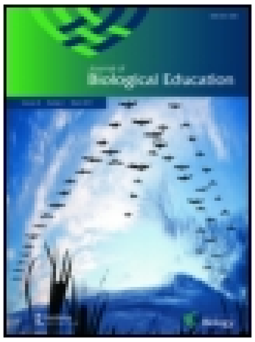

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Hybrid thematic analysis reveals themes for assessing student understanding of biotechnology

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Hybrid thematic analysis reveals themes for assessing student understanding of biotechnology

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ABSTRACT

Despite efforts to increase teaching of biotechnology worldwide, there are concerns that public literacy of genetic technologies remains insufficient. Improved education strategies are expected to empower individuals to make informed decisions about biotechnology. To evaluate the teaching and learning of this complex topic, qualitative assessment tools are needed. In this case study, we performed a hybrid thematic analysis to identify a set of overarching themes that can be used to evaluate individuals' understanding of genetic technologies. We analysed the written justifications students gave for their attitudes on a range of genetic technologies, before and after peer-led discussion of each topic. We identified seven themes commonly detected in student responses, five of which have been previously described in studies of mass media communication of biotechnology. Our preliminary analysis suggests that peer-led discourse can promote changes in student understanding of biotechnology. We conclude that hybrid thematic analysis is a useful approach for evaluating the teaching and learning of genetic technologies. We discuss the utility of the hybrid approach and the themes described here for future studies of biotechnology education.

KEYWORDS

Biotechnology education; biotechnology literacy; genetic technologies; thematic analysis; peer discussion

Introduction

Biotechnology has been widely applied in agriculture and medicine, and it holds promise for other applications including energy and the environment (Gaskell et al. 2010). Yet many biotechnology applications, such as genetic engineering of plants and animals or human embryo gene editing, have social and ethical implications. The rapid speed of biotechnology development likely precludes most individuals from attaining expert knowledge (Gardner and Troelstrup 2015). Accordingly, recent evidence suggests that students' behavioural intentions towards biotechnology applications, such as intent to purchase foods derived from genetically engineered crops or to allow access to personal genetic information, are more strongly associated with cognitive elements – beliefs and thoughts – than with knowledge itself (Fonseca et al. 2011). An important goal for educators, then, is to promote *literacy* of biotechnology, which includes 'the skills of critical discrimination and the abilities and desire to take part in decisions about biotechnological issues' (Gonzalez et al. 2013).

Despite efforts to increase teaching of biotechnology worldwide (Fonseca et al. 2011), there are concerns that public literacy of biotechnology remains insufficient (Bowling et al. 2008; Fonseca et al.

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2011; Gardner and Troelstrup 2015; McFadden and Lusk 2016). For example, it was recently reported that 39% of American adults believe that genetically modified (GM) foods (i.e. foods derived from crops that have been genetically engineered[1]) are worse for health than non-GM foods (Pew Research Center 2016). This is at odds with the evidence-based conclusions of numerous scientific organisations, such as the American Association for the Advancement of Science, American Medical Association, World Health Organization, U.S. Food and Drug Administration (FDA), Health Canada, U.S. National Academies of Sciences, Engineering, and Medicine, French Academy of Science, International Society of African Scientists, Union of German Academies of Sciences and Humanities, and International Council for Science, to name a few. In particular, the U.S. National Academies of Sciences, Engineering and Medicine recently determined that there is 'no substantiated evidence of a difference in risks to human health between currently commercialized genetically engineered (GE) crops and conventionally bred crops' (National Academies Press 2016). Better education practices may lessen the dissonance between scientific evidence and public opinion on GE foods and other controversial biotechnology applications. To achieve this goal, educators must assess which methods for advancing biotechnology literacy are most effective.

Many previous studies have assessed student knowledge and attitudes of biotechnology using Likert-type scales (symmetric agree-disagree scales used to capture the intensity of a response) that generally indicate whether a person approves or disapproves of a particular application (Dawson 2007; Gardner and Troelstrup 2015; Osborne, Simon, and Collins 2003). Although validated Likert-type instruments provide a reliable measure of biotechnology knowledge or attitudes, they ultimately limit the range of subjects' responses. This can be problematic for assessing conceptual understanding of biotechnology in a continuously changing social and technical climate. Therefore, adaptable, qualitative approaches to evaluate biotechnology understanding are warranted.

Qualitative approaches have previously been used to characterise common 'frames' or 'themes' evident in student arguments about biotechnology applications (Dori, Tal, and Tsaushu 2003; Olsher and Dreyfus 1999; Sadler and Fowler 2006; Seethaler and Linn 2004; Simonneaux 2001). However, the scope of these studies was often limited to a single biotechnology application and none used a deductive approach – that is, their qualitative analyses were not informed by existing literature or theory. To our knowledge, a set of overarching themes relevant to general biotechnology understanding has not been published.

In this case study, we used a descriptive and interpretive approach – modelled after the hybrid thematic analysis described by Fereday and Muir-Cochrane (2006) – to characterise students' conceptual understanding of biotechnology. The written justifications students gave for their binary attitudes on a range of genetic technologies served as our sampling units. We postulated that a hybrid approach is advantageous because it integrates themes described in related literature with those that emerge from the data at hand. We tested the ability of this method to evaluate the impact of peer-led discourse on student understanding of biotechnology in a course designed for non-science majors.

We identified a set of seven themes commonly detected in student responses, five of which have been described previously in studies of mass media communication of biotechnology (Maeseele 2011; Navarro et al. 2011; Nisbet and Lewenstein 2002; Nisbet and Scheufele 2009). We applied these themes in a preliminary analysis, and found evidence suggesting that peer-led discourse of evidence-based information influences student understanding of genetic technologies. We conclude that hybrid thematic analysis is a useful approach for assessing students' understanding of biotechnology. The set of themes we describe here may serve as a template in future studies.

Methods

Study design

This study took place in a naturalistic setting – the course, instructors and students were not manipulated in any way. The study involved a general elective 'Genetics and Society' course taught as part

Table 1. Description and demographic information for the study.

Student category	Total (%)
Class size	
Originally enrolled	61
Completed course	56
Participated in study[a]	53 (94.6)
Demographics of students in study	
Females	33 (62.3)
Age <20	46 (86.7)
Freshmen	37 (69.8)
STEM majors	34 (64.1)

[a]Number of students completing the course who participated in the initial surveys.

of a larger Science and Society programme during the Fall quarter, September–December 2015, at a large, land-grant university in the western U.S. The course goals, as stated in the syllabus, are: (1) To provide non-science majors with the basic concepts of genetics and modern methods of biotechnology; (2) To educate students in the process of scientific discovery; (3) To empower students to evaluate for themselves the present and future impact of genetics on society. The instructor, a plant geneticist, had taught the course for 18 years. Both the graduate teaching assistant and the assistant lecturer had previously taught the course. We selected 'Genetics and Society' for our study because non-major science courses have been recognised as a ready opportunity to promote literacy of genetic technologies (Bowling et al. 2008). The surveys and procedures were reviewed and approved by the governing institutional review board (IRB ID 804400-1).

Participants

Students were selected based on their course enrolment. Students were given course credit for their participation in the initial surveys (one biotechnology positions survey and one background survey), and for their written summaries of the discussion sections. Of 56 students who completed the course, 53 participated in the surveys (94.6%). The students (62.3% female) were mostly freshman (69.8%). Although the course is designed for non-science majors, a large proportion of the class (64.1%) was or intended to be science, technology, engineering, mathematics (STEM) majors (Table 1). However, because the vast majority (84.9%) of participants were freshman and sophomores, it is likely that most students had not taken many upper division biology or genetics courses prior to participating in the study and had comparable levels of biotechnology knowledge.

Discussion sections

Group project work and classroom debate have been proposed as strategies for effective teaching of biotechnology and other socioscientific issues (Dawson and Venville 2009; Sadler and Donnelly 2006; Simonneaux 2001, 2002; Thomas et al. 2001). The educational intervention (referred to hereafter as the 'discussion section') evaluated in this study was a once-weekly, student-led seminar that utilised evidence-based education strategies including peer discussion, whole-class discourse and context-based teaching (Bennett, Lubben, and Hogarth 2007; Osborne 2010; Smith et al. 2009). The discussion sections (50 min each, once per week, seven weeks total) supplemented three hours of weekly lecture, and have been a course component for over 15 years. Attendance at discussion sections was mandatory for the entire class.

During each discussion section, an 'expert' panel of 6–10 students presented on a biotechnology topic and led classroom discourse. The panel topics were chosen prior to the beginning of the course by the instructors, based on relevant scenarios upon which a citizen might be expected to vote or make personal decisions (see Figure 1 and Table 2 for discussion topics). Students self-selected the panels on which they presented. Each student presented as an expert only once; the rest of the time, they were

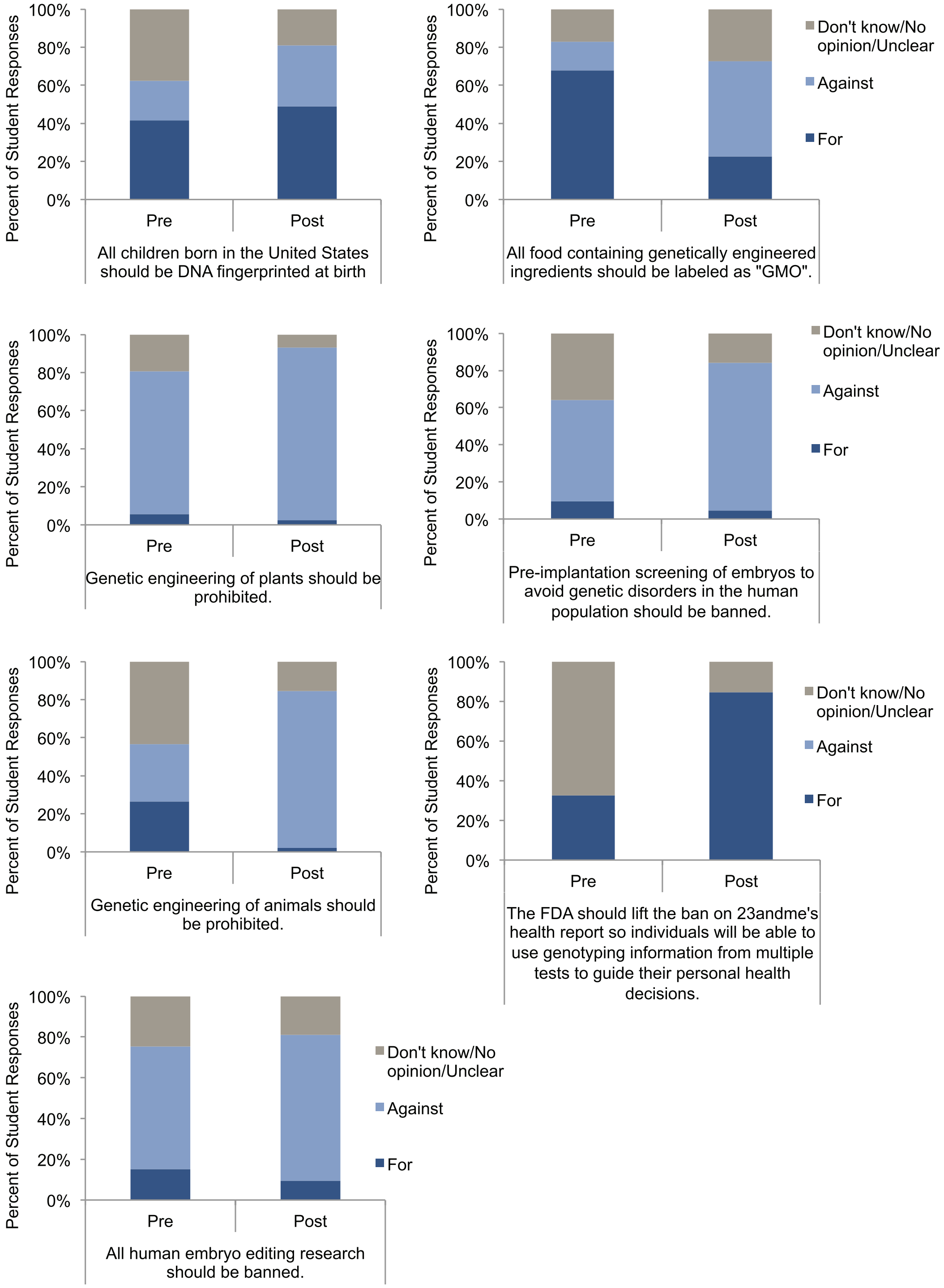

Figure 1. Comparison of students' binary positions before and after discussion sections for seven biotechnology topics.
Notes: Bar graphs represent proportion of student responses in three categories – *Don't know, Against, For*.

required to attend discussion sections as an audience member. A different topic was presented each week; seven topics were presented in total.

Table 2. Statistical analysis of students' binary position changes following discussion sections. Notes: Results of Fisher's sign test on directional change in student positions following discussion sections. A position shift towards 'For' was assigned 1 while a shift towards 'Against' was assigned −1.

Discussion topic	p value (Fisher's sign test)
1. All children born in the United States should be DNA fingerprinted at birth	0.42
2. All food containing genetically engineered ingredients should be labelled as 'GMO'	$8.05 \times 10^{-7,\#}$
3. Genetic engineering of plants should be prohibited	0.02
4. Pre-implantation screening of embryos to avoid genetic disorders in the human population should be banned	0.04
5. Genetic engineering of animals should be prohibited	$3.40 \times 10^{-5,\#}$
6. The FDA should lift its ban on 23andme's health report so individuals will be able to use genotyping information from multiple tests to guide their personal health decisions	$2.38 \times 10^{-7,\#}$
7. All human embryo editing research should be banned	0.65

[#]Below Bonferroni adjusted p value of 0.007 for multiple comparisons.

Prior to their presentation, each panel member was required to select two science-based articles that related to their topic and provide a short summary (3–4 sentences) for each reference. The assistant lecturer and graduate teaching assistant reviewed these sources for scientific credibility (i.e. published by peer-reviewed scientific journals, reputable science organisations, or federal agencies). If articles were obtained outside these sources, students were required to find new articles until reliable sources were obtained. The purpose of this exercise was to enable students to identify peer-reviewed, evidence-based information.

During their presentation, each panel gave relevant background, arguments for, and arguments against the position statements for their topic for 20–25 min. Relevant sources were cited when available. The remaining time (~25 min) was dedicated to whole-class discourse between the panel and the audience. The presentations contained no slides, but chalkboard notes were allowed. Every member of the panel was expected to read the other members' selected papers prior to the presentation. Panellists were graded based on individual and group preparedness, allocation of responsibilities, quality of references, delivery and quality of content, and ability to lead the discussion and answer questions. The instructor and graduate teaching assistant only moderated where necessary (i.e. if incorrect information was given or if the panel or audience stopped asking questions).

All other students participated as audience members. The audience was expected to observe the panel's presentation and to engage in discourse following it. At the end of each discussion section, each audience member was required to submit a written summary describing at least two points that were raised by the panel, with one to two sentences describing each point. Audience members were also required to provide a statement of their final position on the topic with justification. Audience members were given participation credit for their summaries. Participant attendance at weekly discussion sections was 97.0% ± 2.1% (presenters and audience combined; weekly average mean ± SD), with an average of 43.9 ± 1.3 (weekly average mean ± SD) audience members per week.

Data collection

Pre-discussion responses

In the first week of the course, students were sent links to two optional online surveys via the course management system. The first survey asked students to indicate their positions, measured as binary categorical attitudes, on seven biotechnology issues. The issues were the same as the topics for the discussion sections. Students could select 'Agree,' 'Disagree' or 'Don't Know' for each of the seven position statements (see Figure 1 and Table 2 for discussion topics). The survey asked students to briefly justify each position in ~1 sentence. The second survey contained questions regarding students' backgrounds. Students completed the surveys on their own time outside of class and without time restrictions, but prior to the first discussion section.

Post-discussion responses

Immediately following each weekly discussion section, student audience members submitted written summaries containing final positions on each topic, with justification for positions. Summaries were collected only from audience members (i.e. panellists did not submit final summaries for their respective topics). We chose not to include panellists' final positions for two reasons: (1) they had self-selected their presentation topic, and (2) they had researched the topic prior to the discussion section, to prepare for their presentation. Therefore, it is likely that the panellists' incoming knowledge and attitudes were different than those of their peers in the audience. Post-discussion responses were coded by the first author to obtain final student positions.

Qualitative analysis of position justifications

The short, written justifications given by each student to support their positions served as the sampling units for the qualitative analysis. A hybrid approach, modelled after the inductive-deductive thematic analysis method described by Fereday and Muir-Cochrane (2006), was used to identify common themes in student responses before and after four of seven discussion sections (selection of discussion topics described in Results). The thematic analysis began with a literature search to develop an a priori coding template (Fereday and Muir-Cochrane 2006). Multiple studies that categorise student arguments or mass media framing of biotechnology have been published (Dori, Tal, and Tsaushu 2003; Maeseele 2011; Matthes and Kohring 2008; Navarro et al. 2011; Nisbet and Lewenstein 2002; Nisbet and Scheufele 2009; Olsher and Dreyfus 1999; Sadler and Fowler 2006; Seethaler and Linn 2004; Simonneaux 2001). We found that most of the education studies assessed arguments regarding only one or a few specific biotechnology applications, and there was minimal overlap between the sets of themes described in these studies. On the other hand, the studies on representation of biotechnology in the media considered biotechnology much more broadly and exhibited substantial overlap in their framing typologies. We selected the four most similar typologies from mass media communication studies (Maeseele 2011; Navarro et al. 2011; Nisbet and Lewenstein 2002; Nisbet and Scheufele 2009) to inform an a priori template (i.e. preliminary set of themes) for the qualitative analysis.

We first tested the applicability of the a priori themes to the data-set (Fereday and Muir-Cochrane 2006), and we found that many themes were applicable. Using the a priori template as a guide, the data were summarised through an iterative process in which literature-derived themes were applied while emergent themes were accommodated. As stated by Fereday and Muir-Cochrane (2006), 'Analysis … at this stage was guided, but not confined, by the [a priori themes].' Once the data were thoroughly evaluated and all applicable themes (both a priori and emergent) collated, these preliminary themes were compared and collapsed where appropriate, through a second iterative process. A final set of themes was then established, which included succinct descriptions for each (Fereday and Muir-Cochrane 2006). The final coding was performed twice, blind to all previous assessments, to establish intra-coder reliability (Sadler and Zeidler 2005). Each sampling unit could be assigned more than one code in the final analysis. Once coding was completed, the two rounds were compared. If discrepancies were identified between the two rounds of coding, the sampling unit in question was carefully re-assessed to make a final decision. All qualitative analyses were performed by the first author.

Because the field is rapidly changing, we sought to share common themes that are relevant to biotechnology in general, rather than specific to individual applications. We therefore selected themes for final presentation in this study based on two criteria: (1) Each theme had to be detected in >1 discussion section; and (2) Each theme had to be present in ≥5% of all sampling units. These criteria were met by seven themes (Table 3).

Statistics

The impact of each discussion section on students' binary positions was assessed by Fisher's sign test (Fisher 1935) (Table 2). A position shift towards 'For' was assigned 1 while a shift towards 'Against'

Table 3. Summary of themes identified in student responses on biotechnology applications. Themes identified using the hybrid thematic analysis approach described by Fereday and Muir-Cochrane (2006). Note: Most themes do not necessarily indicate valence (i.e. approval or disapproval).

Theme	Description	Examples from student justifications
Progress	• Advancing research, health, food system • Improving quality of life for animals or humans • Or, relating to reversal of progress	Animal genetic engineering should not be banned. There are many benefits to GE animals, especially in terms of pharmaceuticals. Similar to GE plants, genetically engineering animals is a faster way to do the same things as traditional breeding Human embryo editing has the potential to advance human knowledge and save people from genetic diseases
Economic	• Benefits or costs to economy at large • Benefits or costs specifically to consumers or farmers	There should not be a requirement that companies label genetically modified foods … such a measure would likely increase food prices I think that there should not be a ban on animal genetic engineering … it could help the economy by reducing the prices of animal products because of an increase in supply
Morality/Ethics	• In terms of 'right' or 'wrong' • Respecting or crossing thresholds or boundaries • Taking things too far • Moral imperatives or relative ethics • Relating to animal or embryo abuse or welfare	In my opinion GE animals should not be prohibited …I believe it's more ethical to have animals die than humans in testing I think that ultimately, human embryo editing research should be banned …When you mess with an embryo, you are messing with a human life. Additionally, you are making a decision for someone who is unable to make it themselves
Middle way/Alternative path	• Finding a compromise • Often regarding regulation • Issue is not black or white • Considering technologies on a case-by-case basis	I believe individuals should be [DNA] fingerprinted at birth, but this database should be subject to strong laws protecting privacy and access I believe that gene embryo editing should not be banned, but instead regulated so that it only focuses on health risks
Scientific validity/ uncertainty	• Supporting or calling into question scientific consensus or expertise • Most often regarding safety or allergies • Cites known technological limits	DNA fingerprinting can be used as an absolute in the court of law. However, there are many discrepancies, such as human error and human tampering, that could put people's identities at risk I am against the labelling of what the U.S. defines as GMO … there is a scientific consensus that GMOs provide no added health risks to the consumer
Equivalence	• Using arguments based on substantial equivalence • Indicating that there is no functional difference between traditional approaches and biotechnology approaches	I don't think we should label GMOs. GMOs occur in nature, even though they're not specific to our food. Also we've been genetically altering crops for thousands of years Genetic engineering of animals should not be banned. GE is merely the latest step in humanity's genetic modification of animals
Generic risks or benefits	• Mention of 'risks,' 'benefits,' 'pros,' 'cons,' without further explanation • Uses 'helpful' or 'harmful' generically	I don't think GE of animals should be banned, because the apparent/possible benefits outweigh the few suspected risks I still believe that the benefits of researching gene editing can lead to great advancements in the future

was assigned –1. Fisher's test was performed using the Real Statistics Resource Pack software (Release 3.5.3) in Excel (Version 14.6.6). Copyright (2013–2015) Charles Zaiontz. www.real-statistics.com.

Results

Impact of discussion sections on student positions

We identified three out of seven discussion sections that were associated with significant binary attitude changes in student responses: discussions 2, 5 and 6 (Figure 1 and Table 2). Of these three, student responses for discussion 6 indicated an absence of familiarity with the subject – FDA's ban of genetic testing company 23andme's health reports – at the beginning of the quarter. This was evident in student justifications as well as by predominance of the 'Don't Know' position prior to the respective discussion section (Figure 1). The remaining two, related to GMO labelling and animal genetic engineering (GE), appeared to reflect true position changes following the respective discussion sections. In comparison, we found no significant difference between pre- and post-discussion positions on two topics, DNA fingerprinting and human embryo editing (discussion sections 1 and 7, respectively, Figure 1 and Table 2). Because we sought to characterise changes in student understanding that may or may not be independent of binary attitude changes, we selected discussion sections 1, 2, 5 and 7 for qualitative analysis.

Impact of discussion sections on presence of themes in student justifications

We identified two discussion sections (discussions 2 and 5) that were associated with binary attitude changes, and two (discussions 1 and 7) that were not (Figure 1 and Table 2). These discussions represented four distinct genetic technology topics – DNA fingerprinting (discussion 1), GMO labelling (discussion 2), genetic engineering (GE) of animals (discussion 5) and human embryo editing research (discussion 7). We hypothesised that we would see greater changes in the presence of themes following discussions 2 and 5, as compared to discussions 1 and 7, since the former pair was associated with significant binary attitude changes.

The following themes were common among sampling units from the four discussion sections we analysed: Progress, Economic, Morality/Ethics, Middle way/Alternative path, Scientific validity/uncertainty, Equivalence, and Generic risks or benefits (descriptions and examples of use of themes in Table 3). We identified net changes in the presence of multiple themes in all discussion sections (Table 4). The themes that exhibited the most dramatic changes were Scientific Validity (i.e. supporting or calling into question scientific consensus or expertise), Progress (i.e. improving quality of life for humans or animals) and Middle Way (i.e. finding a compromise in the regulation or application of a technology), all of which had net increases in use following multiple discussion sections (Table 4).

One theme, Economic (i.e. costing or benefiting individuals, such as consumers or farmers), was associated with the discussions wherein students changed their position. Specifically, we found that the Economic theme had a net increase in use following discussions 2 and 5 (Table 4).

Discussion

Summary

To our knowledge, this is the first study to use a hybrid thematic analysis approach to evaluate student understanding of biotechnology. We characterise seven themes that are relevant across multiple biotechnology topics (Table 3). Five themes – Progress, Economic, Morality/Ethics, Middle way/Alternative path, Scientific validity/uncertainty – have been described previously, while two – Equivalence and Generic Risks or Benefits – were unique to our data-set. We argue that the hybrid thematic approach is valuable because it builds on previous studies to streamline the coding process, while accommodating novel themes that emerge from unique data. This ability to detect novel themes

Table 4. Output summary of thematic analysis of student responses before and after discussion sections.

Discussion	Theme	no2yes	yes2no	Net change
1	Economic	2	0	2
	Generic	3	1	2
	Middle Way	7	2	5
	Morality	4	2	2
	Progress	2	1	1
	Scientific Validity	8	1	7
	Equivalence	1	0	1
2	Economic	8	0	8
	Generic	0	4	−4
	Middle Way	8	0	8
	Morality	0	0	0
	Progress	1	1	0
	Scientific Validity	12	2	10
	Equivalence	4	1	3
5	Economic	7	0	7
	Generic	9	4	5
	Middle Way	5	0	5
	Morality	3	6	−3
	Progress	14	4	10
	Scientific Validity	2	0	2
	Equivalence	2	2	0
7	Economic	0	0	0
	Generic	3	2	1
	Middle Way	11	2	9
	Morality	6	4	2
	Progress	10	5	5
	Scientific Validity	3	0	3
	Equivalence	2	0	2

Notes: *no2yes* denotes when a theme was not detected in an individuals' pre-discussion response, but was detected in their post-discussion response.
yes2no denotes when a theme was detected in an individuals' pre-discussion response, but was not detected in their post-discussion response.
Net change column is difference between no2yes and yes2no.

is especially important for evaluating individuals' understanding of biotechnology, since its social and technical climates are rapidly changing.

Our preliminary data suggest that peer-led discourse of evidence-based information influenced student understanding of multiple biotechnology topics, as indicated by changes in both binary attitudes and the presence of multiple themes in student justifications following the discussion sections. Because the student panels rotated weekly, it is likely that the intervention itself and not the teaching styles of particular individuals contributed to the changes we observed.

We found that one theme, Economic, exhibited a large net increase in use following both discussion sections 2 and 5, which may suggest an association with binary attitude changes. The financial effects of GMO labelling (i.e. predicted increased costs to consumers due to increased regulation) and genetic engineering of animals (i.e. prohibiting GE animals may lead to greater pharmaceutical costs due to a loss of pre-clinical animal models) may not have influenced students' initial appraisals of each topic, but appear to have enhanced their understanding following the respective discussions.

Three themes, Middle Way, Progress and Scientific Validity, were detected at a higher rate in student justifications following multiple discussion sections but were not specifically associated with binary attitude changes. For example, we detected the Scientific Validity theme at a higher rate following discussion 1, even though we did not observe overall position changes following that discussion section. This suggests that peer discourse may influence understanding of biotechnology without leading to binary attitude changes. Increased detection of these themes following peer discussion suggests that awareness of compromise (i.e. Middle Way), ability to improve quality of life (i.e. Progress), and scientific consensus or technological limits (i.e. Scientific Validity) may promote a more nuanced understanding of biotechnology applications.

Limitations of study

The qualitative analysis we performed only served as a proxy for students' conceptual understanding. We asked students to state their positions on biotechnology applications and justify those positions with relevant information, but we can't be certain to what extent the themes we identified in our qualitative analysis were related to students' conceptual frameworks.

Regarding our analysis of student learning following peer discussion, our approach did not rule out the possibility that additional factors, such as content taught in the accompanying lectures or events outside of class (i.e. media coverage of GMOs, especially AquAdvantage salmon in November 2015[2]) also influenced students' understanding of biotechnology. We did not determine whether the changes in attitudes and understanding we observed were persistent, nor did we concurrently evaluate content knowledge of biotechnology before or after the discussion sections.

Future directions

Because this was a preliminary study, the thematic analysis was performed by one coder. In the future, the rigour of this approach will be improved by involving multiple coders, testing for inter-coder reliability, and performing member checks with the study subjects (Fereday and Muir-Cochrane 2006).

Several important questions remain unanswered by our study and may influence future investigations. For example, the applicability of both the hybrid thematic approach and the set of themes described in this study to other biotechnology education research settings needs to be determined. Additionally, whether peer-led discourse is generally effective, and whether themes such as Economic, Middle Way, Scientific Validity or Progress are found to consistently correspond with changes in students' understanding of biotechnology, is unknown. Future studies can assess whether conceptual changes from interventions such as peer discussion are persistent, and qualitative analyses can be combined with validated instruments to identify relationships between knowledge and conceptual frameworks of biotechnology. Finally, comparative studies between experts and novices may help to formulate a more concrete definition of biotechnology literacy.

Conclusion

Individuals need to be equipped to make informed decisions about applications of biotechnology in society. Yet, the accelerated pace of biotechnology research likely precludes them from attaining expert knowledge. Beliefs and attitudes towards biotechnology, then, may have greater influence on individuals' personal decisions than their explicit content knowledge.

Hybrid thematic analysis is a promising method for elucidating individuals' conceptual understanding of genetic technologies. The themes described in this study provide a ready template for future analyses of the teaching and learning of biotechnology. Improved educational approaches are expected to promote biotechnology literacy in undergraduates, towards a more informed and engaged society.

Notes

1. According to the U.S. FDA, the terms 'genetically modified' or 'genetically modified organism' are not useful in a scientific or agricultural context because they are ill-defined. The FDA recommends stating whether or not food is *derived* from plants that have been genetically engineered.
2. In November 2015, the FDA approved AquAdvantage® salmon for commercial production and consumption. This occurred at the end of the quarter and after the respective Discussion Section.

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