The Role of Expert Disciplinary Cultures in Assessing Risks and Benefits of Synthetic Biology

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Like other technological fields before it, synthetic biology (SB) has been ascribed different definitions by different scholars (Pauwels 2013; Smith 2013; Wang et al. 2013). One commonly used definition of SB is the extraction of living parts for organisms that are then inserted into other organisms to create a "new" organism with parts from the donor and recipient (Benner and Sismour 2005). Synthetic biology has also been described as "the use of computer assisted, biological engineering to design and construct new synthetic biological part" (Hoffman and Newman 2012). Others like the National Science Foundation and the Engineering and Physical Sciences Research Council have noted that synthetic biology is the identification and application of biology in the design of biological parts and systems for use in the creation or redesign of natural biological systems for useful purposes (Engineering and Physical Sciences Research Council 2009).

At first glance, the term "SB" appears somewhat of an oxymoronic label. The word biology is usually defined as the study of life and living organisms, whereas synthetic is often defined as something not of natural origin or alternately as something that is fake or not genuine. A lay understanding of the term could lead one to believe that SB is a combination of living and artificial or unnatural components. However, if instead a definition of synthetic that looks at "synthesis of parts" is used, a more common scientific understanding of SB can be achieved. Such definition differences may be due to distinct "expert cultures" who view the field, its products, and subsequent risks in distinct ways. This work explores these potential

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cultural perceptions and focuses on potential differences in expert groups' beliefs and attitudes regarding risk analysis and governance needs for SB.

This chapter takes a case study approach similar to related work (see Cummings and Kuzma 2017; Trump et al. 2018a; Valdez et al. 2019) to examine a case study in SB, the planned enhancement, and use of the bacterium species *Mesorhizobium loti* (*M. loti;* formerly known as *Rhizobium loti*). The non-SB form of *M. loti* was studied extensively in the 1990s and had its complete genome sequence identified in 2000 (Kaneko et al. 2000). *M. loti* is a Gram-negative bacterium commonly found in the root nodules of many plant species and serves a symbiotic relationship with the plant in nitrogen fixation.

The SB-enhanced version is planned to improve the natural nitrogen-fixing qualities of the bacterium among nonlegumes, thus potentially increasing plant health and crop yield. While the bacterium is being speculated for widespread use, it is still under development. Christopher Voigt, at the Massachusetts Institute of Technology, researches this technology as a method for minimizing fertilizer application by allowing crops that previously relied on nitrogenous fertilizer applications to now rely on nitrogen production from engineered bacteria (Charpentier and Oldroyd 2010). The Voigt lab is also researching two additional pathways for achieving nitrogen fixation in nonleguminous plants, both of which involve engineering the plant instead of the bacteria. Since the two different genetic manipulations (plant or bacteria) would likely have different risk governance issues, we focus on the genetic manipulation of the soil bacteria.

Using this case study, we examine the boundaries and differences between groups of experts who may approach the case from distinct disciplines. We define disciplinarity as a form of cultural similitude between experts who may share similar ontological and epistemological structures, methods, organizations, and assumptions in their professional perspectives (Becher 1994). From this premise, we propose two axes that help us to chart boundaries between "expert cultures."

The first axis is the broad disciplinary grouping of either "natural scientists" or "social scientist," and the second axis is expert positioning of either "upstream" or "downstream" in relation to the technological development (Trump et al. 2018b; Trump et al. 2019). Stemming from the early work of Mary Douglas, Kahan and Braman (2006) identify risk perceptions from their cultural theory of risk that evaluates individuals' worldviews on the basis of "group" and "grid" preferences. In their framework, a "group" represents an individual's beliefs on how individualistic or communal a society should be, while the "grid" represents the individual's beliefs on the organization and durability of authority within society. A "high-group" perspective exhibits desires for a high degree of collective control, while those among the "low group" maintain much lower desires for authority and demonstrate preference for individual self-sufficiency. A "high-grid" perspective is characterized by desires for durable and conspicuous roles and authority structures within society, while the "low grid" is notably more egalitarian in its role orientation. In this chapter, we adapt cultural theory of risk to include academic disciplines as cultures, and we position expert cultures to their relationship with the development of the SB technology to assess potential patterns of cultural perspectives regarding the potential risks associated with the enhanced *M. loti* bacterium.

In order to study this case among expert cultures, we conducted a Policy Delphi study among 48 experts. To guide our inquiry, we posed the following research question: Does the expert group culture affect the views on riskiness of the genetically modified *M. loti*?

This chapter next reviews relevant literature from the fields of anticipatory governance and risk perception; then outlines our methodology and methods used for case study selection, expert elicitation, and data analysis; then reports results from this mixed-method inquiry; and identifies patterns and implications of the differences in expert culture perspectives of *M. loti*. We conclude the chapter discussing the implications for this work in helping to inform risk and governance discussions for emerging technologies in the area of SB.

Literature Review

Risk Analysis and Governance

Risk analysis (RA) includes the "traditional model" of scientific risk assessment employed by many federal agencies. It generally involves human dose-response metrics that are used to determine acceptable levels of risk based on exposure to a particular concern (DeSesso and Watson 2006; National Research Council Staff 1993). In risk assessment methods for genetically engineered plant microbes, human exposure and environmental sensitivities are given a static analysis, and subsequently, a determination on risk is made. Traditionally, RA has come after the technology development process when products are nearing the market for widespread use (Wareham and Nardini 2015).

In the case of emerging technologies, many scholars have called for more proactive governance approaches (Gutmann 2011; Mandel and Marchant 2014; Tait 2012). Anticipatory governance seeks to evaluate and potentially make recommendations on best practices for managing and governing emerging technologies prior to the technology being widely introduced into the public sphere (Guston 2014; Guston and Sarewitz 2002; Kuzma et al. 2008b; Quay 2010). In addition, anticipatory governance strategies have been used as a tool to promote early public engagement around a technology (Macnaghten 2008). One goal of anticipatory governance is, through upstream discussion and analysis, to prepare for emerging technologies and thus minimize potential negative externalities that could occur based on unknown risks associated with the technology's deployment. Given that there may be considerable uncertainty in a pre-dissemination technology, anticipatory governance often involves evaluating multiple factors that could affect society and similarly will likely involve evaluating multiple endpoint scenarios for the technology (Kuzma and Tanji 2010).

Anticipatory governance can be seen as an umbrella concept, under which many practical tools are held. One such tool, real-time technology assessment (RTTA), is an argument made for moving beyond the traditional static risk assessment model and, instead, adopting a more adaptive system that allows for "real-time" evaluation of societal and ethical implications of a technology under development (Guston and Sarewitz 2002). This reorientation provides new risk evaluation structures to be placed "upstream" where experts can incorporate this feedback into the design of a technology which may allow developers and researchers to craft a product that better maximizes benefits and minimizes potential risks. RTTA also provides a mechanism for making incremental changes, thus providing iterative feedback on the effectiveness of each step.

Similarly, the use of upstream oversight assessment (UOA) encourages experts to think beyond the traditional RA framework when considering potential data, information, and regulatory oversight needs of an emerging technology (Kuzma et al. 2008a). Both UOA and RTTA can be considered anticipatory governance approaches. This work's practical framing uses UOA, which has been defined as the advanced consideration of technology case studies to explore risk, regulatory, and societal issues (Kuzma et al. 2008a). Defining the emerging technology is a critical step in conducting a UOA. Once the emerging technology is defined, selecting a representative case study within the technology helps to ground conversations. Whereas a rigid definition is not required, boundaries for the technology that help determine potential oversight needs must be developed in order to have a fruitful discussion of options. Upstream oversight assessments are conducted by analyzing a case study from an emerging technology to "highlight oversight issues" by thinking through the potential deployment of the technology in society and how that technology fits into the current regulatory landscape (Kuzma et al. 2008b). Case studies are a way for anticipatory governance strategies such as UOA to proceed with discussions of specifics and to make progress in highlighting issues associated with SB applications (Kuzma and Tanji 2010).

Anticipatory governance seeks to capture a wider range of voices earlier in technological development. For example, Stirling's (2008) *Science, Precaution, and the Politics of Technical Risk* argues that including precautionary and participatory approaches complements the traditional "science-based" risk assessment. Furthermore, the incorporation of precautionary and participatory principles, such as expanded RA methods and increased public engagement, can improve democratic legitimacy and provide a more comprehensive decision-making process. Stirling notes "deliberate attention to potential blind spots" as one of several key features of a precautionary approach. While our assessment of *M. loti* does not explicitly seek to promote a precautionary approach, we do deliberately investigate potential blind spots in RA and governance needs assessments by evaluating commonalities in perceptions that are shared among expert cultures.

We employed expert elicitation methods to collect data on expert group risk perceptions and governance preferences. These methods are particularly germane in emerging areas, such as SB, for which data and information are scarce and uncertainty is high (Otway and von Winterfeldt 1992). Whereas these methods have been used and accepted in policy decision-making (Morgan 2005; Swor and Canter 2011), we must be cautious to recognize potential cognitive biases and overconfidence of the expert group (Morgan 2014).

Risk Perception

For many cases similar to *M. loti*, little data or information exists regarding risk governance needs. Thus, expert judgments become a valuable source of governance strategies and potential outcomes related to the technology (Cummings and Kuzma 2017). However, experts themselves are influenced by their disciplinary cultures, as well as their individual life experiences, interests, motivations, and specific knowledge. Mile's law (Miles Jr. 1978), which notes that "where you stand depends on where you sit," captures the potential unassuming bias likely to influence decision-making processes of all types, including those regarding risks. In looking at perceptions of risk, scholars have explored several theories to explain perceptions that are based on factors other than the physical riskiness (harm from a dose or exposure) of an application.

One prominent theory in this area is the cultural theory of risk. This theory posits that risk perceptions are influenced by our cultural worldviews. Cultural cognition looks at the characteristics of a group to which an individual belongs to explain part of that individual's worldview. In turn, this worldview influences the perception of risk that the individual holds (Kahan and Braman 2006). The cultural theory of risk thus proposes that an individual's affiliation with cultural groups will determine which types of hazards resonate with that individual. Kahan and Braman's model of cultural cognition uses continuous attitudinal scales to measure where an individual falls on two measures: (1) the hierarchy-egalitarianism scale and (2) the individualism-communitarianism (solidarism) scale. Those who have a low-group (individualistic) worldview expect individuals to be self-resourceful and have little expectation of group support. Those who have a high-grid worldview (hierarchical) expect that resources be divided based on characteristics specific to a given social order; conversely, low-grid (egalitarian) individuals expect resource allocation to be equitable and not consider any social ordering.

Case Study: Genetically Modified *M. loti*

Kuzma and Tanji (2010) argue that discussions regarding SB in general are too broad for evaluation of anticipatory governance options. As such, this work uses a specific application within SB, genetically modified *M. loti* for extending nitrogen fixation to nonlegumes, as a method for grounding conversation in UOA in SB. The use of genetic engineering applications on plant microbes to extend nitrogen fixation to nonleguminous plants has been studied for many decades (Charpentier and

Oldroyd 2010; Wang et al. 2013). The process involves multiple genetic manipulations before a successful new symbiotic relationship between microbes that already has the ability to fix nitrogen can interact with a plant that does not already pose the ability to host the microbe (Wang et al. 2013).

Currently, *M. loti* is the only bacterium known to have a naturally occurring symbiotic relationship with legumes (Charpentier and Oldroyd 2010). It is this natural symbiotic relationship between *M. loti* and the plant that has interested researchers to attempt to modify *M. loti* to similarly be able to fix nitrogen among nonlegumes including rice cereals. The benefits of the relationship to both organisms are readily available food supplies and host sites for the bacteria. For the symbiotic relationship to be established, there is a multistep process that must take place between the two organisms (Oldroyd and Dixon 2014; Santi et al. 2013). First the legume will secrete flavonoids into the soil, which are detected by *M. loti*. The bacteria will secret Nod factor in response to the recognition of the flavonoids. The Nod factor, once recognized by the legume, leads to the creation of nodules in the plant root hairs. These nodules become the host site for the bacteria, and the *M. loti* colonize within the nodules. Once the bacteria have infected the plant host, and colonized in the root nodules, the symbiotic exchange of essential nutrients begins (Oldroyd and Dixon 2014). The plants provide the bacteria with needed organic matter, and the bacteria provide the plant host with ammonium. In contrast to the atmospheric nitrogen, ammonium provides a readily available source of nitrogen for the plant. An overview of this symbiotic relationship is shown in Fig. 1.

The genetic engineering goal for symbiosis is to extend the abilities to cereal crops, including rice, wheat, and maize. Some benefits that have been discussed around this technology include decreasing global nitrogenous fertilizer demands

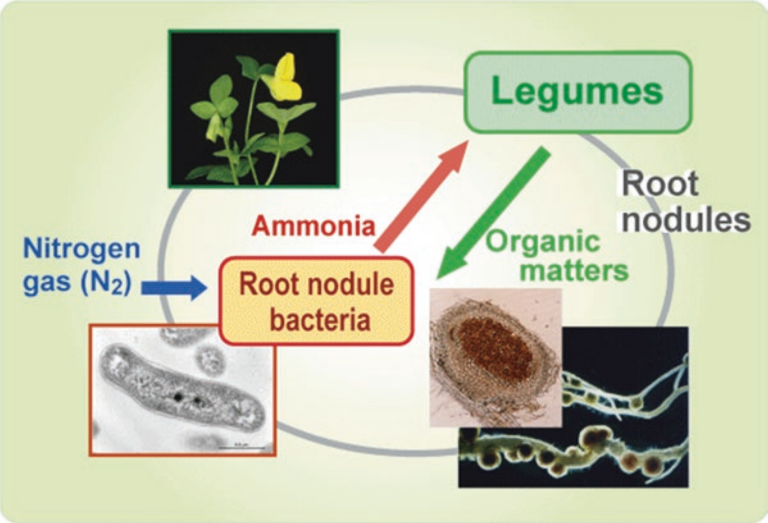

Fig. 1 Overview of symbiotic nitrogen fixation in legumes

and increasing crop yields for cereals, which could potentially lead to less environmental degradation due to fertilizer application and a partial solution to address global hunger needs. Having a readily available source of nitrogen has been shown to be a limiting factor in climates that would otherwise support cereal crop growth (Oldroyd and Dixon 2014).

There are at least eight genes involved in root nodule symbiosis (RNS) once the Nod factor has been recognized by the host plant (Oldroyd and Dixon 2014). These eight common symbiotic components (SYM) are thought to have common ancestry with arbuscular mycorrhizal (AM) symbiosis. Cereal crops possess AM genetic materials and are thought to have had an ancient symbiotic relationship with other soil bacteria that also provided essential nutrients (Charpentier and Oldroyd 2010). Given that cereals already possess genetic material that could be used for SYM pathways and that the bacteria needed for the symbiotic relationship already colonize the soil where cereals exist, there has been considerable hope that a series of genetic modifications could lead to the successful symbiosis of cereals and nitrogen-fixing bacteria. Also, given the global significance of rice crops in diets, the potential for extending the symbiosis to rice has been studied by many scholars (Oldroyd and Dixon 2014). This case study represents an emerging technology in SB that is nearer-term and where similar genetic engineering technologies have been developed (U.S. Environmental Protection Agency 2013), thus making it a good candidate for our overall project's aims.

Methodology

We use a mixed-method design to evaluate the case study among distinct expert cultures as part of a larger Alfred P. Sloan grant (PIs Kuzma and Cummings, *Looking Forward to Synthetic Biology Governance: Convergent Research Cases to Promote Policy-Making and Dialogue* [#556583]).

The project first reviewed multiple SB applications in early development and identified four case studies: biomining using engineered microbes, cyberplasm, de-extinction, and, the currently explored case, nitrogen fixation using engineered plant microbes. After the case studies were selected, more detailed descriptions were written by research staff using interview data from the technology's developers and available literature. These case study descriptions were then shared with the recruited expert panel to elicit feedback on governance needs for each case study specifically, as well as for SB holistically using Policy Delphi approach.

The Delphi method has been used for many decades to obtain group consensus from experts using iterative controlled intensive questionnaires (Landeta 2006). Originally named after the Oracle of Delphi, this method attempts to forecast potential risks and evaluate myriad policy options to maximize benefits and identify risks and areas of uncertainty that warrant greater information and attention. In this way, Delphi studies can serve an agenda-building function to promote areas of concern and create new goals and objectives for study in areas of need. The method is best used “when accurate information is unavailable or expensive to obtain, or evaluation models require subjective inputs to the point where they become the dominating parameters” (Linstone and Turoff 1975).

Delphi methods have been used extensively in social science research to reduce hindrances to group processes like group think, dominant personalities, and inhibition. The Delphi method has been used often in natural and social sciences, and scholars have upheld its validity for forecasting and supporting decision-making (Landeta 2006). A Policy Delphi differs from the traditional Delphi methods by seeking to uncover a range of policy options and pros and cons of those options (Turoff 1970). Our Policy Delphi study aimed to elicit expert-stakeholder perceptions regarding potential risks and benefits of a technology, as well as the potential ethical, legal, and societal (ELSI) issues associated with the case studies under evaluation to uncover a range of SB risk analysis and governance needs from participants through iterative individual and group reflections.

The overall project’s Delphi consisted of four rounds. The first round consisted of a standardized open-ended interview, which is a form of qualitative data collection that is more structured than most other interview methodologies and thus [a]increases comparability of responses (Patton 2002). The second round included an online quantitative survey that was drafted from results drawn from Round One. Within the survey, panel members were asked to respond to a variety of scale items regarding risk and governance issues pertaining to each cases. The third round consisted of a face-to-face workshop where the goal was to envision ideal governance for SB in coming generations. The final round consisted of a second short online survey used to assess general trends among the sample. Data presented in this chapter come primarily from the first and second rounds of the project, and the interview protocol and survey are detailed in the following section.

Interview and Survey Methods

Prior to the beginning of Round One, experts were introduced to the *M. loti* case in the form of a two-page dossier that summarized the scientific goals of the developing technology and outlined the current state of the research. This summary was vetted for accuracy by a set of SB experts who were not participants in this study. Participants were asked to refer to the summary and any other information they had gathered as they completed the Round One qualitative interview.

In the interview, participants were primarily asked the following three questions during the interview with regard to RA of *M. loti* and the other case studies: (1) What are the types of data and information needed to assess the risks and benefits? (2) What are the associated uncertainties with this application, and how might they affect oversight? (3) How can risk analysis methods be used in the face of such uncertainties? The interviews were conducted via Skype and telephone, and audio files from the interviews were sent to a service for transcription. Transcribed data were then imported into NVivo software for coding and analysis.

A few weeks following the completion of the Round One interviews, we conducted the second round of the Policy Delphi study which consisted of an online survey with quantitative and open-ended questions that were based on initial themes that emerged from the Round One interviews. The Round Two survey posed questions to the expert panel on potential risks and uncertainty associated with each of the four case studies and asked experts to provide scaled responses to questions such as "How beneficial are engineered plant microbes to the environment?" Experts were also able to give feedback on the governance structures that they deemed most appropriate and which entities are, or should be, primarily responsible for oversight of the technology. These questions helped to further elicit expert opinions of governance, risk analysis, and data needs for regulating engineered plant microbes, such as *M. loti*.

The following background information was provided to the experts prior to the Round Two survey:

> Background: Many plant microbes are being researched for their ability to assist in crop production. One such example, the bacterium Mesorhizobium loti [M. loti] is being engineered to improve nodulation signaling for rice crops, thus allowing the two to enter into a symbiotic relationship where the M. loti colonize the newly formed nodules of the rice crop and provide a readily usable form of nitrogen. For the following survey questions, please assume that Engineered Plant Microbes are to be used in situ with open-release for agricultural purposes.

Respondents were then given the option to answer on a Likert scale of 1–10, with 1 representing the lowest response possible and 10 representing the highest.

1. How certain or uncertain are the risks of engineered plant microbes?
2. How likely is engineered plant microbes to be commercially developed and used in the next 15 years?
3. How potentially hazardous is engineered plant microbes to human health?
4. How potentially hazardous is engineered plant microbes to the environment?
5. How manageable are the potential hazards of engineered plant microbes?
6. How beneficial is engineered plant microbes to human health?
7. How beneficial is engineered plant microbes to the environment?
8. What might be the level of public concern regarding the risk of engineered plant microbes?
9. To what degree are the potential hazards of engineered plant microbes irreversible?

In addition, experts were asked to give an ordinal ranking to a list of potential issues for risk research concerning engineered plant microbes that could fix nitrogen for cereal crops. The list of options included the following:

1. Biopersistence
2. Competitiveness with other organisms
3. Disposal
4. Ecological system effects
5. Economic trade-offs with using other technologies

6. Environmental trade-offs with using other technologies
7. Genetic stability
8. Horizontal gene transfer
9. Life cycle
10. Organism tracking in situ
11. Pathogenicity
12. Regulation of tools
13. Regulatory approval process
14. Route of exposure to humans
15. Route of exposure to other organisms
16. Toxicity and biogeochemical cycling
17. Other

Experts could also select "other" and provide additional items to be considered in the ranking. Items were ranked between 1 and 17, with 1 being a risk consideration with highest priority and 17 being a risk consideration with lowest priority. Following the data collection in Round Two, we shifted efforts into classifying our expert panel into distinct cultural groups that would support our inquiry in answering our research question.

Expert Disciplinary Culture Classification

For the current analysis, the expert sample was classified into "expert cultures" from two data points. First, self-reports were used to classify individuals by their academic area of expertise into either "natural" or "social" sciences. Natural sciences have been found to promote more linear methods than social sciences and also have been found to promote hierarchical methods more readily than social sciences (Neumann and Becher 2002). Second, expert position of either upstream or downstream was determined by conducting searches of CVs or other published information in order to determine the expert role in *M. loti* development. Downstream experts are those involved with evaluation of the technology, policy, or societal concerns involved with the technological application. Examples of downstream scientists would include lawyers and risk scientists shown in Fig. 2. In contrast, upstream experts are involved with the technology or social science innovation or creation, like the ethicists and natural scientists shown in Fig. 2.

Survey data from 38 participants of the Policy Delphi were available for analysis of our defined expert cultures. Given the nature of such small expert studies, we compared expert cultures along the two axes, of upstream vs. downstream and natural science vs. social science, but did not group the experts into dual-axes categories, such as "upstream-natural scientists." In our final counts, we identified relatively equal expert culture groups between downstream ($N = 20$) and upstream ($N = 18$) groups and natural science ($N = 19$) and social science ($N = 19$) groups.

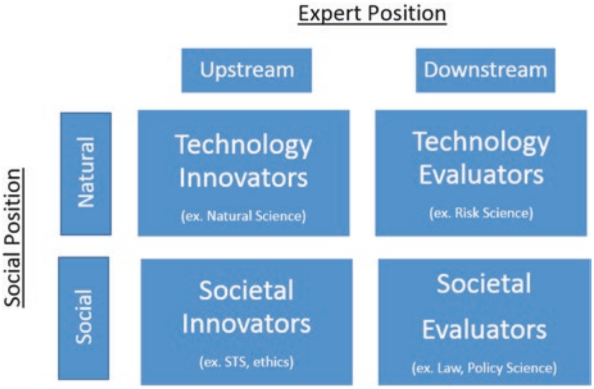

Fig. 2 Expert grouping by position and academic discipline

Results

Round One: Interview Data

The Round One interview asked individual experts to consider the data and information needs for genetically modified *M. loti*. The risk analysis need stated most by expert regardless of their disciplinary culture concerned gene flow and gene transfer from genetically modified *M. loti* after introduction into the natural environment or microbial population. Other risk assessment needs that were repeatedly mentioned by the experts included the need for human health metrics of toxicity, allergenicity, and pathogenicity. Another risk criteria that were highly mentioned among experts were competitiveness of the microbe in the environment. There were also three experts who voiced opinions that the existing risk assessment framework for traditional organisms is sufficient for governing all GMOs. A cross-tabs analysis of subthemed risk analysis needs that emerged from interview data categorized by disciplinary culture is shown in Fig. 3.

A diversity of opinions around risk analysis needs emerged and were distinct between disciplinary cultures. In total count of references for top RA needs, “downstream experts” (technology and policy evaluators) listed 32 concerns compared with 21 needs identified by “upstream experts” (technology and policy innovators). When looking at natural scientists, we see 36 RA needs were identified compared to 17 from the social scientists. The RA criterion most mentioned was gene transfer, with a total of 28 references. This was mentioned most by natural scientist with 10 total references and least by social scientist with only 4 mentioned. For upstream and downstream experts, both groups mentioned gene transfer seven times. When comparing downstream to upstream expert preferences for human health metrics, downstream experts made 15 references to allergenicity, toxicity, and pathogenicity compared to only 3 from the upstream experts. Similarly, natural science experts mentioned human health concerns more than social science experts with 14 references compared to 4.

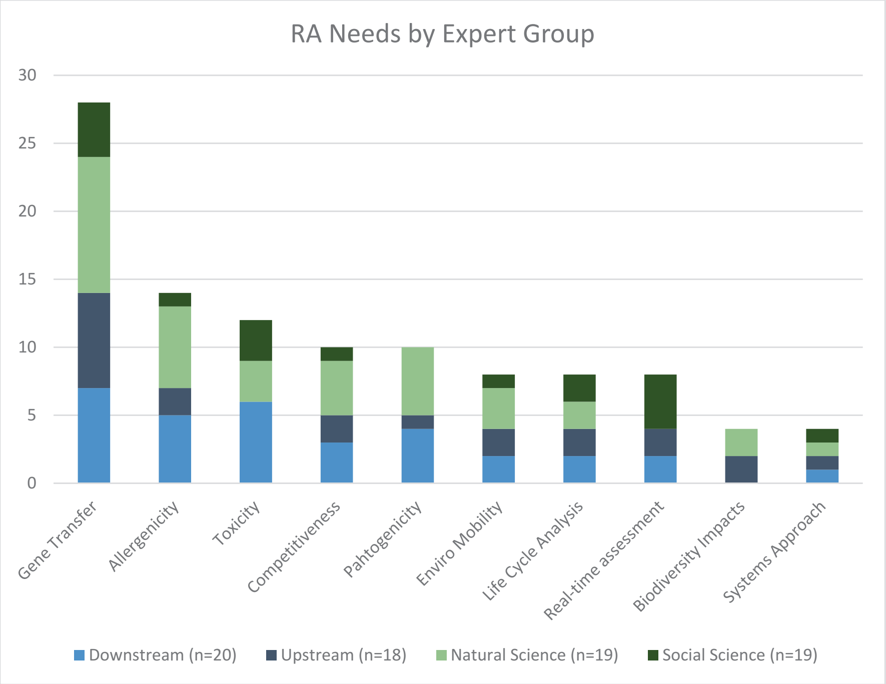

Fig. 3 Counts of risk analysis needs expressed by expert types

When asked about at RA needs, three alternative methods of assessment were mentioned by the experts: life cycle analysis, real-time assessments, and systems approaches. Life cycle approaches and system approaches were mentioned the same number of times by experts in all four groups, with two and one references per group, respectively. Real-time assessment was referenced most by social scientists with a total of four references, followed by two references from both upstream and downstream experts, and no references from natural scientists.

Round Two: Risk Perception Data

The Round Two survey consisted of multiple segments. The first asked our expert panel to answer nine questions pertaining to their risk perceptions for engineered *M. loti*. Responses were reported on a 10-point semantic differential scale where the poles reflected the core content of each question, and higher scores indicate increased risk perceptions. Figure 4 visualizes the results for each expert culture, and Table 1 reviews the descriptive statistics among each group and item.

When looking at uncertainty of risk for engineered plant microbes, we find that social scientists believe the risks to be slightly less certain with a score of 5.9 and

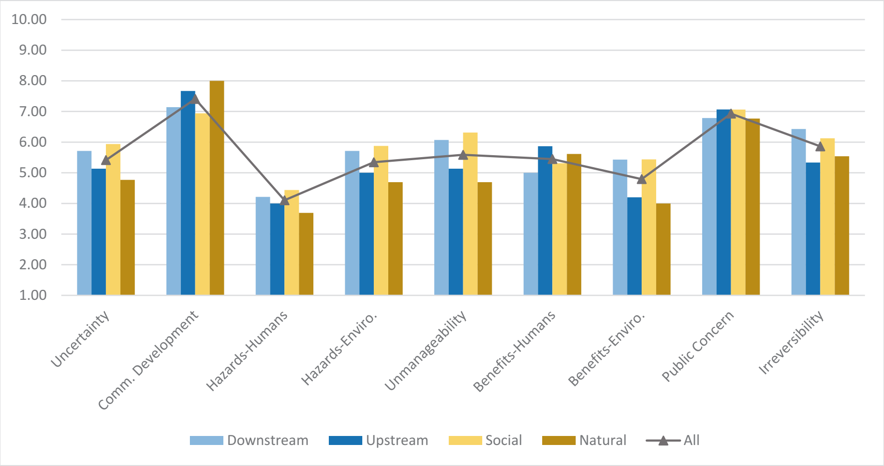

Fig. 4 Risks and benefits ratings by expert group

that natural scientists have slightly lower perceptions of uncertainty with a score of 4.8. We also find downstream scientists to be slightly less certain of risk than upstream scientists.

All four expert groups see this technology as likely to be commercially developed within the next 15 years, with natural and upstream scientists expressing highest scoring of likely development with score of 8.0 and 7.7, respectively. Upstream experts showed higher expectation of near-term development than downstream scientists, and natural showed higher expectation than social. This higher expectation from upstream and natural scientists could be due to greater experience with other genetically engineered microbes in the environment.

When looking at hazards and benefits of this technology to humans and the environment, we see the entire expert group perceives the hazards to environment as greater than the hazards to human health, but the benefits to human health greater than the benefits to the environment. Downstream scientists perceive hazards to both the environment and humans to be slightly greater than hazard perceptions from the upstream scientists, and social scientists perceive hazards in both areas as greater than their natural science counterparts. In contrast, environmental benefits were perceived as higher by downstream and social scientists than by the upstream and natural counterparts. However, upstream scientists assigned slightly higher human health benefits than did downstream scientists, and natural scientists gave slightly higher human health benefits than social scientist.

Downstream scientist expressed greater concern over manageability of this technology than did upstream scientists, and social scientist expressed greater concern than the natural scientist counterparts. Similarly, downstream and social scientists expressed greater concern than upstream and natural science groups regarding concerns over irreversibility of effects from this technology.

Table 1 Risk data by expert groups

	All experts (n = 29)			Downstream (n = 14)			Upstream (n = 15)			Social (n = 16)			Natural (n = 13)		
	Mean	Std. Dev	Range	Mean	Std. Dev	Range	Mean	Std. Dev	Range	Mean	Std. Dev	Range	Mean	Std. Dev	Range
Uncertainty	5.4	2.0	8	5.7	2.2	8	5.1	1.7	5	5.9	2.1	8	4.8	1.6	5
Commercial development	7.4	1.7	7	7.1	1.9	7	7.7	1.4	5	6.9	1.9	7	8.0	1.2	4
Hazardous to humans	4.1	1.8	7	4.2	1.9	7	4.0	1.6	6	4.4	1.9	7	3.7	1.5	6
Hazardous to the environment	5.3	1.4	6	5.7	1.6	6	5.0	1.0	4	5.9	1.3	6	4.7	1.2	4
Unmanageability	5.6	2.1	9	6.1	2.1	9	5.1	2.0	6	6.3	2.0	9	4.7	1.9	6
Benefit to humans	5.4	2.0	8	5.0	1.4	5	5.9	2.3	8	5.3	1.5	6	5.6	2.4	8
Benefit to the environment	4.8	2.0	8	5.4	1.4	5	4.2	2.3	8	5.4	1.7	6	4.0	2.1	7
Public concern	6.9	1.7	6	6.8	1.8	6	7.1	1.7	6	7.1	1.4	5	6.8	2.0	6
Irreversibility	5.9	1.6	6	6.4	1.5	6	5.3	1.4	5	6.1	1.6	6	5.5	1.5	5

When asked about public perceptions of risk for this technology, all groups expected moderate public concern. Downstream experts expected slightly greater perceptions of public concern than did upstream experts, and social scientist expected greater concern than natural scientists.

Round Two: Ordinal Ranking Data

In Round Two, we also explored the ordinal ranking of RA needs data that were provided by experts. To give an overall group ranking to risk assessment items ranked individually by experts, values within each expert group were averaged, and overall rank for each criteria was shown for each expert group. The results are shown in Table 2.

When looking at the top three RA needs identified by each of the expert groups, we see consistency among groups for the top three priorities. Biopersistence was ranked as the most important criteria for all expert groups, with the social scientists ranking both biopersistence and ecological system effects as equally most important. Other RA considerations ranked in the top three for any expert group include horizontal gene transfer and competitiveness with other organisms. The same four RA needs were ranked in the top three for each expert group; additionally, these four needs are the highest ranked overall when looking at the combined dataset for all experts.

Overall, the disciplinary groups showed fairly consistent ranking of RA needs. Ranked values were highlighted in instances where an expert group's ranking of RA needs differed from the overall group ranking by more than two. For downstream experts, we find that 12 of the 17 RA needs are similar to the overall group ranking, with differences of 2 or less. For upstream and social science experts, we see similarity in 15 of 17 of the RA needs ranking compared to the overall group and, for natural science experts, similarity across 16 of the 17 RA needs.

We also see some agreement between the ranking of RA needs from this ordinal data and the most frequently mentioned RA needs from the interview data. "Gene transfer" was the most mentioned RA theme during interviews and also was ranked in the top three RA needs. Competitiveness, another RA need ranked in the top three, was also mentioned frequently during the expert interviews.

Based on theories of disciplinary cultures (Becher 1994; Valimaa 1998; Trump 2017), it might be hypothesized that factors that involve expanding the traditional RA framework, such as considering environmental and economic trade-offs, would be favored by social sciences that are more accepting of multiple frameworks. However, those considerations were ranked the same for both natural and social scientists. However, the downstream scientists of both groups ranked the concerns considerably lower than the upstream scientists. Not surprisingly, the "route of exposure to other organisms" and "route of exposure to humans" were ranked higher for downstream scientist than for upstream scientists. In fact, the ranking for "route of exposure to other organism" from downstream scientists differed from the

Table 2 Ordinal ranking of RA needs by expert groups

Potential issues for risk research	Priority ranking based on averaged ranking scores				
	All experts[a] (*n* = 29)	Downstream (*n* = 14)	Upstream (*n* = 15)	Social (*n* = 16)	Natural (*n* = 13)
1. Biopersistence	1	1	1	1	1
4. Ecological system effects	2	2	3	1	4
2. Competitiveness	3	3	4	3	3
8. Horizontal gene transfer	4	5	2	5	2
7. Genetic stability	5	4	6	4	5
6. Environmental trade-offs	6	9	5	6	6
5. Economic trade-offs	7	11	7	7	7
11. Pathogenicity	8	7	8	9	9
10. Organism tracking in situ	9	12	9	14	8
3. Disposal	9	7	12	8	12
9. Life cycle	11	13	11	10	11
13. Regulatory approval process	12	14	9	13	10
15. Exposure to other organisms	13	6	15	11	15
14. Exposure to humans	14	10	14	12	14
12. Regulation of tools	15	16	13	15	13
16. Toxicity and biogeochemical cycling	16	15	16	16	16
17. Other	17	17	17	17	17

[a] The numbers shown by each "RA need" correspond with the numbering shown in the list of RA needs provided in the methodology section for this article, with full descriptions of each need. Ordinal rankings where the expert disciplinary group deviated from the overall group ranking are highlighted

overall ranking more than any other RA need ranking. This differential in upstream and downstream scientists' prioritization of exposure supports previous findings that downstream scientists are more concerned about potential environmental and human health effects from emerging technologies than their upstream counterparts (Powell 2007). Disposal is another RA need where we see some variation in expert rankings. Upstream and natural scientists have the lowest ranking of this consideration (12 of 17), while downstream and social scientists have higher rankings (7 of 17 and 8 of 17, respectively).

Discussion

There has been limited work on the study of "disciplinary culture" as a factor in risk perception. Through interviews of a small sample of scientists ($n = 20$), Powell (2007) was able to show preliminary findings that disciplinary cultures of "upstream" and "downstream" expert position can influence risk perceptions. Specifically, downstream scientists are generally more concerned with human health and environmental risks from nanotechnology, another field of emerging technologies. Powell also suggests that experts who are "upstream" in the developmental process perceive less uncertainty with the technology than their "downstream" counterparts. When evaluating the expert responses to the risk questions, we see results that support Powell's findings. In this study, downstream experts also had greater uncertainty in risk perceptions as well as greater perceptions of potential human and environmental hazards than did upstream scientists.

In addition, this work also found differences in risk perceptions between natural science disciplines and social science disciplines. Our natural science experts stated lower expectations of human and environmental hazards than did our social science experts but also stated lower concerns regarding irreversibility of environmental effects and unmanageability of this technology. This dataset, though limited in size, supports "disciplinary cultures," as a component affecting risk perceptions, similar to our "cultural cognition" groups.

This also suggests that the two "axes" for "disciplinary culture" studied in this work of "discipline" and "position" both influence perceptions of risk and governance needs for this technology. Future research could evaluate the relative influence of each of these axes in overall perceptions of risks. Additionally, more specific measures of cultural cognition could be examined by administering a scaled test specific to cultural cognition among area experts.

One limitation of this work is the lack of targeted testing of the standard cultural cognition paradigm of group and grid preferences. Future studies that include specific measure of cultural cognition factors, in addition to disciplinary group factors, could be tested to explore the relative influence of each component in risk perception. Corley et al. (2009) tested nanotechnology policy opinions of expert nonscientists using explicit measures of some cultural cognition factors. They found that academic disciplinary grouping may influence experts' opinions regarding regulatory needs for nanotechnology, thus providing some support for cultural cognition influences in risk perception of emerging technologies.

From a theoretical perspective, this work seeks to begin a discussion on whether expert opinions of RA needs for SB are more aligned with the standard cultural cognition paradigms of group and grid preferences or with disciplinary culture. Practically, this work can help provide a framework for understanding how inclusion or exclusion of expert groups may bias or limit strategies for anticipatory governance. It shows how having a diverse group of upstream and downstream experts and natural and social scientists is likely to expand the conversation during deliberative assessments of technology and its oversight so that a full range of options is considered. According to postnormal science (Funtowicz and Ravetz 1992) and responsible research and innovation (Stilgoe et al. 2013), as well as recent National Academies of Science (2017) and International Risk Governance Council reports (2015), a broad inclusion of these perspectives is important for appropriate governance of synthetic biology which is accompanied by high complexity, novelty, and uncertainty.

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