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Promoting Sustainability in University Classrooms Using a STEM Project with Mathematical Modeling

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Abstract: The purpose of this study was to explore how a science, technology, engineering, and mathematics (STEM) project with mathematical modeling influenced student competencies regarding sustainability in a university classroom. We used mixed methods with a convergent parallel design. Forty-two students participated in a STEM project during six consecutive sessions of an algebra class. Before and after the STEM project, the students completed surveys about their perceptions of the mathematical modeling approach. Semi-structured interviews and daily reflection sheets from 10 volunteers were used in qualitative analyses. According to the results of the quantitative analysis, after the completion of the STEM project students perceived that mathematical modeling is a useful tool for recognizing problem situations in the present, for predicting future societal changes, and identifying possible solutions to balance the needs of present and future generations. Our qualitative examination revealed that students' modeling processes did not necessarily follow processes suggested by prior studies. In fact, students perceived more opportunities to practice modeling processes than we predicted. In addition, students indicated that their increased awareness of STEM projects provided opportunities to practice an interdisciplinary approach and to consider current and future real-world situations. We discuss the implications of our results for teaching sustainability using STEM projects and offer suggestions for future research.

Keywords: sustainable development; STEM education; higher education; teacher education; mixed methods

1. Introduction

With the advent of the fourth industrial revolution, the need for harmony among the environmental, economic, and social domains is rising [1]. Whereas the first and second industrial revolutions prioritized the efficient use of resources, the third and now fourth industrial revolutions emphasized the coexistence of humans, technology, and nature [2]. The coexistence of humans, technology, and nature demands a balance between human needs and the protection of nature, which encompasses the sustainable development of humankind.

Sustainable development allows natural systems to maintain themselves while still allowing economies and societies to achieve human development goals [3]. That is, sustainable development means that current actions must not impair the ability of future generations to meet their needs [4,5]. According to the sustainable development paradigm, well-designed education for sustainable development (ESD) shapes key competencies to allow students to develop harmoniously, function actively in the present, make responsible decisions, and support the sustainable development of society in the future [6–8].

ESD aims "to empower and equip present and future generations to meet their needs using a balanced and integrated approach to the economic, social, and environmental dimensions of sustainable development" [9] (p. 7). In other words, ESD allows students to understand changes in the real-world, predict the future, identify problem situations present in both current and future societies, and make decisions collaboratively. Students who will be living in future societies need not only to acquire knowledge but also to learn to use knowledge to diagnose and solve problems and ultimately find ways in which humanity, society, and nature can cooperate [10,11]. That is, school education must equip students with a variety of competencies as well as simple knowledge to enable sustainable development.

Innovative pedagogical strategies, interactive teaching, and learning environments, and learner-centered learning methods are necessary to meet the requirements of ESD [12]. Traditional teaching and learning methods, such as teacher-centered lectures, limit opportunities for students to think critically by forcing them to passively listen and accept lecture content [13,14]. Eliminating opportunities for students to think critically prevents them from growing into responsible citizens, which ultimately makes ESD impossible. Therefore, teachers, education policymakers, and administrators should reform their teaching and learning approaches.

To explore an innovative pedagogical strategy for ESD, in the current study, we focus on science, technology, engineering, and mathematics (STEM) education using mathematical modeling. In the context of ESD, we wanted to examine how students would predict future societal trends and solve problems that could arise in future societies. In particular, we offered mathematical modeling as a strategy that students majoring in mathematics education could use to solve problems, using a STEM project focusing on mathematics as an example. Mathematical modeling describes a set of comprehensive processes used to transform real-life problem situations into mathematical models, draw mathematical conclusions, and then apply those conclusions back to the real world. Mathematical modeling can be used to carry out STEM tasks that students will face in future societies, and thus, it can ultimately be used to implement ESD. Since mathematical modeling is based on real-world situations, using mathematical modeling for the STEM task aligns with the purpose of ESD.

We chose mathematical modeling as an effective pedagogical strategy for solving STEM tasks based on previous research [15,16]. Therefore, Research Question 1 examines how students' perceptions of mathematical modeling changed as the task progressed. Changing student perceptions of mathematical modeling is an important issue in ESD because such changes indicate changes in attitudes about dealing with real-world situations or problems. We posed Research Question 2 to analyze the process by which students completed the STEM tasks, which could contribute to the establishment of a refined ESD model using STEM education. Finally, we asked Research Question 3 to investigate what students thought about future societies as they completed the STEM project. The results of this question should represent how interested students are in future societies and what kinds of predictions they are making.

To find answers to the following research questions, we collected data through surveys, journal writing, and interviews about the processes students used to conduct STEM tasks.

- Research Question 1. How did students' perceptions of mathematical modeling change before and after the STEM task?
- Research Question 2. By what process did students solve STEM tasks? (Is the solution procedure for the STEM task sequential?)
- Research Question 3. As a result of carrying out the STEM tasks, what impressions did students have about predicting future society?

2. Literature Review

The three main keywords for this study are STEM education, ESD, and mathematical modeling. It is critical to understand how we wove those three concepts together in this research. Therefore, in this section, we explain their meanings by drawing on prior research.

2.1. STEM Education

STEM is an acronym standing for science, technology, engineering, and mathematics. Depending on the context, the abbreviation STEM has various meanings [17]. STEM is often used simply as a generic term for science, technology, engineering, and mathematics, but it is sometimes used to describe an educational approach to solving real-world problems by using knowledge from various fields [18]. In this paper, we use STEM to refer to an interdisciplinary curriculum of science, technology, engineering, and mathematics subjects.

The main reason that STEM has become an important issue in education is that STEM fields determine national competitiveness [19]. Despite the importance of STEM majors, many developed and developing countries have problems with college students avoiding STEM majors, which leads to workforce deficits in STEM fields [20]. To encourage students to select STEM majors, educators and researchers have worked to increase student interest in STEM subjects [21]. STEM education is part of that effort.

Another reason that STEM education needs to be emphasized is that STEM education can improve students' creativity, interdisciplinary thinking skills, and sustainable development, which are critical competencies they will need in the future [22–28]. As explained above, STEM education involves an interdisciplinary curriculum that incorporates diverse subjects into each lesson [17]. For example, even in a mathematics lesson, a teacher can apply an interdisciplinary curriculum that asks students to solve real-world problems such as reducing poverty and pollution using mathematical algorithms for big data analysis. In this type of project, students apply diverse lines of knowledge from fields beyond their mathematics lessons, including technology, engineering, science, social studies, or even art. When students conduct interdisciplinary exploration to solve STEM tasks using the knowledge they have learned previously in addition to the information they learned during class on that day, they exercise much more spontaneous and creative thinking than they do when they are given a problem with a fixed answer [29].

In this study, we suggest STEM education as a practical approach to ESD. One of the characteristics of STEM education is that most classes are based on real-world problems, a feature that is neatly aligned with the ESD goal of empowering and equipping present and future generations to meet their needs using a balanced and integrated approach to economic, social, and environmental challenges. Therefore, in this study, we asked students to perform STEM tasks and predict the future by using various kinds of knowledge, including mathematics.

2.2. The Significance of Promoting Sustainability in STEM Education

Sustainability is a crucial challenge for people around the globe. A United Nations (UN) report entitled *Transforming Our World: The 2030 Agenda for Sustainable Development* declared intentions to end poverty, combat inequalities, bring peace and justice, protect human rights, and protect the planet by 2030 [30]. The UN's declaration was based on its vision of a better future:

> "We envisage a world free of poverty, hunger, disease and want, where all life can thrive. We envisage a world free of fear and violence. A world with universal literacy. A world with equitable and universal access to quality education at all levels, to health care and social protection, where physical, mental and social well-being are assured. A world where we reaffirm our commitments regarding the human right to safe drinking water and sanitation and where there is improved hygiene; and where food is sufficient, safe, affordable and nutritious. A world where human habitats are safe, resilient and sustainable and where there is universal access to affordable, reliable and sustainable energy." [p. 7]

In essence, sustainability is a concept that urges practical actions to allow everyone around the globe to build a positive future together. Sustainability considers both present and future generations [30]. The UN recognizes three dimensions of sustainability—economic, social, and environmental. With those dimensions in mind, the UN suggests 17 Sustainable Development Goals [31] that cover a vast range of topics, including poverty, health, education, gender equality, climate action, and peace and justice. One of the essential paths toward sustainability is ESD.

The notion of ESD [32] emphasizes the importance of education in "developing competencies that empower individuals to reflect on their own actions, taking into account their current and future social, cultural, economic and environmental impacts, from a local and a global perspective" (p. 7). Through ESD, current and future generations will become able to "promot[e] societal, economic and political changes" (p. 8). Prior publications addressing ESD proposed several key competencies as learning objectives: (i) Systems-thinking, (ii) collaboration, (iii) strategic competency, (iv) self-awareness, (v) normative competency, and (vi) action skills [7,32–34]. Roughly summarized, these competencies emphasize the ability to understand the multiplicity of a given situation, consider underlying values, harmoniously work with others, deal with uncertainty, and reflect on one's own practice. Education researchers have been examining how ESD could be brought into STEM classrooms. Their investigations over a range of topics, including the environment [35–37], society and sociology [38,39], whole-systems design [40], and art [41]. Although mathematics is not often foregrounded, the variety of topics suggests that STEM classrooms, in general, could be successfully reshaped as a space for teaching and learning sustainability.

Several features contribute to successful integration of STEM and ESD. The first is the utilization of real-world contexts [36,40,42]. Remington-Doucette, Hiller Connell, Armstrong, and Musgrove illustrated this point by examining the effectiveness of a course that introduces university students to the concept of sustainability [42]. The course was centered on case studies, which invite students to deal with complex real-world problems. After taking the course, the students showed increases in sustainability competencies. That is, the results indicated that ESD can be effective when instructors include real-world contexts that are relevant to their students' daily lives.

Another important feature is the promotion of group interactions [37,42,43]. Shriberg and MacDonald [37] studied 50 ESD programs and interviews with 20 program directors and found that the program directors value group interactions because they allow students to achieve more than they would by working individually and because peer-to-peer learning was the most effective course feature they have experienced. In addition, the directors asserted that peer-based and cohort-building activities, including group projects, are essential parts of ESD.

Finally, having students work with self-collected data has been shown to be helpful [44,45]. Rogers, Pfaff, Hamilton, and Erkan developed ESD modules for STEM education [45] consisting of an introduction, engaging in course-specific activities, writing technical reports, evaluating technical reports from others, and completing a summary activity. The actual investigation happened when students engaged in course-specific activities. In order to make this part effective, course instructors were required to provide guidance to their students starting with the actual data collection phase, all the way through to the analysis and interpretation.

The present study extends on prior research by introducing mathematical modeling, as explained below. Using mathematical modeling, real-world situations may be brought into the classroom context naturally. In addition, using a mathematical modeling exercise allows students to work as groups and collect their own data.

2.3. Mathematical Modeling

Teaching and learning methods for implementing STEM education as part of an interdisciplinary curriculum vary widely [46], including project-based learning, problem-based learning, inquiry-based learning, and technology-based learning, each of which can be used differently depending on the classroom situation [17]. In the current study, we used mathematical modeling as an instructional approach to implement STEM education because mathematical modeling is based on real-world situations, which is aligned to the purpose of ESD.

Mathematical modeling [47] has been defined as "using mathematics or statistics to describe (i.e., model) a real-world situation and deduce additional information about the situation by mathematical or statistical computation and analysis" (p. 5). Although the expressions that define mathematical modeling can vary [47,48], they all begin with real-world situations [49,50]. That is, when using mathematical modeling as an instructional approach, students are given an opportunity to translate a real-world situation into mathematical form by using mathematical terms, representations, and models.

The process of mathematical modeling is dynamic [51,52]. Although previous studies have defined various processes for mathematical modeling, they commonly point out that the process of mathematical modeling is cyclic rather than linear [47,53]. For example, Common Core State Standards for Mathematics (CCSSM) [54] suggested a mathematical modeling process beginning with a problem and ending with a report. Between those ends, steps for formulation, validation, interpretation, and computation occur repeatedly. Dossey and colleagues [52] described a modeling process that was a closed system with four steps: Formulate real-world data using a mathematical model, analyze the mathematical model and make mathematical conclusions, interpret the mathematical conclusions and make predictions and explanations, and test those predictions/explanations against real-world data. The critical point of any mathematical modeling cycle is that it allows students to begin with a particular phase and progress to any other phase based on their needs, which was not made explicit in previous studies [47,51,52].

Furthermore, when applying a mathematical modeling process to a lesson, it needs to be emphasized that the process includes problem finding as well as problem-solving. Identifying a real-world and converting it into mathematical form is not a task that has often been implemented in math classrooms. Rather, mathematics problems are usually given to students. Therefore, mathematical modeling tasks include high cognitive barriers and demand that students use diverse thinking abilities, including making assumptions and decisions, optimizing a situation, interpreting results, and modifying a solution [49]. In these ways, mathematical modeling differs from other mathematical tasks, which is why it needs to be incorporated into STEM education.

In the current study, we offered mathematics-focused STEM tasks to students majoring in mathematics education. Based on previous studies regarding mathematical modeling processes [47,51–53], we hypothesized that students would perform STEM tasks using seven steps: Understanding the problem, simplifying the problem, mathematizing the problem, drawing mathematical conclusions, interpreting the mathematical conclusions while considering the real-world problem, verifying the mathematical models created and presenting their final conclusions. We also provided students with opportunities to find problems by themselves, which of necessity relates to their real lives.

2.4. Contribution of This Study to the Literature

We reviewed research on STEM, ESD, and mathematical modeling. Based on our review, we identified the potential of STEM education as an approach to ESD. We also found that ESD in STEM classroom could be effective in STEM classrooms when it is connected to real-world problems, encourages group work, and invites students to work with the data they themselves have collected. In order to meet these three criteria, we chose to draw on mathematical modeling, which is an approach that has long been used in STEM education.

This study is exploratory in that it is based on the literature we reviewed, which shows there are no strong connections existing between ESD and mathematical modeling. In this study, we sought to close this gap by demonstrating how mathematical modeling can be implemented for the promotion of sustainability. In particular, we aimed to determine the effectiveness of mathematical modeling by examining quantitative and qualitative data collected from university students in STEM-related majors.

3. Methods

We designed this study as a mixed methods study using a convergent parallel design [55] to explore how students solved STEM tasks using a mathematical modeling approach and how students' experiences with the STEM tasks affected their attitudes toward mathematics modeling and sustainability. We used data collected from a nationally-funded research project in both the quantitative and qualitative phases of the study. Although the quantitative and qualitative data were collected at the same time, the two data types were used to answer different research questions. That is, we answered Research Question 1 using quantitative data and Research Questions 2 and 3 using qualitative data. For Research Question 1, quantitative analyses (e.g., cross tab, *t*-testing, Cronbach's alpha) were used, and for Research Questions 2 and 3, qualitative analyses (e.g., organizing interview transcripts and drawing themes) were conducted. We prioritized the qualitative data because of the importance of Research Questions 2 and 3.

3.1. Participants

The participants in this study were college students ($n = 42$) enrolled at a top-ranked university in South Korea who took an algebra course in the Department of Mathematics Education at the College of Education. Of our sample, 59.5% ($n = 25$) were men and 40.5% ($n = 17$) were women. The College of Education has several departments, such as Mathematics Education, Computer Education, and General Education. In our sample, 76.2% of the students were majoring in mathematics education, with 7.1% and 2.4% majoring in general education and computer education, respectively. About 9.5% of the participants were from outside the College of Education and majoring in statistics. About 4.8% of the participants were graduate students who took the algebra course as a prerequisite for their graduate program. Of the undergraduate students, 32 (73.8%) were in their first year, one was in their second year, six were in their third year, and two were in their fourth year. For the quantitative analysis, 42 and 34 students provided responses to the pre- and post-tests, respectively. For the qualitative analysis, we selected 10 students for semi-structured interviews. The 10 participating students were chosen from among those who volunteered to be interviewed and attended all six class sessions. In addition, we considered their familiarity with mathematical modeling using answers from their daily reflection sheets for the first and the last sessions. Our initial plan was to invite students who reflected decreased, maintained, and increased familiarity with mathematical modeling. No student, however, reported a decrease in their familiarity with it, and only one student maintained his familiarity. Therefore, we grouped students according to their degree of increase and invited two to three students from each group. Table 1 provides more participant information.

Table 1. Interviewee information.

Student	Change in Familiarity	Gender	Major	Year
Student 1	+1	Male	Mathematics Education	First year
Student 2	+1	Female	Statistics	Third year
Student 3	+2	Female	Statistics	Third year
Student 4	+2	Male	Mathematics Education	First year
Student 5	+3	Female	Statistics	Third year
Student 6	0	Male	Educational Studies	Third year
Student 7	+3	Male	Mathematics Education	First year
Student 8	+3	Female	Statistics	Fourth year
Student 9	+2	Male	Mathematics Education	First year
Student 10	+4	Male	Mathematics Education	First year

3.2. STEM Project for Sustainability

The project consisted of six consecutive sessions of 75 min each. It was administered in the middle of the semester during an algebra course for mathematics education majors. A coauthor of this article led the sessions with assistance from two graduate students. The main goal of the project was to engage in a mathematical modeling project using a Markov chain to make future predictions. Table 2 summarizes the project.

Table 2. The science, technology, engineering, and mathematics (STEM) project.

Session	Main Activities	Intended Outcomes	Artifacts and Data Collected
Session 1	An introduction to the Fourth Industrial Revolution. An introduction to mathematical modeling.	Develop understanding of the Fourth Industrial Revolution and mathematical modeling.	Pre-test survey. Individual reflection sheet with a question asking their familiarity with mathematical modeling.
Session 2	An introduction to Markov chains. Application of a Markov chain to income mobility data (part 1).	Develop understanding of Markov chains.	Worksheet. Individual reflection sheet.
Session 3	Application of a Markov chain to income mobility data (part 2).	Experience using a Markov chain to predict the future. Understand prediction as estimation (as opposed to fortune telling).	Worksheet. Individual reflection sheet.
Session 4	Identifying a topic for future prediction using a Markov chain. Collecting and organizing data from classmates. Using a Markov chain to predict the future.	Understand the conditions to which a Markov chain can be applied. Build an initial database for which a Markov chain is applicable.	Worksheet with identified topic and student-generated database. Individual reflection sheet.
Homework	Collect more data from people who are not enrolled in the course.	Enrich the database.	
Session 5	Apply a Markov chain to the enriched database to predict the future. Compare the prediction from the initial database with that from the enriched database. Discuss an action plan based on the predictions. Prepare a poster.	Understand prediction as estimation (as opposed to fortune telling). Apply mathematical results to the real world. Organize findings and insights in a sharable form.	Enriched student-generated database. Worksheet with data analysis results and interpretations. Working poster. Individual reflection sheet.
Session 6	Finalize the poster. Visit other groups' posters and leave comments using sticky notes.	Organize findings and insights in a sharable form. Read and make sense of others' modeling work.	Finalized poster. Sticky notes with questions to other groups. Individual reflection sheet with a question asking their familiarity with mathematical modeling. Post-test survey. Contact information from interview volunteers.

At the beginning of the project, students formed groups of three in which to collaborate on activities. Although we implemented the project within six sessions, it could be extended to seven or more sessions. That is, this STEM project is extremely flexible and rich, depending on how an instructor uses it. A possible extension could happen when applying a Markov chain to income mobility data (sessions 2 and 3). An instructor could introduce technological tools for matrix calculation. Depending on the tool, a programming language could be introduced. In addition, an instructor could sharpen the focus of the project by modifying the activities in sessions 4 to 6. That is, the project could be enacted during a biology course by asking students to identify biological topics or during any STEM course or even non-STEM courses. Moreover, statistics and engineering could be discussed when collecting and organizing data (session 4). In fact, the students in this study used an online survey form and web spreadsheets to complete their tasks. Instead of leaving it to students, an instructor could introduce knowledge or tools related to data gathering and reporting.

3.3. Data Sources

For the quantitative analysis to answer Research Question 1, we used an 18-item survey that we adapted from Gould [56]. The original survey examined in-service teachers' perceptions of mathematical modeling. Because most of our participants were pre-service teachers, we revised the sentences and contexts of some items to accord with pre-service teachers' situations. The survey consists of four sections: Students' prior experiences with mathematical modeling, mathematical models, mathematical modeling, and mathematical modeling and education. The first section included two items and asked whether participants had experience or had received lessons in mathematical modeling. The second section contained six items about mathematical models and asked whether participants agreed that fraction bars, pattern blocks, equations, coordinates, and blueprints are mathematical models. Two additional items in the second section asked about the practical aspects of mathematical models. The third section contained six items about mathematical modeling, and the fourth section contained five items about mathematical modeling and education.

For the qualitative analysis to answer Research Questions 2 and 3, we drew on interviews, worksheets, and reflection sheets. During each of the six sessions, students filled in a reflection sheet to self-report their engagement, participation, and learning. Worksheets were given in sessions 2 to 5 for students to record their processes and conclusions from each session. The interviews were held individually at the principal investigator's office between 7 and 14 days after the final STEM project session. A coauthor and two graduate students conducted the interviews. We scheduled the interviews so that two people joined the interview, one as the main interviewer and the other as the sub, to maintain some level of consistency across ten interviews. Two participants were interviewed by only one interviewer because of a schedule conflict. The participants were told that the interview would take about 90 min, but most of the interviews lasted only about an hour. Because all three interviewers were present during three or more STEM project sessions, the participants were familiar with them. The worksheets and reflection sheets were provided to the participants as references during the interviews. Each interview was semi-structured. The research team designed a checklist, but the interviews were closer to a conversation than a question-and-answer session. The checklist included questions asking students to define in their own words the seven modeling steps, the kinds of activities they did for each step, and their definition of mathematical modeling. Interviews were voice recorded and transcribed.

3.4. Data Analysis

Before we conducted the main analyses for Research Question 1, we calculated the correlation coefficients for the items. To verify the reliability of the measurement construct, Cronbach's alphas were calculated for each factor using SPSS. Cronbach's alphas for the three sections were 0.860 (mathematical model), 0.833 (mathematical modeling), and 0.904 (mathematical modeling and education), all higher than 0.6, which validates their reliability [57]. To compare the scores of each factor between the pre- and post-tests, we calculated composite variables using the mean scores of each factor. Using those composite variables, we conducted *t*-testing. The results from the *t*-tests indicated whether participants' perceptions of mathematical modeling changed. When statistically significant results indicated that participants' attitudes toward mathematical modeling differed before and after the intervention, we scrutinized crosstabs for specific items to supplement the findings for Research Questions 2 and 3.

Interview transcripts were the main data source used to answer Research Questions 2 and 3. We used Nvivo to organize the transcripts and search them for themes. According to Braun and Clarke [58], the significance of a theme does "not depend on quantifiable measures, but rather on whether it captures something important in relation to the overall research question" (p. 82). Therefore, we focused on identifying intriguing incidences that pertained to STEM as a field for teaching sustainability. During the first round of analysis, we generated 13 initial codes. In reviewing them, we compared them with the questions in the survey to find the themes visible in both the quantitative and qualitative data. In that way, we narrowed them down to six themes, three for each of the two qualitative research questions. We recorded the transcripts using those six themes and selected "vivid, compelling extract examples" (p. 87) that highlight students' experiences while participating in the STEM project.

4. Results

4.1. Research Question 1

The composite variables for the three sections were computed and used for *t*-tests, which were conducted to compare the mean values of the pre- and post-test scores for each section. The results of the *t*-tests are reported in Table 3. For all three sections, the mean values from the post-tests were higher than those from pre-tests, and the differences between the pre- and post-test scores were statistically significant.

Table 3. Paired-sample tests.

		Paired Differences							
		Mean	Std. Deviation	Std. Error Mean	95% Confidence Interval of the Difference		*t*	*df*	Sig. (2-Tailed)
					Lower	Upper			
Section 2	Pre – Post	−1.667	2.266	0.394	−2.470	−0.863	−4.226	32	<0.001
Section 3	Pre – Post	−1.833	1.594	0.273	−2.390	−1.277	−6.705	33	<0.001
Section 4	Pre - Post	−1.964	2.169	0.378	−2.733	−1.195	−5.201	32	<0.001

Note. Section 2: Mathematical model; Section 3: Mathematical modeling; Section 4: Mathematical modeling and education.

For items 8 and 12 regarding the process of mathematical modeling, crosstabs comparing the frequencies from the pre- and post-tests are reported to supplement the findings for Research Question 2.

According to the crosstab for Item 8 (Figure 1), no students gave lower scores in the post-test than in the pre-test. The students who answered "don't know" in the pre-test showed changed perspectives in the post-test and tended to agree with the item, "Each step of mathematical modeling can be repeated several times." Students who gave a score of 3 (i.e., about half the time) or 4 (i.e., usually) in the pre-test reassigned similar scores rather than showing stronger agreement in the post-test.

		Post Item 8						
		Don't know	Never	Occasion-ally	About half the time	Usually	Always	Total
Pre Item 8	0=Don't know	0	0	0	3	11	2	16
	1=Never	0	0	0	0	0	0	0
	2=Occasionally	0	0	0	0	1	0	1
	3=About half the time	0	0	0	2	2	0	4
	4=Usually	0	0	0	0	11	2	13
	5=Always	0	0	0	0	0	0	0
	Total	0	0	0	5	25	4	34

Figure 1. Each step of mathematical modeling can be repeated several times.

The results for item 12 (Figure 2) are similar to those for item 8: No students gave lower scores in the post-test than in the pre-test. One student who answered "don't know" in the pre-test gave the same response in the post-test. The remaining 13 students who replied "don't know" in the pre-test gave scores of 2 (i.e., occasionally, two students), 3 (about half the time, two students), 4 (usually, three students), and 5 (always, six students) on the post-test. As a result, 29 students in the post-test answered 4 (usually) or 5 (always) to the item, "Modification and revision are required at each stage of mathematical modeling."

		Post Item 12						
		Don't know	Never	Occasion-ally	About half the time	Usually	Always	Total
Pre Item 12	0=Don't know	1	0	2	2	3	6	14
	1=Never	0	0	0	0	0	0	0
	2=Occasionally	0	0	0	0	0	0	0
	3=About half the time	0	0	0	0	2	0	2
	4=Usually	0	0	0	0	7	7	14
	5=Always	0	0	0	0	0	4	4
	Total	1	0	2	2	12	17	34

Figure 2. Modification and revision are required at each stage of mathematical modeling.

Taking into account the results of questions 8 and 12, students did not understand mathematical modeling well before exploring this STEM task, so they mostly answered that they did not know about the mathematical modeling process. As the students experienced the STEM task, they noticed that the process of mathematical modeling was not linear and could be repeated by modifying each step. These results are consistent with the qualitative results, which will be presented in the next section.

Items 17 and 18 asked whether mathematical modeling helped the students understand scientific and humanities phenomena, and we used them to help answer Research Question 3.

In the pre-test, about one-third of students answered that they did not know the answer, giving neither a positive nor negative response (Figure 3). After the STEM tasks, no students replied that they did not know, and all but one student gave 4 (i.e., "I agree somewhat") or more points to the item.

		Post Item 17							
		Don't know	Disagree at all	Generally disagree	Disagree somewhat	Agree somewhat	Generally agree	Agree at all	Total
Pre Item 17	0=Don't know	0	0	0	0	5	3	3	11
	1=Disagree at all	0	0	0	0	0	0	0	0
	2=Generally disagree	0	0	0	0	1	0	0	1
	3=Disagree somewhat	0	0	0	0	1	0	0	1
	4=Agree somewhat	0	0	0	0	3	4	1	8
	5=Generally agree	0	0	0	1	2	2	3	8
	6=Agree at all	0	0	0	0	0	1	3	4
	Total	0	0	0	1	12	10	10	33

Figure 3. Students can improve their ability to understand scientific phenomena more deeply through mathematical modeling.

		Post Item 18							
		Don't know	Disagree at all	Generally disagree	Disagree somewhat	Agree somewhat	Generally agree	Agree at all	Total
Pre Item 18	0=Don't know	0	1	1	2	6	3	3	16
	1=Disagree at all	0	0	0	0	0	0	0	0
	2=Generally disagree	0	0	0	1	3	0	0	4
	3=Disagree somewhat	0	0	0	1	2	0	0	3
	4=Agree somewhat	0	0	0	0	2	3	0	5
	5=Generally agree	0	0	0	0	2	1	0	3
	6=Agree at all	0	0	0	0	1	1	1	3
	Total	0	1	1	4	16	8	4	34

Figure 4. Students can improve their ability to understand humanities phenomena more deeply through mathematical modeling. (ex. language, literature, history, art, social science).

The changes in student answers on Item 18 (Figure 4) are similar to those on Item 17. Students who responded with 0 (i.e., "I don't know") in the pre-test did not choose 0 again in the post-test. However, unlike the result for Item 17, one, one, and four students answered with 1 (i.e., "I do not agree at all"), 2 (i.e., "I generally disagree"), and 3 (i.e., "I disagree somewhat"), respectively. However, more than half of the students gave 4 (i.e., "I agree somewhat") or more points to the item.

4.2. Research Question 2

Our initial examination of the student reflection sheets showed that students engaged in the STEM project in ways we had not expected. When we designed the project, we expected students to follow a circular process, as Blum [59] described. According to Blum [59], mathematical modeling consists of seven steps: Understanding the task, simplifying/structuring, mathematizing, working mathematically, interpreting, validating, and presenting. When modeling, one uses a circular process, proceeding from step 1 to step 6 and then revisiting steps 2 to 6 until reaching satisfactory results to be presented to the world in step 7. We expected students to engage in steps 1 to 3 during the early sessions and smoothly move to the later steps as the project proceeded. We hypothesized that they would take the circular path described above. The student reflection sheets, however, told us a different story. A vast majority of the students indicated that they engaged in the later steps during the early meetings and in the first steps during the later meetings. We wanted to further understand the modeling process they used. From the interviews, we inferred three noteworthy findings: The students (i) took an alternative circular path, (ii) recognized the steps as intertwined, and (iii) repeated modeling processes when engaging with outsiders.

4.2.1. Students Took an Alternative Circular Path When Mathematically Modeling a Real-World Situation

The research team sought to empirically validate whether students, in fact, went through the predicted repetition of steps. In the interviews, we found evidence that they used a circular approach slightly different from what Blum [59] originally presented. When asked to which step she thought she should go back to validate the work, Student 8 responded either step 1, the understanding step, or step 2, the simplifying step. The interviewer asked why.

> Interviewer: From the beginning?

> Student 8: Yes. Simplification is about selecting the variables, but deciding which variable to include or not happens during the first step. If you found another variable after validation, then you want to go back to the understanding step. If the variable you considered not to be significant, turned out to be significant, then you go back to the simplifying step.

Thus, Student 8 showed her awareness of the circular nature of the modeling process. She thought that during step 6, the validation step, one could go back to either the understanding or the simplifying steps. Which step to go back to would depend on the nature of the variable. If a new variable should be added to the model, one should start from the very beginning. If a less appreciated variable were found to be important, then one could start from the second step.

The following excerpt from the interview with Student 2 is another example of a similar understanding.

> Interviewer: So, which of the seven steps do you think includes verifying the transition matrix?

> Student 2: Can't be only one step. Rather, I think it is both steps 4 and 6. In step 4, you draw the conclusion, hence the need for validation. When it comes to step 6, I think you need to validate everything before you reach the final conclusion.

> Interviewer: So, you just said validating everything. When doing so, did you start with the first step? From which step did you do the validation?

> Student 2: My group did it from the first step to be sure with the topic because our topic was somewhat vague.

Toward the beginning of the interview, Student 2 shared that she considered finding the transition matrix to be part of mathematizing, the third modeling process. Later, she mentioned that her group recalculated the matrix multiple times to make sure it was correct. The interviewer asked which step encompassed that recalculation. As in the excerpt above, Student 2 thought the recalculation was part of validation, step 6. Then, she described step 6 as the step at which you "validate everything." When the interviewer probed to which step she went back, she said that she and her group members revisited step 1 because the topic they chose was not completely clear. Both Student 8 and Student 2 said that they went back to step 1 after validation, but their reasoning was different. Student 8 did so due to her choice of variables, whereas Student 2's case had to do with her uncertainty with the topic. These findings show that students may take the processes different from Blum's [59] model. Such difference suggests ideas for enhancing our understanding of the modeling process.

4.2.2. Students Recognized the Steps as Intertwined Rather Than Discrete

The reflection sheet indicated that from the students' perspective, they engaged in almost all seven modeling steps in each session. In the interviews, we found that students recognized the steps more as intertwined ideas than as independent entities. That recognition was strong enough for them to think that they had engaged in steps that had technically been completed in a prior session. The excerpt below is from the interview with Student 4.

> Interviewer: You said that during our sixth meeting you engaged in step 1, understanding the task, to the degree of 4 out of 5, which is a moderate engagement. What activity led you to answer that way?
>
> Student 4: During the fourth session, I did well on the steps 1 through 4, so that continued to the fifth and sixth sessions.

On the reflection sheet, Student 4 indicated that he engaged in step 1 during the sixth session, which was a poster session. That is, the students were expected to be done with steps 1 to 6 by the end of the fifth session and to focus on step 7 during the sixth session. Puzzled, the interviewer asked why he answered that way. Student 4 responded that his rating for steps 1 to 4 during the fifth and sixth sessions depended on his work in the fourth session. Because he thought he had done well on those steps, he allocated the same number to them even when he was not given an opportunity to engage in them during the following sessions.

Student 5 justified a similar approach in allowing prior sessions to influence later ones.

> Interviewer: In your reflection sheet for the fourth session, you gave a 4 for step 1. For the fifth and sixth sessions, the numbers decreased to 3 but not zero. Is there a reason for giving a 3?
>
> Student 5: Because I kept thinking about the topic. Basically, what I do involved the topic, which is in my head.

As shown in the excerpt above, Student 5 rated step 1 a 3 out of 5 (i.e., mild engagement) even though she was well aware that in the fifth and sixth sessions, no activities could be denoted as step 1. Still, she gave a 3 to step 1 because she was thinking about the results, she got from step 1 during the later sessions. Although the activities presented to her were intended to engage the later modeling steps, she had to keep the problem situation, step 1, in mind to successfully engage in those later steps. Student 9 explicitly pointed out that connection, saying "if a step is done during the previous meeting, I still gave a five in the following sessions' reflection sheets because the step was done." These excerpts indicate that students did not necessarily understand the steps as discrete. Instead, they considered the steps as a continuum to the extent that they thought of prior steps as present in a session even if they did not explicitly practice those steps.

4.2.3. Students Revisited the Modeling Steps When Reading Others' Work and Sharing Their Own Work

The reflection sheets from the last class session showed that several students engaged in multiple modeling steps, which differed from our initial expectation. During the last session, students gave a poster session of the topic they had explored during the past two class sessions. When reading others' posters, students wrote any questions or comments they had on sticky notes. After the poster session, each group collected its sticky notes and thought about how they could respond to the comments. During this set of activities, we expected them to engage in step 7, which is presentation. In reality, students expressed that they used other steps as well. The interviewer asked the students why. It turned out that students considered what happened after step 7 as a kind of modeling activity. That is, they were able to interpret both reading other groups' posters and understanding comments from others on their poster as activities that involved the modeling steps.

> Interviewer: The sixth step is validation. Could you explain how you validated it?
>
> Student 3: I visited another group's poster and scrutinized whether it was not because of age, the variable they had chosen, but because of the difference between high school and college, and some unclear parts from selecting variables, such as the difference from the respondents' perspective.

When asked how she engaged with step 6, Student 3 immediately answered by sharing what she did during the poster exhibition. As she looked at the posters, she mentally tried to verify the validity of another group's modeling process.

Student 6 had a similar experience.

> Interviewer: The sixth session was to finalize your poster, present it to your classmates, and then collect comments on sticky notes. What activity made you think you engaged in understanding the task, step 1?
>
> Student 6: It was about understanding others' problem situations. I really understood most of the situations, so I rated high on that step.
>
> Interviewer: And you marked zero for simplifying, step 2. Why is that?
>
> Student 6: It was difficult to simplify the situation because on the poster there were no calculation processes included. I could only see their conclusions.

Student 6 considered his identification of the problem when reading others' posters as an activity addressing step 1. When comprehending each poster, Student 6 began by understanding the problem. The poster, however, presented well-organized results, so he did not need to simplify the situation. Because the poster writers did not disclose their data set, Student 6 could not access the situation for simplification. Therefore, he marked 0 on the simplifying step. The zero could have meant that he did all the simplification during prior meetings, but that was not the case for Student 6. Instead of considering her own work, Student 6 took the activity of reading others' posters into consideration.

Some students considered reading sticky notes from classmates as part of mathematical modeling. To them, responding to questions from people outside of their group was a meaningful modeling experience.

> Interviewer: Which activity have you considered as presenting, step 7?
>
> Student 6: My group read the sticky notes on our poster. Although we had no opportunity to share our responses to the notes during whole-class discussion, we did share them in our group.

As shown in the excerpt above, Student 6 considered reading outsiders' comments as part of presenting, step 7. The original definition of this step includes poster sharing. Student 6 expanded that to include responding to others' comments, even though the responses were not shared publicly. Later in the interview, she indicated that discussing comments within the group sufficed to be considered part of step 7.

Student 10 also recognized this as part of the modeling process.

> Interviewer: Why did you mark 5 on understanding the task for the sixth class session?
>
> Student 10: I considered the sticky notes as the task to be understood.
>
> Interviewer: Your sticky notes? Or the ones on others' posters?
>
> Student 10: The notes from other groups on my group's poster. I understood and responded to them well, so I gave a five.

When asked why she thought he had engaged in step 1, Student 10 reasoned that in the process of making sense of the comments and preparing responses, he revisited his group's problem situation. As with Student 6, Student 10 did not have a chance to share his group's response with her classmates, but he considered what he experienced while preparing the responses as a valuable part of the modeling. The numbers on the reflection sheets and the excerpts from the interviews show that the students naturally embraced their interactions with people other than their group members as a modeling activity. Considering that sustainability requires sharing an agenda not only with people who are equally interested in it but also with those who are relatively new to the idea, we hypothesize that the students' responses open a pedagogically rich space for ESD.

4.3. Research Question 3

To create a sustainable future, cognitive awareness is never enough. Practical action to bring changes into the real world must follow. Therefore, we explored students' perceptions of the connection between STEM tasks and society. We found some indirect evidence from the worksheets, reflection sheets, and posters. More direct evidence was available from the interviews. In this section, we present excerpts that shed light on students' recognition of real-world contexts. We have no evidence to assert that the excerpts presented in this section represent all students' status. In fact, our goal here is not to offer a representative sample. Our focus is on sharing cases suitable for promoting ESD through STEM projects.

4.3.1. Students Recognized the Connection between STEM and Real-World Situations by Engaging in Mathematical Modeling

At various points in the interviews, students indicated that the STEM task they did was strongly connected to real-world contexts. For example, after the six sessions with the research team, Student 1 felt comfortable with mathematical modeling because of its wide applicability to the real world.

> Interviewer: What aspect of the sessions do you think increased your familiarity with mathematical modeling?
>
> Student 1: Well, because we dealt with changes around my daily life, it has lots of applicability. Weather, population migration, and lots of other areas. To think about the wide applicability, my familiarity increased.

Thus, Student 1 became aware of the great potential of STEM as a tool for solving problems in the real world. Student 2 said, "I thought mathematics is very abstract. It was incredible to see how math is applied to something so close to my life." Student 4 also showed confidence in using STEM to address real-world issues.

Interviewer: Could you explain to a friend what mathematical modeling is about?

Student 4: Solving real-world problems using mathematics based on some assumptions.

Interviewer: Which activity would you consider as doing mathematical modeling?

Student 4: It could be applied to statistics. I think I could make algorithms, like using a certain algorithm to classify mail based off the postal numbers.

Interviewer: Is there a particular reason for choosing mailing service?

Student 4: I recently received mail. That's all.

During the interview, Student 4 explained that mathematical modeling has to do with real-world situations. When asked to provide an example, Student 4 immediately drew on his daily experience without any hesitation. In a later part of the interview, Student 4 said that doing mathematical modeling with a topic from his daily life definitely helped him engage with it. He hypothesized that if the topics were far from his daily life (e.g., ecosystem), the chance for him to make sense of the situation was likely to be low. Student 10 agreed that mathematical modeling is an effective way to see the practicality and applicability of mathematics. He said that she wished she could do a modeling activity as closure for each lesson. These students' responses support our claim that students do actually better understand how to use STEM to solve problems close to their lives as a result of completing this STEM project. The role of mathematical modeling in enhancing students' awareness of the connection between STEM and the real world is thus empirically supported.

In addition to the direct testimonials above, we found evidence that students did, in fact, consider real-world contexts during the six class sessions. The interviews revealed that they frequently referred to real-world contexts as they progressed in their modeling activities.

Interviewer: How was the interpretation step? You did this as a group.

Student 2: I did, but the result was too extreme, so I wasn't sure. Is it right? I had no problem drawing the conclusion, but right after that, I recalculated it many times.

Interviewer: In what sense was it extreme?

Student 2: The rating increased a lot. Normally, the number of viewers decreases as a show progresses into the next season, but mine increased radically.

The group Student 2 was in investigated rating changes for a television show. From her experience, she knew that the ratings normally decrease season after season. Her data, however, told the opposite story. According to her prediction, the rating for the show would increase rapidly when the new season was released. Instead of accepting that as a valid prediction, she reviewed her process in search of mathematical errors. That is, Student 2 reflected on her mathematical work using real-world contexts and tried to understand the meaning of the numbers.

Student 8 also expressed her awareness of real-world contexts during the meetings. She shared the limitations of her work.

Interviewer: From the fourth to sixth meeting, you were asked to select your own topic of interest and work on it. Did you ever engage in understanding the task step?

Student 8: I did understand the situation, but not enough because the sample was very limited. And I guess I simplified reality too much. I didn't get to collect data from those who did not come to college or went to less prestigious colleges. So, I think understanding the problem situation was only partially done.

As shown in the excerpt above, Student 8 thought she only partially understood the problem because her group collected data from people in her university, which is prestigious. Her group's topic was the degree to which students were satisfied with their university. Recognizing the limitation of her data set, she thought that she could have reached a better understanding if the data represented a wider range of people, including those who did not come to college. This shows her consistent effort to go beyond the domain of abstract mathematics. She could have been satisfied with her calculations being flawless, but instead, she critically examined what her data were telling or not telling her by seriously considering real-world contexts.

4.3.2. Students Thought in Interdisciplinary Ways While Completing a STEM Project on Mathematical Modeling

When students are engaged in a STEM project, it is natural to expect them to make connections among the natural sciences. The participating students indicated that they indeed made such connections. For example, Student 7 said, "I think the mathematizing step is to come up with mathematical expressions or organize the data using statistics." The STEM project gave Student 7 an opportunity to work on the intersection between mathematics and statistics. What was somewhat unexpected was students' recognition of the connection between STEM and humanities. When asked to explain mathematical modeling in her own words, Student 3 responded as follows.

> Interviewer: Do you feel like you can explain what mathematical modeling is to your friend?
>
> Student 3: Yes.
>
> Interviewer: How?
>
> Student 3: From an existing phenomenon, I mathematicise the portion I want, measure it, represent it as a table of some sort, and then draw out the humanistic implications.

To Student 3, interpreting the mathematical conclusion requires that the humanistic view be meaningful. Moreover, she indicated that the humanistic view is important for other modeling steps as well. When asked how she would describe her contribution to the group, she responded: "I was a raconteur." She explained, "Being a raconteur means being someone who gives humanistic ideas. I think it's important when selecting the topic, making the poster, and interpreting the results." Basically, Student 3 considered the humanistic view to be valuable throughout the whole process of mathematical modeling except for the steps requiring mathematical calculations.

To be fair, not all students were able to see the intersection between STEM and the humanities, but even they acknowledged the intersection with the social sciences. For example, Student 9 expressed confidence in using mathematical modeling activities once he becomes a teacher. The interviewer wondered if he was considering an interdisciplinary move as an option.

> Interviewer: When enacting modeling activities, have you thought about cooperating with teachers from other disciplines?
>
> Student 9: Humanities, I guess would be difficult. Social sciences, economics, statistics would be good, science is fine too. I'm not sure about art, music, or gym.

Thus, Student 9 responded that although he was not certain about connecting mathematical modeling with humanities, he was relatively confident with other disciplines, including the social sciences. This shows that students recognized STEM's interdisciplinary potential is promising, suggesting the feasibility of using STEM projects to address many topics in non-STEM disciplines. Considering that sustainability is often discussed in the context of natural sciences, such as ecology, this finding confirms STEM projects' potential to explore sustainability issues from different angles.

4.3.3. Students Recognized the Potential of Mathematical Modeling as a STEM-Based Tool for Future Prediction

Consideration of future societies is intertwined with an awareness of sustainability. During the interviews, we found positive indicators that using STEM tasks increased students' consideration of the future. Student 8 said she was not at all familiar with mathematical modeling at the beginning. In her reflection sheet for the sixth session, she indicated that her familiarity with mathematical modeling had increased. The interviewer asked her to describe mathematical modeling.

> Interviewer: How would you explain mathematical modeling to your friend?
>
> Student 8: I'd use examples to explain it, like, mathematical modeling is about coming up with a model to explain a phenomenon, predict the future, or draw the kind of conclusion I want. I might give more specific examples as well, such as a Markov chain. I'm reading web comics, and one of them is entitled "how to do mathematics well." The main characters in it try to solve an equation, which explains a natural phenomenon. I think that's mathematical modeling, too. It's about predicting how it would change. To think about it, I saw in an American television show a mathematician who could super precisely foresee phenomena, including the movement of a drop of water. All those sorts are modeling. If we could predict the trajectory of a drop of water from a fountain, we could make one that doesn't splash water to people.

Student 8 passionately stated her understanding of mathematical modeling, which is a tool for prediction. She drew on cultural references such as comics and television shows. The equation she was referring to is the Navier–Stokes equation to describe the motion of fluid substances. The examples Student 8 gave address mathematics connected to real-world situations. The end goal of such mathematical investigations for prediction, as embedded in Student 8's example of developing a water fountain, is to improve human lives. One could consider mathematics as an abstract activity disconnected from daily lives. Student 8, however, became able to appreciate using mathematics to predict the future to improve society.

Student 9 developed a similar perspective.

> Interviewer: Please explain mathematical modeling to me.
>
> Student 9: It is an activity that organizes real-world problems into data, transforms those data mathematically, and then goes through a certain process, such as a Markov chain, to reform the data to be used in the future.

Student 9 thus indicated that mathematical modeling has to do with organizing existing data for future use. He hesitated over the "certain process" part because the Markov chain was the only mathematical tool used in this project, and he wanted to try other mathematical tools. He showed no hesitation in stating that the purpose of modeling is to prepare data for future use. These excerpts support that STEM projects are well positioned to stimulate students' consideration of future society.

5. Discussion

Without question, bringing ESD into school classrooms is a critically important issue. In this study, we investigated how to bridge STEM education using practical mathematical modeling with ESD. According to our findings, STEM education using mathematical modeling induces positive changes in students' perceptions about the effective use of STEM for predicting future societies and sustainable development.

Our findings suggest that STEM education using mathematical modeling is an effective strategy for teaching students to predict the needs of future societies and make responsible decisions that promote harmony among the environmental, economic, and social domains. To enable sustainable development, education should help students grow into democratic citizens who can see society changing and make decisions appropriate for current and future generations. To achieve these goals, school education should provide students with experiences that anticipate reality and future situations and with experiences in making reasonable decisions by communicating with others. According to the results of our survey about students' perceptions of mathematical modeling, they had learned to recognize mathematical modeling as a useful strategy for exploring STEM tasks about the present and future situations and making good decisions for themselves, the environment, and society. Therefore, we suggest that future teachers, especially mathematics teachers, develop lesson plans that combine STEM tasks with mathematical modeling to improve their students' competence in areas required for sustainable development. In addition to mathematical modeling, it is also possible to utilize activities observing and simulating individual and social behaviors [60] or ruling the evolutionary processes embedded in robots [61] in order to promote each student's competencies for predicting future societies and making reasonable decisions, which is in turn necessary for sustainable development.

In this study, we focused on mathematics among other STEM subjects. Considering that mathematics has seldom been discussed as a subject for teaching sustainability, this study's contributions are significant. More research that foregrounds mathematics should follow. In this study, we focused on Markov chains, but students could use other mathematical concepts to understand the present and future society. A possible extension of this study would be inviting students to choose not only the topic but also the mathematical approach to use. By participating in the STEM project we designed, students became more confident in using mathematics to deal with real-world situations. The project, however, is not entirely practical because students were asked to use a Markov chain. Thus, students had to choose a topic to which a Markov chain could be applied. A follow-up project could allow students to choose any topic of investigation and then identify the proper mathematical tools to solve the problem. Such a project would require significant preparation from the instructor, could only be run with a small number of students, and would require other supports to allow significant interactions between the instructor and the students. Nonetheless, it is worth exploring because practically contextualized tasks are known to be effective for teaching sustainability [42].

It is important for students to realize that the process of problem-solving in the real world is not as linear as simple mathematics problems. Realizing that problems in the real world are complex and experiencing them in advance could help students improve their problem-solving competency. That is, through STEM education, students could accumulate experiences of problem-solving that will strengthen their willingness to solve problems. In the sense that willingness is a critical component of mathematical problem-solving competency [50], the change in students' perceptions toward mathematical modeling that resulted from our STEM project has important implications for education.

In this study, we showed that changes made at the course level can effectively teach sustainability through STEM, echoing the findings of prior research [42]. A three-week long intervention was sufficient to allow students to recognize STEM as a relevant area for discussing sustainability. We wonder, however, whether the effect could be even more substantial had the project lasted half a semester or even a whole semester. As discussed earlier, the STEM project we implemented can be easily extended in a variety of ways. In addition, we have not investigated the long-term effects of our STEM project on the students who completed it. Perhaps those students will continue thinking about sustainability in the future, but we do not have evidence for that. In fact, previous researchers claimed that support beyond the course level is needed to create substantial changes [62]. Students could benefit from institution-wide support that offers full-semester long courses about sustainability and invites students to take multiple courses before they graduate.

The STEM project implemented in this study was developed by following suggestions from prior research to promote group interactions [43]. Although we grouped students, hoping that they would collaborate productively with one another, we are well aware that small group work is not always productive [63]. That is, students take more or less productive positions depending on their group interactions [64,65]. Some students said during the interviews that they enjoyed working as a group and that all group members contributed during the project. Perhaps most students in our study worked productively, but we cannot make that generalization about all students everywhere. Therefore, we suggest that future researchers closely examine how students interact in groups when learning about sustainability in a STEM course. Considering that sustainability is essentially about society and the real world, student backgrounds might have a larger effect than when they work on abstract STEM.

We developed the STEM project we implemented in this study ourselves. In our design, we did not intend for the poster session to be an opportunity for student learning. During the interviews, however, students indicated that they practiced modeling skills when reading each other's posters. In addition, the students conceptualized the modeling process somewhat differently from our predictions based on the literature. Therefore, one significant contribution of this study is the discovery of a learning opportunity that has often been neglected and of alternative paths students might take during the mathematical modeling process. Despite our research findings, we do not expect all university instructors or K–12 teachers to have the resources needed to develop projects for teaching sustainability. In other words, all university instructors and K–12 teachers may not be well positioned to introduce sustainability in STEM classrooms, no matter how much they are interested in it. One way to address this obstacle is an online repository for educators and researchers to accumulate projects that promote sustainability.

The project was implemented to a selected group of students, but we argue that it speaks to a wide range of people. First, the Markov chain, the main tool used in the project, is mathematically simple. To understand and use the Markov chain, it requires some experience with linear equations and matrix multiplication only. Secondly, Markov chain is used in a range of situations, including STEM fields, economics, sociology, and other diverse disciplines. Therefore, this project can be applied when teaching or training people from different backgrounds while meeting their present and potential future needs.

The results reported here validate the effectiveness of STEM tasks for promoting ESD. Providing opportunities to participate in a STEM project, such as using mathematical modeling to predict the future, supports the development of positive learning outcomes for students. Selecting a topic close to their lives allowed students to deeply engage with it. As a requirement of the project, students were asked to predict the future and suggest action plans based on their predictions. This study offers an example for educators who want to use STEM courses to stimulate student thinking about sustainability.

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