropriate Participants and Methods* sections, we discussed tensions in terms of the competing factors influencing who to include, what methods to use, when to conduct engagement, and what type of goals to pursue. Here, we emphasize three tensions: 1) the tension between inclusion and exclusion; 2) the tension between opening up deliberation and narrowing in on a decision; and 3) the tension between informal and formal engagement.

The first tension is between the inclusion and exclusion of participants, both in terms of when there is a need to exclude certain potential participants to achieve other engagement goals and in terms of factors that complicate efforts to be inclusive. First, there may be potential participants who are situated in such a way where they would be motivated to strategically disrupt engagement activities. Those whose interests align with the status quo or existing power structures may try to disrupt processes, including engagement activities, that could change the current state of affairs (Oreskes and Conway 2011). While this makes clear the potential need for purposeful exclusion of certain participants, this can be a challenging decision. What counts as disrupting a process or not engaging productively varies greatly based on one's perspective. In addition, making such a claim against someone can sometimes be a response to not wanting to engage with, or being able to understand, the substantive point they are raising. As a result, decisions to exclude should be carefully scrutinized.

Second, when considering how to define and achieve inclusivity it is important to keep in mind differences in power. Not every potential participant will be situated equally with regards to time, resources, and types of knowledge and perspectives seen as legitimate (Ozanne et al. 2009). For example, if those organizing engagement provide open invitations to a diversity of groups but then expect participants to volunteer their time and pay their own travel expenses, the resulting participants will be skewed toward those with a large amount of resources—reinforcing certain power dynamics. Covering travel costs and providing an honorarium, or arranging for methods that are not burdensome for participants can help address this (Kleinman et al. 2011). Furthermore, certain worldviews and framings, such as those built upon risk assessment or neoliberal economics, are likely to be the norm in technological development and decision making realms, so making engagement design choices that provide openings for marginalized views, such as indigenous

worldviews, to be expressed and heard is essential (Wynne 2002, Holifield 2012, Richmond et al. 2013).

The second tension is between engagement approaches that help open up space for exploring differences across worldview, values, or discipline and those that help narrow in on a decision (Stirling 2008, Delgado et al. 2011, Dana et al. 2012). Opening up requires time, deliberation, and bringing in more perspectives—the goal being to explore how perspectives differ, why they differ, and what is at stake in those differences. Using engagement to help make a decision, however, requires narrowing the range of possibilities and choosing to privilege certain worldviews, values, or disciplines over others. While this can help engagement stay decision-relevant, it is also more likely to involve conflict since certain perspectives may be excluded, even when consensus is not the goal. This conflict should not be avoided and may provide useful insights for participants as well as for engagement organizers (Bouwel and Oudheusden 2017). The engagement we propose requires navigating this tension productively based on the needs of the particular context.

The third tension is between formal engagement and informal engagement. If the goal of engagement is the 'sharing and exchange of knowledge, perspectives, and preferences between or among groups who often have differences in expertise, power, and values' (National Academies of Sciences, Engineering, and Medicine 2016), there are less formal versions of that which can take place relatively easily. One could do informal engagement on ETII-related topics by, for example, conversing with colleagues with different expertise or values, holding a seminar with an interdisciplinary group of colleagues, or sharing and receiving feedback on work at a conference. In addition to not needing to design an engagement process, find resources, or select appropriate participants, these informal actions are quick enough to easily keep pace with the fast moving speed of research and development. Having connections with colleagues holding a diversity of worldviews and disciplines, including from the social sciences and humanities, can help one receive strong critical feedback in these informal interactions. And while some contexts may call for such informal engagement, there are also significant limitations to it. First, the lack of transparency and public awareness that results from such informal practices, will decrease its visibility and trustworthiness. Second, the diversity in expertise, worldview, and power of participants is likely to be greater if engagement is deliberately designed and conducted. One is more likely to encounter views that vary from their own if they engage outside their established circles. Third, the quality and depth of reflection possible in these short informal interactions is qualitatively different than those possible through longer and more deliberate engagement like workshops.

SWD Engagement Project

We navigated these tensions in a variety of ways when designing engagement for proposed SWD emerging biotechnologies. First, we utilized informal engagement with colleagues from different disciplines (across the natural and social sciences) to help design our formal engagement activities. Second, we both opened up spaces for deliberation and narrowed to inform decision making. The focus groups represented a time where participants could grow the list of potential adverse effects, benefits, research actions and management actions while hearing why others added the items they did. The survey is an approach to prioritize these lists to see what will emerge as most important to stakeholders involved with potential SWD emerging biotechnologies. Third, we conducted the focus groups at a SWD meeting so that additional travel was not necessary and decided upon a survey for the latter part of the research to make participation easier for a broader group of participants.

Discussion

Engagement will be an essential component of any successful deployments of ETII. Exactly how engagement should be envisioned and conducted in the context of ETII needs to be a focus of ETII research going forward. To contribute to this exploration of engagement for ETII we reviewed relevant engagement literatures and proposed three best practices for engagement. We argue that well designed engagement should take place across decision phases (problem framing; research and development; risk assessment; regulatory review; and deployment, management, and monitoring) and sectors (government; industry; NGOs; and academia), and should utilize context appropriate methods and involve context appropriate participants. In addition, tension and conflict need to be recognized and navigated within engagement for it to be successful.

Lessons From Spotted-Wing Drosophila Engagement

The SWD engagement project provides a few key insights for our discussion about engagement for ETII. First, while the completed and proposed activities are fairly limited in scope compared to the full set of decision phases and potential participants, the findings are still useful. The focus on stakeholders and expert stakeholders in the focus groups allowed for useful insights from groups representing key SWD constituencies and contributing different types of expert knowledge. An even broader set of participants will be included in the survey, which is an easier method for reaching more people. There are also many other decision phases that exist for the SWD that would benefit from engagement, whether that is the analysis stage of risk assessment, regulatory review, or deployment, management, and monitoring. While this project sought to engage at a useful point (problem formulation stage of risk assessment) given the current state of development of these technologies, there is still a broad need for additional research. Second, this project, which began with focus groups and interviews and then moved to a survey, exemplifies the integration of methods to achieve different and complementary engagement objectives.

A Path Forward for Engagement

Calls for engagement on emerging technologies, especially biotechnologies, continue to proliferate (Jasanoff and Hurlbut 2018, Kofler et al. 2018, Medina 2018). A burgeoning literature explores available conceptual frameworks and what form such engagement can and should take (Hartley and Kokotovich 2018, Stirling et al. 2018, Barnhill-Dilling and Delborne 2019, Buchthal et al. 2019). The diversity of ideas can help address the challenges posed by ETII, but they could also contribute to two key potential dilemmas.

First, there is the potential for feeling overwhelmed when faced with the task of designing engagement for a particular ETII application. For example, looking at the diversity of decision phases, sectors, potential participants, and potential methods that exist for an ETII (see *Engagement Best Practice 1: Pursue Engagement Across Decision Phases and Sectors* and *Engagement Best Practice 2: Select Context-Appropriate Participants and Methods* sections) can make designing engagement seem impossibly complex and difficult. It is easy to see why some may try to sidestep these challenges by avoiding engagement altogether. It is essential to note, however, that this does not remove these challenges, it just punts them further down the road. And the challenges may, in many cases, become larger when trust has been lost, resources spent, and experiments already conducted. As explored in this article, there are many reasons for why it may be easier to have difficult conversations up front than

to wait and have them after the fact. To avoid overwhelm, there is also a need to support the development of the intellectual and emotional capacities required to be with the tensions and conflicts that surround ETII and engagement. In addition, it is important to not let the perfect get in the way of the good, while still recognizing the limitations of the good. As described above, the project with SWD is limited in scope, but was the available starting point for fostering important conversations.

Second, with so many approaches to engagement in circulation, it is also possible to choose the engagement path of least resistance instead of the one that will lead to the best result. To navigate this potential, there needs to be forethought and reflexivity brought to the planning process of engagement itself (Delborne et al. 2018b). One way to accomplish this is through bringing social scientists or those with experience in engagement into the planning process. Social scientists and natural scientists collaborated in the design of the SWD project described here. Having someone with a different discipline or worldview involved with the planning process can help raise important questions or help reflect on what is at stake in making certain design decisions over others.

On the other hand, the vast conceptual and methodological tools of engagement are well situated to help improve the design and deployment of ETII. No matter the decision phase or sector that is relevant to the ETII or the resources and potential participants available, there is a potential role for engagement to play in improving how we make decisions about ETII. And as more engagement takes place, there will be further opportunities to reflect on what does and does not work and how we can continue to improve our design of engagement.

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