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Evaluating the Use of System Mapping Tools to Support Researcher Understanding of Knowledge Diffusion in the Bio-economy

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Evaluating the Use of System Mapping Tools to Support Researcher Understanding of Knowledge Diffusion in the Bioeconomy

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Abstract

Surveys of bioengineering facilities within the bioeconomy highlight a limited diffusion of socio-technical knowledge and expertise about new innovations at the pilot and demonstration scales, compared to technical knowledge. To improve on this, it is critical to develop awareness among new technology developers about different stakeholders within the bioeconomy, as well as about the non-technical impacts of their work within a broader context. This paper describes a workshop with graduate bioengineering researchers. The use of system mapping tools for improving socio-technical knowledge diffusion at their bioengineering institute are evaluated. Participants were asked to describe the impacts of their research projects on non-technical stakeholders using system mapping tools in teams of 3-8 people. Each individual was also surveyed before and after the workshop to better understand their learning goals, projects, and awareness of system mapping. Structural coding was used to study resulting maps and survey data, against a conceptual framework for systems thinking. Most maps only focused on the diffusion of technical knowledge from the research field outwards to the public and assumed that good research from academia would lead to overall good in the system. Although most teams identified various stakeholders on their maps, only technical expertise was acknowledged across many of them. For the few instances where regulations, ethical, social, environmental and economic considerations were included on maps, this knowledge was considered as limiting technical research and scale-up and not supporting it. Participant surveys suggest that the application of mapping tools allowed them to shift into more holistic thinking about their roles and impact on biotechnology adoption. For some participants, this holistic view was encouraging as it moved them away from taking their impact too personally, to understanding that their work exists in a broader context of relationships and non-linear networks of causal effects. For others, the largeness of socio-technical implications felt overwhelming. Introducing system mapping topics to bioengineering students at a slower more gradual pace over multiple teaching events may improve this sense of overwhelm. In addition, using the conceptual framework as an explicit prompting device to structure mapping activities may address the ambiguity experienced by participants from task instructions at the workshop. As a next step, it would be interesting to facilitate this exercise with a group having more mixed stakes and roles, over multiple events or in a graduate course setting.

Introduction

Engineers have a unique role in designing and improving socio-technical systems. A system consists of both technical and social/contextual components as well as the relationships between these components [1]. Since these are interdependent, small interactions between system components can lead to large impacts. Positive change in a system may be enacted once these interactions and relationships are better understood [2]. Increasingly, there is emphasis on teaching systems thinking to engineers, so that they may better understand the broader impacts of the technologies they develop, and better share this understanding within multidisciplinary teams and with stakeholders [3].

Bioengineering is a discipline in chemical engineering that focuses on using microbial or enzymatic processes to transform biological material into industrial products [4]. These bio-based products are positioned as renewable alternatives to traditional petrochemical products [4]. Adoption of new biotechnologies and products may help us reduce greenhouse gas emissions, in line with the goals set out in global agreements on climate change management [5, 6, 7]. However, new biotechnologies often run up against a "valley of death" in their journey to public adoption; this is often attributed to lack of clear policy regulations, issues with land access, and poor public perceptions [8-11], among other factors. It is important that new biotechnologies be better understood by policy-makers, the industry, as well as consumers. Furthermore, surveys of bioengineering facilities within the bioeconomy highlight a limited diffusion of socio-technical knowledge and expertise about new innovations compared to technical knowledge at the pilot and demonstration scales of technology development [12]. Therefore, graduate students at these pilot and demonstration scales may benefit from understanding the socio-technical impacts of their work on broader audiences in the government, industry, and public sectors. Additionally, being able to communicate this learning within their teams and with stakeholders may help narrow gaps in new biotechnology adoptions.

System mapping tools are visualization techniques (such as iceberg models or causal loop diagrams) that offer a common vocabulary for people with different perspectives in a conversation [13]. Often with specific prompting structures, system mapping tools make use of systems thinking principles to highlight connectivity between components, illustrate causal links that perpetuate a system's behaviour over time, and uncover the implicit values or beliefs that hold these structures in place [14]. System mapping tools may be used to explore underlying structures and assumptions in the bioeconomy. This paper describes a workshop with graduate engineering students that applies two common system mapping frameworks to explore and understand the commercialization of bio-products in the Canadian bioeconomy (namely, actor mapping and causal loop mapping). The goal of the workshop is to evaluate the use of these system mapping tools for improving socio-technical knowledge diffusion and learning at a local bioengineering institute. The research questions guiding this work are:

1. What kinds of insights does system mapping allow graduate researchers to uncover about their own research's socio-technical impacts in bioengineering?
2. How might we improve the way we teach systems thinking to engineers?

Background on Systems Thinking

A systems philosophy can be characterized by the following primary orientations [15]:

- An understanding of interrelationships, the dynamics of which encompass an ontology
- A commitment to multiple perspectives, which reflect an epistemology
- And an awareness of boundaries and the acknowledgment of multiple perspectives, reinforcing the ethics of a systems philosophy

Learning about systems allows people within them to understand not just action and consequences but encourages them to reflect on the underlying structures and assumptions that lead to those actions and consequences [16, 17]. These underlying structures and assumptions are also sometimes called 'mental models.' A mental model is a representation of someone's perception of a system. It is an approximation of the real world that is generated through learning and informed by feedback [17]. Schön and Rein explore the extent to which it is possible to change mental models through reflection-in-action, which is described as: "the capacity of professionals to consciously think about what they are doing while they are doing it" [18]. Systems thinking may be understood as a practice of reflection-in-action to uncover underlying belief structures and governing variables within an organization/institution/or system. It has been described as a process of generating mental models that better align with real-world systems [19].

Four simple patterns to further describe systems thinking are presented by the Cabrera Research Lab at Cornell University [19]. According to Cabrera and Cabrera, these patterns (also known as the DSRP rules) must all exist together in a thought process in order for it to be described as systems thinking. They argue that systems in the real world can also be organized along these patterns. Learning to describe individual mental models using these patterns can therefore help increase model 'accuracy' with respect to the real world. These patterns are as follows:

- Distinctions: Any idea or thing can be distinguished from other ideas and things.
- Systems: Any idea or thing can be split into parts or lumped into a whole.
- Relationships: Any idea or thing can relate to other ideas or things.
- Perspectives: Any idea can be a point or a view of a perspective. How a system is organized from one perspective might not be the same from another.

Different stakeholders can come together to establish a shared understanding of complex systems by comparing their mental models. This process involves visualizing the aforementioned DSRP cognition rules that underlie their individual mental models and aligning them through team discussion to establish shared mental models [19.].

Conceptual Framework

Grohs et al. present a framework to apply systems thinking to ill-structured problems [20]. This framework was developed through a multidisciplinary exploration of literature on problem solving in engineering education, critical thinking in philosophy, and theories on leadership development and community building. The framework discusses three dimensions: problem, perspective, and time. According to Grohs et al. "These three dimensions…and their interactions [describe] elements of a systems thinking approach to problem-solving that is sensitive to the complex and ambiguous nature of wicked problems" [20]. The constructs associated with each of the dimensions are presented in the table below which summarizes the framework.

Table 1: The three dimensions of Grohs et al.'s systems thinking framework [20]

Grohs et al.'s Dimension	Problem Dimension	Perspective Dimension	Time Dimension
Purpose	Names technical and contextual elements that a problem exists in.	Elaborates how different stakeholders might be viewing the problem differently	Evaluates how historical interactions might influence the problem at present and into the future
Connection to systems philosophy	Awareness of boundaries	Commitment to multiple perspectives	Understanding of interrelationships
Constructs	Identification/ structuring Information needs Underlying assumptions Goal clarity / defining success Constraints/ resource adequacy Stakeholder identification Incorporation of stakeholder specific knowledge/expertise	Differential framing of problem/ goals Implementation challenges	Historical influences on problem formation Varied stakeholder involvement over time Short and long term effects Unintended consequences Feedback loop for planning and intervention

Workshop Design and Data Collection

The methods in this section have been previously reported [21]. Briefly, graduate students and researchers from a bioengineering center attended a 3-hour workshop. The 27 attendees included undergraduate interns, master's students, PhD students, post-docs, research associates, staff, and professors. Only individuals from the center were included in the study to focus on their specific perspectives. Participants were organized into lab-based teams, with larger teams split by research topics. Those who were not part of a specific lab group were formed into their own team.

The workshop began with a brief lecture on DSRP rules for systems thinking cognition, which were also used to frame the session activities. The mapping exercises were aimed at exploring the adoption of biotechnologies. Teams were given the overall goal of identifying barriers to scaling up their lab technologies to commercial scale. Participants were encouraged to consider non-academic perspectives on their research's reception by external stakeholders. The exercise prompts focused on map construction steps, allowing participants to interpret and illustrate their knowledge freely. They first mapped their projects and relevant actors/resources using the Plectica software and shared these actor maps in group discussions. Next, they created causal loop diagrams to explore bottlenecks in knowledge transfer and commercialization. After each activity, a class-wide debrief was held.

Participants were surveyed before and after the workshop to gather demographic data, personal learning goals, prior awareness of system mapping, and their own research context. Consent for data access was obtained during registration, and personal identifiers were removed before analysis. The maps they constructed at the workshop have been analyzed using Grohs et al.'s model in the Results and Discussion section.

Analysis Methods

A structural coding analysis was conducted to study the maps. First each map was read carefully to generate codes and to identify evidence of DSRP structuring. Then these conceptual phrases were grouped by each of the constructs from Grohs et al.'s model. If any of the constructs were not represented by any codes, that was also noted. From the overall groupings, descriptions of each construct were generated by highlighting similarities, differences and relationships between codes. These descriptions present insights about the problem, perspectives and time dimensions explored at the workshop about the biotechnology adoption system.

Results and Discussion

This section presents insights about biotechnology adoption that were expressed in the maps through an exploration of the mapping data along Grohs et al.'s dimensions, serving to address the first research question. The usefulness of the mapping tools and vocabulary (for e.g. using DSRP patterns for mapping exercises) in guiding student thinking along the associated dimensions in Grohs et al.'s conceptual framework is discussed. Potential modifications of workshop activities and system mapping tools to incorporate more of the constructs are suggested. That in turn addresses the second research question. A representative example of the maps that were drawn at the workshop is shown in Figure 1.

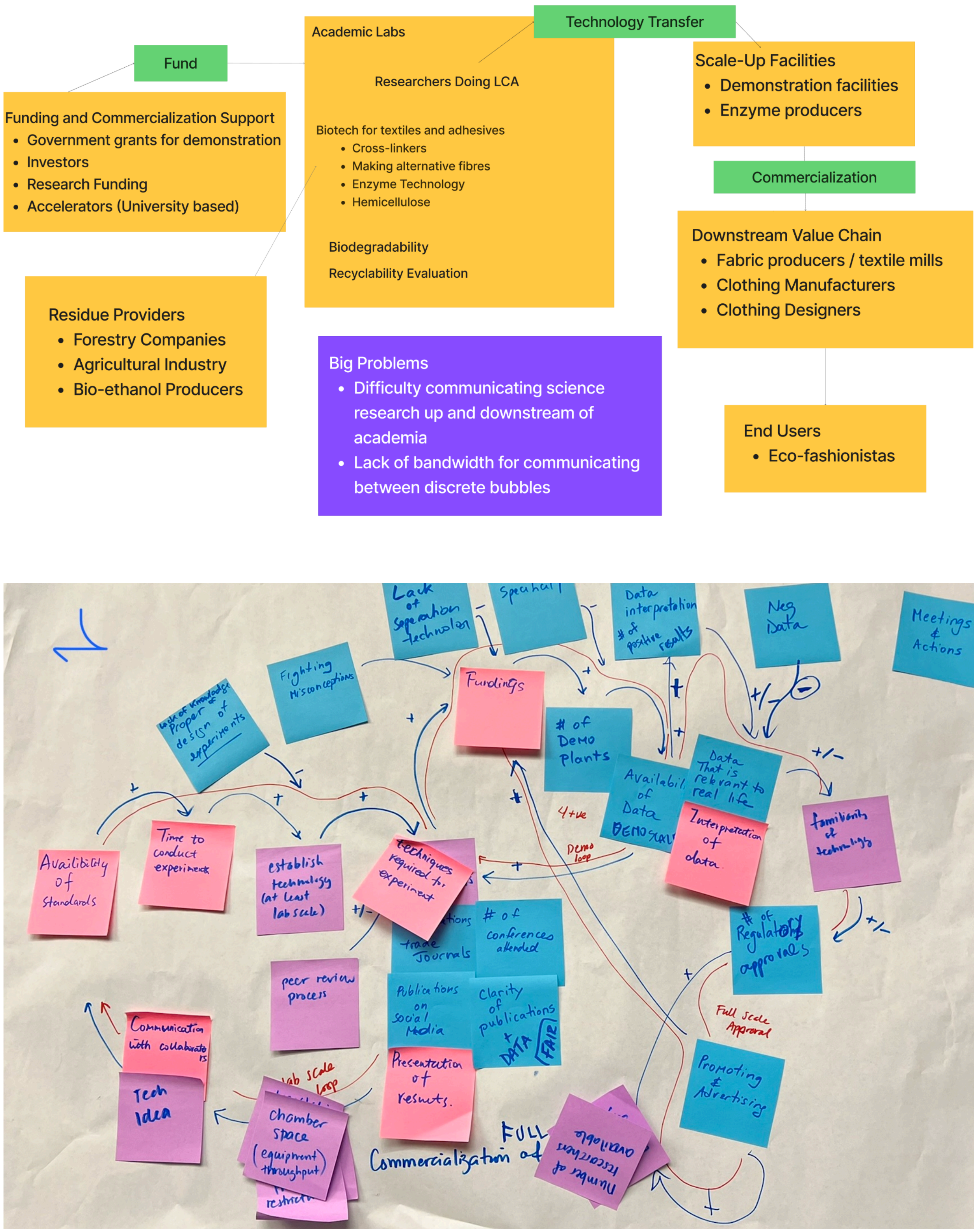

Figure 1: Sample actor network (top) and causal loop map (bottom) generated by participants.

Insights on Bio-product Commercialization from Maps

Figure 2 shows a summary of the constructs that were represented in the first set of codes for each of the maps (across the rows). Information on each of the dimensions in Grohs et al.'s model was then compared between the maps (down the columns 2) and is discussed below.

	Problem Dimension						
Map ID	Identification / Structuring	Information Needs	Underlying Assumptions	Goal Clarity/ Defining Success	Constraints / Resource Adequacy	Stakeholder Identification	Incorporation of Stakeholder Specific Expertise
A1	☑	☑	☐	☐	☑	☑	☑
C1	☑	☐	☐	☐	☑	☑	☑
A2	☑	☐	☐	☑	☑	☑	☑
C2	☑	☑	☐	☐	☑	☑	☑
A3	☐	☑	☐	☑	☑	☑	☐
C3	☑	☑	☐	☑	☐	☑	☑
A4	☑	☐	☐	☑	☑	☑	☑
C4	☑	☐	☐	☑	☑	☑	☑
A5	☑	☐	☐	☑	☐	☑	☑
C5	☐	☐	☐	☑	☑	☑	☐

	Perspective Dimension		Time Dimension				
Map ID	Differential Framing of Problem / Goals	Implementation Challenges	Historical Influences on Problem Formation	Varied Stakeholder Involvement Over Time	Short and Long Term Effects	Unintended Consequences	Feedback Loop for Planning and Intervention
A1	☑	☐	☐	☐	☐	☐	☐
C1	☑	☐	☐	☑	☑	☑	☑
A2	☐	☐	☐	☐	☑	☐	☑
C2	☑	☑	☐	☑	☐	☐	☑
A3	☑	☑	☑	☑	☑	☐	☐
C3	☑	☐	☐	☐	☑	☑	☑
A4	☑	☑	☐	☐	☑	☑	☐
C4	☑	☐	☐	☑	☐	☐	☑
A5	☐	☐	☐	☐	☐	☐	☐
C5	☑	☐	☐	☐	☐	☐	☑

Figure 2: Constructs represented in workshop maps. Map ID is constructed with a letter identifier for the type of map (A is actor network and C is causal loop diagram) and group number.

Overall, it was encouraging that almost all constructs were represented in the maps drawn at the workshop. This is a good indication that the mapping tools supported participants to shift towards systems thinking. This is also reflected in the shift in participant self-reporting on familiarity with systems thinking (Figure 3). Across the five teams, one addressed all but 1 of the constructs in their maps, three addressed 11 of the 14 constructs across their two maps, and one team addressed only 7 of the 14 constructs. A key takeaway that participants seemed to have from these mapping exercises is that consumers of biotechnology have a lot of influence over where funding and policy supports are applied in their research sectors, and that in turn has a huge impact on the degree to which researchers' work gets translated and commercialized.

Problem Dimension: Taken together, actor maps identified knowledge transfer and funding as main problems. The causal loop maps presented specific barriers that impacted knowledge diffusion, namely suggesting that the public has misperceptions about the bioeconomy and its actual sustainability impact. Some maps went further than others when discussing goal clarity/successes. Most maps defined success from the technology developer/researcher's perspective, and a few also added environmental or economic metrics for success for other stakeholders. Surprisingly, no assumptions were acknowledged in any of the maps, and few identified limitations/information needs. However, all of the maps did include stakeholder identification, with researchers, funding groups, and policy makers recognized by all. A few maps also recognized the environment, and technology artifacts as stakeholders. Consumers of technologies were defined differently based on what scope was selected by each group. Most maps made a distinction between technical knowledge and business/policy knowledge, but only one mentioned community knowledge. In general, increasing the variety and number of stakeholder relationships seemed to help people better identify how knowledge exists and moves in this system.

Perspective Dimension: Only three of the maps included some form of perspective based framing and acknowledged the impact of different perspectives on the map. Typically, these maps would discuss public (mis)perceptions about the bioeconomy due to misinformation through the media and how this hindered technology adoption as there were no market incentives to drive funding or policy support towards new biotechnologies. Alternatively, one of the three maps framed this same dynamic more positively, saying how good science engendered public trust and that in turn facilitated more funding support and industry interest in projects. All but two maps identified implementation challenges that resulted from differences in perspective such as disconnected networks, intellectual property issues, public perception and bias, as well as ethical concerns. Examples of outcomes from these challenges that were included on the map are: limited access to scale-up facilities and demonstration data, information transfer hindered by the looming threat of getting scooped, (mis)interpretation of data in promotion/advertising, public having NIMBY mindsets, and biased media hype around what is a good technology or a big enough problem to address.

Time Dimension: Few historical influences were identified on maps. However, the causal loop maps did indicate varied stakeholder involvement over time, stemming from factors such as evolving interests, intellectual property filings, and trade secrets. Staff turnover at research groups was also highlighted, underscoring the loss of technical knowledge over time. Three maps revealed unintended consequences of knowledge diffusion, impacting researchers directly. For instance, the risk of getting scooped despite increased publications boosting public demand for biotechnologies was frequently illustrated. This sparked discussions on intellectual property profit culture and alternative dissemination methods to foster collaboration.

Unintended consequences to the environment and society were rarely illustrated on the maps. Few diagrams addressed the end-of-life for bio-products, raising concerns about perpetuating linear consumption models under the guise of sustainability. Feedback loops in the causal loop maps helped participants speculate on future planning, while it was harder to do so using actor maps. One group did note how public feedback influences research priorities on their actor map, a mechanism that was repeated across most of the other causal loop maps with variation in detail.

Comments on Mapping Process and Overall Themes

A key process insight from assessing the problem dimension across the maps is that both the actor mapping and causal loop diagramming tools did not push participants to explain their own assumptions or pause to consider/collect the information they did not have access to. To a degree this makes sense; time constraints in the workshop did not leave much opportunity for secondary research. Although most teams identified stakeholder expertise and knowledge, it was also surprising that only technical expertise was considered in many of these cases. Most maps only focused on illustrating the diffusion of technical knowledge from research fields outwards to the public and assumed that good research from academia would lead to overall good in the system. For the few instances where regulations, ethical, environmental and economic considerations, and feedback from the public were included on the maps, this expertise was considered as limiting technical research and scale-up and not supporting it or informing it. In general, these observations make sense because people are more comfortable speaking to their own skills and were not prompted to consider stakeholder expertise from other disciplines explicitly in the assigned tasks. It is troubling that most participants did not question whether their own assumptions were impacting the way they framed the system so similarly across the class. Despite a focus being placed on all four of the DSRP patterns in systems thinking during the workshop, external perspectives were rarely highlighted.

Participant Self-Reporting on Learnings from Survey Data

Of the 27 participants, 23 completed the pre-workshop survey, and 18 completed the post workshop survey. There were 16 people who completed both the pre- and post-workshop surveys. Only specific questions are discussed below, to better focus the discussion on the second research question of this study.

Figure 3 illustrates the pre- and post-workshop survey response to the Likert-scale rating of participant familiarity with systems thinking. For the 16 participants who completed both surveys, the average Likert-scale rating increased from 2.19 to 4.75 on a 7-point scale after the workshop, where 1 is not familiar at all, 4 is somewhat familiar and 7 is expertly familiar. Including the unpaired respondents, these averages are 2.22 on the pre-workshop survey, and 4.72 on the post-workshop survey. All but one of the paired respondents reported an increase in familiarity after the workshop: the one individual who did not report a change, rated their familiarity at a 6 out of 7 both times.

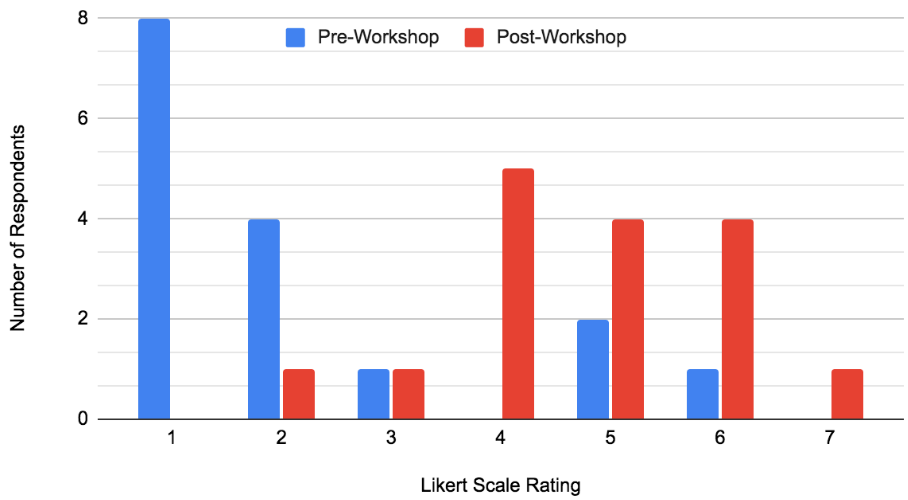

Figure 3: Participant familiarity with systems thinking (n=16), self-rated rated out of 7, where 7 is expertly familiar and 1 is not familiar at all.

In their post-workshop survey responses to qualitative questions on whether their learning goals and expectations were met, all but two participants expressed satisfaction or enthusiasm, and some reflected on workshop content. Although most answers were quite general, more specific responses focused on how system mapping tools allowed participants to explore the context of their research (n=5), as well as different perspectives (n=2) and relationships (n=2) in the biotechnology research sector. This is valuable because it shows how participants self-describe their experience of learning at the workshop across two of the three dimensions in Grohs et al.'s model (problem and perspective). As well, these descriptors align with the ontology, epistemology and ethics of a systems thinking practice, as described in the background section. Only one out of the 18 post-workshop survey respondents expressed disappointment with the workshop, saying how they thought they would learn about the bioeconomy, but that they did not.

Some questions were repeated between the pre- and post- workshop surveys, with a note appended to them in the latter survey that asked respondents to integrate any learnings from the workshop. Responses to these questions allowed an indirect interrogation of the extent to which participants were able to apply learnings from their workshop. Findings from one of the repeated questions is compared across the 16 paired responses; table 2 below contains representative samples from the response set.

Table 2: Characteristic responses to the question “How would you describe the potential impact of your research/work, as well as the challenges in the way of achieving that impact?”

Category of response	Pre-Workshop Survey Response	Post-Workshop Survey Response
Answered different part of the question (n=2)	Sustainable engineering is always a hard sell to industry stakeholders and can also be met with resistance from the general public, due to fear of "THE NEW" or the Unknown. (challenge)	Reduction in humanity’s carbon footprint, GHG emissions, and increasing sustainability of the bioeconomy.
Thinks/reflects on general learning at workshop, but doesn’t answer direct question (n=3)	I think the impact of my work will be a benefit to local people who are suffering from chemical contaminants. The big challenge is to achieve the goal cost-effectively.	It is a very useful workshop. I learned how to use these factors to continue my research [in] a more logical and organized way.
Different details addressed (n=4)	Reducing wasted biomass and creating low carbon products	Allowing others to see the use of sustainable technologies in product development and influencing purchasing choices
More specific response (n=3)	Making money saving the environment	Remediating water laden with heavy metals, and addressing the heavy metal shortage crisis
Broadened to integrate workshop learnings (n=3)	It’s a small step or push in the right direction, but will not solve the complex problems within the environmental remediation space. I am very focused on a few enzymes or reactions, whereas this research space has thousands of potential pollutants for degradation	I think it was interesting in our causal loops to discuss how much of an impact funding has on our research, but then also how public perception of environmental remediation and contaminants changes our research. If a new pollutant comes to the forefront, then we may lose funding on current projects.

No responses to this question were unchanged between the pre- and post- workshop survey. At a bare minimum, since the question had two components, participants just answered a different part of the question in their second response. Some participants opted to change their response to one of the two components but kept the other one unchanged. The shifts in their answers addressed a different impact/challenge than the one they had previously described. For instance, if a participant had more environmental impacts highlighted in the pre-workshop response, they opted to highlight more social or economic aspects in their post-workshop response to the same question. This suggests that the workshop might have helped them consider alternative perspectives while thinking about their work’s impact and challenges. It also might have helped them build more awareness about different perspectives. For three participants, the specificity of the response increased, but the topic remained unchanged. Another three did not address the questions directly in their post-workshop survey but instead reflected on the usefulness of the workshop material. And the final three participants incorporated learnings from the workshop to change the structure of their response. Instead of responding descriptively, they wrote out feedback loops, suggesting dynamic thinking in connection with Grohs et al.'s time dimension.

Since there is a shift in how participants responded to the same question after the workshop, it can be inferred that the intervention encouraged participants to think differently. Since there are respondents who incorporated systems thinking concepts or broadened the scope of their answers (incorporating non-technical impacts), it is suggested that a single workshop session on systems thinking may be useful in supporting holistic thinking and learning about the bioeconomy. The caveat here is that there were just as many people whose responses did not change, either because of time constraints or a misunderstanding of survey questions and workshop tasks. Nevertheless, many of the responses address different dimensions of the conceptual framework, which is encouraging. Many participants also report having learned new ways to think about their work in the biotechnology sector.

Overall, from participant feedback and teaching observations, it was found that the application of mapping tools at the workshop allowed participants to shift into more holistic thinking about their positions and impact on biotechnology development and adoption. For some people, this holistic view was encouraging as it moved them away from taking their impact so personally, to understanding that their work exists in a broader context of relationships and non-linear networks of causal effects. For other people, the largeness of socio-technical implications felt daunting. This may be a limitation of how little time the participants had during the three-hour session. Introducing system mapping topics to bioengineering students at a slower more gradual pace over multiple teaching events may improve this. In addition, using the conceptual framework as a prompting device in future iterations of the workshop is recommended. This could help address the ambiguity experienced by participants from the task instructions while building maps.

Study limitations

The generalizations that can be made about survey answers are limited, because of how small the sample of respondents is. This was a single workshop event spanning three hours. The short amount of time and the relatively small number of people overall limits the conclusions that can be drawn about any long-term learning and impact. Additionally, the composition of the group was also pretty narrow, with all the participants working at the same institute and with very similar backgrounds in academic research. Therefore, these findings cannot be applied to researchers in other contexts outside of academia. Furthermore, the maps that are drawn at the session are inherently incomplete. This was because the aim of the study was to find added insights but not to generate a detailed or accurate assessment of barriers to technology adoption. As a result, key factors impacting scale-up of biotechnologies are quite likely missing, and the map findings should be considered in context of the broader body of literature around technology scale-up, commercialization, and adoption that already exists elsewhere.

Next Steps

Through an evaluation of system maps against Grohs et al.'s conceptual framework, this work explores gaps in the participants' knowledge about commercialization within the bioeconomy. These gaps may later be addressed by introducing mapping concepts to the graduate curriculum through a course. It was found that different mapping tools allow participants to focus readily on different aspects of the system; therefore, a combination of tools is more useful than using just one of them. As well, more explicitly introducing the three dimensions of Grohs et al.'s conceptual framework (i.e. problem, perspective, and time) to participants could be useful in future exercises, since it would help to balance the complexity of the research questions. Although the mapping tools offer specific instructions on how to organize information, it is still important to supplement these organizational instructions with content-specific information and knowledge. This might be achieved in the future through more active engagement of multidisciplinary collaborators. It would be interesting to facilitate this exercise with a group having mixed stakes and roles. Diverse groups with representation from the industry or government, as well as people in academia, would likely have a harder time arriving at a synthesis at a short workshop. However, with a course-based offering of system mapping tools for graduate students, industry collaborators can be engaged as guest speakers and lecturers over a longer term, similar to what is done in the undergraduate course on system mapping at UofT.

Conclusion

This paper discusses a participatory system mapping workshop at a local research center that was designed to explore how graduate researchers in bioengineering experience barriers to knowledge dissemination from the academia out to the public. Their maps highlighted the importance of consumer demand to drive funding and resources towards new research projects. Participants expressed concerns about consumer misperceptions of new biotechnologies. Overall, the application of system mapping tools allowed participants to grow their shared understanding of knowledge diffusion in bioengineering at the session. It also encouraged them to consider the socio-technical implications of their research, in addition to the technical ones. The workshop shows promise of how supplementing the bioengineering curriculum at the graduate level with system mapping tools can encourage more holistic learning among students.

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Appendix A:

A detailed agenda outline for the workshop is shown below, adapted from [21]:

Activity (Duration)	**Notes**
Set-up (10 min)	Extra time to submit pre-workshop survey (QR code)
Introductions (20 min)	Acknowledgement for research participation, icebreaker activity
Presentation (15 min)	Intro. to volunteer observers Systems thinking motivation Definitions Example (i.e. policy recommendations for gene drives) Plectica software tutorial
Mapping Activity #1 (40 min)	Guided actor-network mapping exercise via Plectica 1. Individual brainstorm of nodes online (10 mins) 2. Pair up to group/organize nodes (10 mins) 3. Identify/label relationships in teams (10 mins) 4. Elicit and record insights in teams (10 mins)
Short break (5 min)	Buffer time
Class Discussion (15 min)	Ask each group to share their experience + insights with room Focus on things they are now curious about and how their thinking is shifting
Mapping Activity #2 (30 min)	Causal Loop Mapping 1. Identify changing elements that impact the flow of knowledge on separate sticky notes (5 mins) 2. Draw causal links (based on secondary research conducted in situ - 10 mins) 3. Identify feedback loops (5 mins) 4. Track knowledge dynamics - and identify insights (10 mins) Alternative: Continue actor mapping - second iteration
Short break (5 min)	Buffer time
Class discussion (15 min)	Ask each group to share their maps and insights with room Prompt them to pay attention to map's organization as well as content
Closing Remarks (10 min)	Connection to facilitator's research Levers of change + system interventions
Closing (15 min)	Share post-workshop survey QR code Observer's leave for facilitator reflection activity

Appendix B:

Pre-workshop Survey Questions:

1. Enter a pseudonym for yourself below. Please record this name somewhere safe since you will need it again to fill out the post-survey. This is to help us link your responses anonymously.
2. Role: PhD student/MASc student/Supervisor/Staff/Undergraduate student
3. Gender
4. Do you identify as belonging to a racialized group?
5. What are your expectations and intended learning goals for this workshop? Consider what got you interested in attending the event.
6. Describe your main project/work in the bioeconomy space (2-3 sentences).
7. How would you describe the potential impact of your research/work, as well as the challenges in the way of achieving that impact?
8. How familiar are you with Systems Thinking?
9. (1 bulb = not at all familiar, 4 bulbs = somewhat familiar, 7 bulbs = expertly familiar)
10. Please elaborate (on what you know about systems thinking, where you learned it and/or how you have seen/applied it in the past).
11. Any additional comments/questions/accommodation requests?

Post-workshop Survey Questions:

1. Enter your pseudonym. This should be the same one that you used for your pre-survey submission
2. How did the workshop today meet your intended learning goals? Please elaborate.
3. Describe your main project/work in the bioeconomy space (2-3 sentences, integrating learnings from the workshop, if relevant).
4. How would you describe the potential impact of your research/work, as well as the challenges in the way of achieving that impact? (integrate any relevant learnings from the workshop)
5. What elements of your training/prior experiences did you draw on to help you today? Were there any experiences that you were not able to share/articulate using the mapping tools?
6. How familiar are you with Systems Thinking? (1 bulb = not at all familiar, 4 bulbs = somewhat familiar, 7 bulbs = expertly familiar)
7. Please elaborate
8. On a scale of 1 to 7, how comfortable would you be explaining systems mapping concepts to someone else (e.g., a colleague or student at your lab who could not attend the workshop today)? 1= not at all comfortable; 4= somewhat comfortable; 7 completely comfortable
9. Please elaborate.
10. What new insights have you gained about the circular bioeconomy? Which parts of the workshop supported you in uncovering these insights?
11. Additional feedback on the content and delivery: 1) What is one thing you would suggest we avoid doing next time, one thing we should keep doing, and one thing we should start doing for this workshop next time?