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Integrating Sustainability Reflection in a Geographic Information Science Capstone Project Course

Forrest Hisey¹, Valerie Lin² and Tingting Zhu^{1,*} ¹ Department of Geography, Geomatics and Environment, University of Toronto Mississauga, 3359 Mississauga Rd., Mississauga, ON L5L 1C6, Canada² Institute for Management & Innovation, University of Toronto Mississauga, 3359 Mississauga Rd., Mississauga, ON L5L 1C6, Canada* Correspondence: tingting.zhu@utoronto.ca; Tel.: +1-905-569-4556

Abstract: Higher education institutions have played a central role in building sustainability awareness. However, current models only show an effect on students' knowledge about sustainable development, with a large gap in transformative solutions that shift from understanding problems towards solutions. This case study explores a new model that integrates sustainability reflections in a Geographic Information Science (GIS) Capstone Project course. Through collaborations with external partners and reflections on sustainability modules, students analyzed complex problems and developed sustainability competencies. The assessment tool adopted in this study combines reflective writing, scenario testing, performance observation, and self-assessment. Based on the set of key competencies in sustainability, half of the students developed systems-thinking and strategies-thinking, while a quarter of the students developed futures-thinking and values-thinking. Their development of sustainability competencies went beyond simply acquiring knowledge, also critically evaluating different perspectives and implementing or integrating the concepts when addressing the problems. Geospatial information tackles three key aspects of sustainability, which are relational, distributional, and directional, making it ideal in analyzing sustainability issues and providing insights for informed decisions. This study fills another important gap of integrating sustainability competency development in GIS education.

Keywords: integrated sustainability education; reflective assignments; geographic information science; combined assessment tool

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1. Introduction

As a response to complex anthropogenic problems including climate change, biodiversity loss, and social tensions, private and public sectors are rapidly increasing the incorporation of sustainability-related values and practices into individual and organizational decision-making [1,2]. However, sustainability solutions require intensive collaborations with a multitude of diverse stakeholders and are grounded in different systems including economic, environmental, social, and cultural aspects [3]. Such complexity can challenge existing decision-making frameworks, where collaboration and synthesis slow as professionals struggle to integrate information.

To address these issues, higher education institutions (HEIs) have been actively contributing to the United Nations (UN) Sustainable Development Goals (SDGs) through outreach, assessment and reporting, research, education, and campus operations [2]. As a major framework for guiding sustainability teaching, SDGs seek to promote a shared socio-cultural and socio-ecological resilience within our global society [4]. The 17 goals,

including no poverty, zero hunger, good health and well-being, quality education, affordable and clean energy, climate action, and so on, paint a blueprint for peace and prosperity now and in the future that cannot be achieved without global partnership and strategic assessment of goal achievements (<https://sdgs.un.org/goals>, accessed on 15 May 2022). HEIs have played a central role in building sustainability awareness, producing and disseminating knowledge, and supporting responsible research with funding [5]. Although this model has an effect on students' knowledge about sustainable development, research shows its limitation in transformative solutions that require problem-solving, interpersonal competence, systems-thinking, futures-thinking, and strategic and normative competencies to make actionable changes [6,7]. It is suggested that integrating SDGs into higher learning should not reduce these frameworks to just reflections on present-day problems but must instill new behaviors that facilitate strategy development skills [8]. Such new behaviors move beyond the boundaries of traditional academic or research organizations and foster leadership of transdisciplinary partnership by weaving a network connecting government, business, civil society, and academia to put knowledge and competencies into action [6].

The sustainability competency framework, first proposed by Wiek et al. (2011) and later revised by Redman and Wiek (2021) [9,10], includes systems-thinking, futures-thinking, values-thinking, strategies-thinking, implementation, inter-personal, intra-personal, and integration competencies. Since then, there has been a slight shift to action competence-oriented education [11]. This provided an opportunity for sustainability pedagogy to create and support differing value-systems, often through experiential action-oriented learning [12]. In other words, it addresses a mismatch between what students are being taught and what they “do” [13].

Sustainable solutions involve integrating interdisciplinary knowledge, considering spatial interactions, and projecting trends. Geospatial technologies have been applied in multiple domains to assess sustainability and address sustainability-related issues, such as in agriculture and renewable energy [14,15]. This is because geospatial information addresses three key aspects of sustainability, which are relational (attributes), distributional (space), and directional (time) [16]. These align with the key sustainability competencies, including systems-thinking and futures-thinking. For example, by integrating interdisciplinary information regarding social, economic, and environmental aspects in the geographic information science (GIS), it allows decision makers to systematically think about the relational impact on all these aspects. The spatial analysis and geographical inquiries help students understand connections among places and establish collaborations at different scales. With the directional analysis, we can monitor how sustainability issues evolve over time. Most importantly, the maps and other visualizations created by GIS can facilitate understanding about complex sustainability issues [16]. However, the integration of geospatial technologies and sustainability in pedagogy is still a conceptual model with few implementations. This study explores the interconnectedness between sustainability and geospatial thinking, and it addresses the role of GIS education in advancing sustainability goals.

2. Sustainability in Higher Education

2.1. Sustainability and Higher Education Institutions

HEIs have taken active measures to contribute to sustainable development since the UN Conference on the Human Environment in 1972, significantly increased their engagement in sustainability after the UN Conference on Environmental Education in 1987, and have increasingly published their impact on sustainable development since 2014 [2]. Their initiatives have mostly focused on outreach, assessment and reporting, and non-academic impacts of research, followed by education and campus operations [2]. The research on

educational interventions around sustainability has mostly assessed students' changes in their perceptions and attitudes, or their acquisition of knowledge on sustainability concepts [17]. Assessments on competency, especially non-cognitive dimensions, have been limited [7,18].

Many institutions have created new sustainability-related programs to attract students, teach concepts, and help students develop competencies. In the meantime, researchers call for a more holistic approach to develop sustainability competencies in all students across different departments [19]. The holistic approach is two-fold; one to enhance the individual's interdisciplinary knowledge and systems-thinking to overcome the fragmentation of knowledge and perspectives in higher education [20], and the other to integrate curriculum into other programs such as business and computer technology [21,22]. The awareness of the need for a complex, holistic, and transdisciplinary approach to sustainability has been increasingly growing [20].

2.2. *Integration of Sustainability in GIS Education*

The integration of sustainability education in other programs, besides environmental and engineering-related topics, has emerged recently [23]. It has been rarely implemented in many educational domains [24]. The challenges include the lack of leadership at the faculty and university level [25]. However, to support sustainability goals, interdisciplinary collaboration and integration across programs are necessary, as this helps students to understand how their actions and decisions affect the environment and society [21].

Sustainable solutions require mitigation strategies across disciplinary, spatial, and temporal boundaries. Geospatial technology provides an interactive platform to analyze complex location-based relationships and integrate information from different layers through a spatial framework that supports students' critical thinking, analytical, and communication skills [26]. Empowered by computation, it provides a universal medium—maps that are geared toward the human brain to facilitate cognition about complex sustainability issues [16]. Elshof (2009) stated that technology education has a great opportunity to help young people build sustainability and called for integrating sustainability concepts into technological literacy, preparing youth to create a positive and sustainable future [27].

As of today, very few studies have reported the integration of sustainability in GIS education, with even fewer providing assessment of such integration. Hwang (2023) [16] proposed a conceptual model for university students to explore sustainability issues using five geospatial inquiries, including spatial distribution, spatial interactions, spatial relationships, spatial comparisons, and temporal relationships [16]. Technological pedagogical content knowledge (TPACK) model was proposed and implemented in both secondary and university classrooms [8]. At the university level, four activities were designed to integrate the TPACK model into geography education; however, the results have not been reported [8]. Other efforts were mostly focused on geography teacher training [12,28]. This lack of study provides a sizable gap to explore, especially considering the role that GIS has in supporting the SDGs. For example, GIS can support novel transportation planning [29], assessing social vulnerability [30], and managing land sustainably, which contribute to SDG 11—sustainable cities and communities, SDG 10—reduced inequalities, and SDG 15—life on land, respectively [31]. As GIS provides powerful tools for collecting, analyzing, and visualizing spatial data, it is critical for understanding and providing solutions for sustainability challenges such as climate change, biodiversity loss, resource management, and urban planning. Integrating sustainability into GIS education allows future GIS professionals better analyze and address sustainability-related issues. As such, GIS education equips students not only with technical proficiency but also with ethical awareness and applied knowledge that can drive positive social impacts.

2.3. Sustainability Competency Framework

Wiek et al. (2011) proposed a widely accepted set of key competencies in sustainability, including systems-thinking, futures-thinking, values-thinking, strategies-thinking, and interpersonal competencies [9]. Systems thinking is defined as the “ability to collectively analyze complex systems across different domains (society, environment, economy, etc.) and across different scales (local to global), thereby considering cascading effects, inertia, feedback loops and other systemic features related to sustainability issues and sustainability problem-solving frameworks” [9]. Values-thinking, also called normative competence, is focused on “ability to identify, map, specify, negotiate, and apply sustainability values, principles, and goals” [9,10]. Futures-thinking refers to the “ability to carry out or construct simulations, forecasts, scenarios, and visions: (1) to anticipate future states and dynamics of complex systems and sustainability problems; and (2) to anticipate how sustainability action plans (strategies) might play out in the future (if implemented)” in the modified framework [10]. With slight modifications in the updated framework, strategic-thinking looks to the “ability to build and test viable strategies (action plans) for interventions, transitions and transformations towards sustainability” [10]. Interpersonal/collaborative competency centers on the “ability to motivate, enable, and facilitate collaborative and participatory sustainability research and problem solving” [9]. Later, it was expanded to implementation competence, inter-personal competence, intra-personal competence, and integration competence [10]. These competencies collectively emphasize putting sustainability strategies into actions through collaboration, resilience, and self-care. Integration competence refers to the “ability to apply collective problem-solving procedures to complex sustainability problems in collaborative and self-caring ways” [10]. A group of experts reviewed the framework of key competencies and set detailed learning objectives that can operationalize the framework [32]. They also highlighted the importance of critical thinking as a basic academic competency. Several experts proposed an implementation competency, defined as “the collective ability to realize a planned solution toward a sustainability-informed vision, to monitor and evaluate the realization process, and to address emerging challenges (adjustments), recognizing that sustainability problem-solving is a long-term, iterative process between planning, realization, and evaluation” [32].

Unlike the agreement on a competency framework, a consensus has not been reached regarding assessment tools for sustainability competencies. These can be categorized into eight distinct types, including scaled self-assessment, reflective writing, scenario test, focus group/interview, performance observation, concept mapping, conventional test, and regular course work [7]. A recent review suggested a shortage of empirical evidence of whether pedagogies were successful in developing students’ sustainability competencies due to a lack of intentionally selected tools [7]. Another review found that the modeling and measurement of non-cognitive competencies was under-researched [18].

Most of the non-cognitive outcomes were self-reported by participants instead of direct indicators [18]. Such measurements were mostly based on individual’s subjective perceptions and may not be accurate if individuals interpret the scales differently. Nevertheless, self-assessments are easy to administer, analyze, and scale, making them popular. Each type of assessment has its own strength and weakness. For example, reflective writing is easy to administer or be included as a course assignment and has been proved to support student learning, but its analysis can be time consuming. Scenario tests allow students demonstrate competence in a real situation, but they only include a limited and hypothetical representation of reality. Therefore, it is suggested that combining tools may be the best way to address the shortcomings of any assessment [7]. Effectively assessing the pedagogical innovation in sustainability education remains a critical gap.

2.4. Action-Oriented Approach

Successful sustainability curriculums should provide students with frameworks, tools, and skill sets that prepare them for addressing complex challenges and facilitate sustainable development [33]. One such strategy is equipping students with the competencies that will facilitate actionable and sustainable transformations [7]. However, after reviewing 357 studies published between 2013 and 2020 on higher education for sustainable development, Probst (2022) did not find coherent insights into what should be learned and how [34].

Recently, many researchers have emphasized action competence, which goes beyond simply acquiring knowledge and understanding sustainability issues [17,35]. The focus is shifting towards empowering individuals to critically analyze issues, evaluate different perspectives, and actively contribute to sustainable development. Wiek and Lang (2016) argue that sustainability learning has two distinct streams of research [33]. Firstly, the descriptive–analytical stream focuses on addressing problems through a process where they are described and analyzed with a systems approach. This process builds a thorough understanding of “wicked” environmental issues that cut across aspects of social, political, economic livelihoods [36]. Secondly, the transformational approach is focused on developing solutions through an evidence-supported process and real-world applications. The transformational sustainability approach requires suitable methods that are transparent, structured, and replicable to provide detailed action plans on how to solve the problem and reach the vision [33]. Such actions will be applied in real-world problems that depend on stakeholders’ willingness to implement, therefore requiring close collaborations between academia, business, government, and civil society [33].

In order to provide supportive pedagogy to foster transformative sustainability learning, real-world opportunities and a variety of formal and informal spaces are necessary [37,38]. These spaces can include self-guided, experiential, interactive, interdisciplinary, and reflective processes for students to encounter and explore such “wicked” problems [36]. Experiential learning and participatory learning approaches have been proven to be effective in developing action competence [17]. Brundiers et al. (2010) found that reflections in upper-level capstone courses provide students with space to reflect on advanced theories and solutions while understanding the difficulties of real-world problem-solving [37].

3. Research Goals

In this case study, we explored another possible model where students can collaborate with multiple stakeholders in addressing real-world sustainability issues and gain sustainability competencies through the experience of a GIS capstone project. The purpose of this model was to assist in filling several gaps, including the integration of sustainability into another field—GIS education—and the expansion of insights into how experiential learning strategies can be deployed to support students in solving “wicked” problems. To encourage critical thinking and analysis of sustainability, we developed modules and integrated reflective practices throughout the term. The reflections prompted students to think about how the presented examples relate to, or inform, their current projects, future careers, or personal life. The assessment tool combined different types, including self-assessment, reflective writing, scenario testing, and performance observation, which fills another gap. We aimed to answer the following research questions.

- (1) In what ways do reflective practices on sustainability modules affect how students develop competencies on sustainability in the context of completing a GIS project?
- (2) How do sustainability competencies developed by students through reflections transfer into their GIS capstone projects?
- (3) What are the limitations of the integrated reflections on sustainability modules?

4. Case Study

4.1. Institution and Course Context

The experiment took place in a research-intensive public institution in Canada that offers both graduate and undergraduate programs. About 30% of the undergraduate students are international students. The top three countries of the international students' origin were China, India, and The United States. The faculty-to-student ratio was 1:6.

Our department offers five undergraduate programs, including GIS, physical geography, human geography, environmental science, and environmental management. Sustainability-related courses are offered in environmental science or management programs. SDGs such as good health and well-being, as well as reduced inequalities, may be integrated in GIS courses as part of spatial analyses, but these have not been systematically taught in the GIS program. A connection between sustainability and GIS has not been established yet. Other courses in the GIS program include introduction to GIS, spatial data science I and II, cartography, geographic information processing at introductory and advanced levels, remote sensing courses at different levels, cloud-based image analysis, spatial database, space time data analysis, and applications in different fields such as transportation, health, biogeography, and environmental modeling.

Over the past three years, we have been implementing the model in a 4th year undergraduate GIS Capstone Project Course. It has been designed as an experiential learning course where students propose solutions to real-world problems brought by external partners. The partners include local communities as well as global business stakeholders. There have been a total of 12 projects and 10 distinct partners in the past 3 years. Students formed groups of 3–4 students when completing the projects. The course ran for 12 weeks with an additional reading week around the mid-term. Each project had its related sustainability goals. For example, the project on automated prediction of crop yields in Togo targeted SDG 2 of zero hunger, food security, and improved nutrition. Another project on congestion analysis of electric vehicle charging stations targeted SDG 7, affordable and clean energy.

The three co-authors designed and drafted modules to prompt the students to think critically about sustainability and to support the integration of sustainability design in their capstone projects. The students were asked to submit a reflection on the modules on a weekly basis in 2022 and on a biweekly basis in 2023 and 2024. The change in frequency was due to student feedback showing an overburdened workload. More details about the sustainability modules are provided in the next section.

4.2. Sustainability Modules and Reflections

Nine modules were developed for the course. Topics included systematic thinking and business, connecting local to global, introduction to the SDGs, urban agriculture, air pollution, water quality, clean energy, and university–city partnership. Each was structured into three distinct parts, including reading, commentary, and discussion questions. Two example modules are provided in the Supplementary Material, and a brief description of each part is provided below.

Reading—Each begins with curated readings that provide a robust foundation of knowledge on various sustainability topics. These readings include academic articles, case studies, government reports, SDGs, or videos that highlight the multifaceted nature of sustainability challenges and solutions.

Commentary—Following the readings, we drafted commentary that delves deeper into the subject matter. This section aims to clarify complex concepts, offer diverse perspectives, and connect the readings to broader themes and current events. The commentary serves as a bridge between theoretical knowledge and practical applications.

Discussion Questions—To foster critical thinking and active engagement, each module concludes with a series of discussion questions. These questions are designed to provoke thoughtful reflections, encourage dialogue, and challenge students to consider how they can integrate sustainability principles into their projects, future careers, or personal life.

The students were asked to submit a reflection to respond to discussion questions after reading an assigned module or a module of their choice. The reflections were assigned as individual assessments and posted on a discussion board in a learning management system. After a student posted their own reflections, they received access to view other students' posts and were encouraged to comment on their peers' reflections. Reading and commenting on how peers reflected can bring about new learning opportunities as well.

4.3. Participants, Survey, and Data

We surveyed the entire class population across 3 years. After removing the responses from students who did not consent to have their data collected, a total of 34 samples were collected, with 6, 12, and 16 participants from years 1, 2, and 3, respectively. The sample represents 74% of all students enrolled in the course. Out of the 34 participants, only 3 of them previously had taken a course where they worked on collaborative projects with partners outside the university. About 13 students had experience with reflective assignments prior to this course. All data collection occurred after receiving ethics approval from the University of Toronto, protocol number 41470.

To ensure the validity of the research with a small sample size, we adopted strategies such as triangulation and adequate engagement [39]. We collected multiple sources of data including a survey and reflections, and we cross-checked the participants' responses through observations of the students' performance. We spent adequate time collecting data through term-long reflections and engagement with students inside and outside of the class.

A web-based survey was conducted during the last week of each term. The survey was co-created by a research assistant and the course instructor, with consultation from an educational developer. The questions covered (1) prior experience with collaborative projects and reflective assignments and (2) experience with reflective assignments on sustainability modules in this course (see Supplementary Material). These questions explored how the students benefited from reflecting on sustainability modules at three different levels, including (1) the cognitive level of remembering and understanding sustainability concepts; (2) the critical thinking level of analyzing different perspectives; and (3) the action-oriented level of implementing or integrating the sustainability concepts. According to the revised Blooms' Taxonomy [40], "remember" refers to "retrieving relevant knowledge from long-term memory" and understand is "determining the meaning of instructional messages". Critical thinking cuts across multiple dimensions of Blooms' Taxonomy, including analyze, evaluate, and judge [41]. The integration and implementation competencies are defined in Section 2.3. The students were also invited to comment on how to improve future assignments, encouraging active participation and critical thinking.

The survey results were first independently coded by two of the authors using NVIVO 12. We followed the five phases of thematic analysis [42]. First, two authors independently became familiarized with the data, generated initial codes, searched for themes, and reviewed themes. Following this, the initial findings were compared, and a consensus was reached after discussion. With the common codebook, we recoded each survey and extracted the coded responses for further analysis and discussion.

4.4. Performance Observation

In this course, the instructor graded all the formative assessments and provided feedback to students on a weekly basis. The students' reflections as well as their project implementation were graded and analyzed. Rubrics were provided to the students prior to each assessment due date. After the course concluded, we further conducted content analysis on the reflections based on the set of key competencies in sustainability as the framework. The analysis of the assessments provided insights into the students' competency development and the level of integration of sustainable design into their projects.

In summary, our assessment tool is a combination of self-assessment, reflective writing, scenario test, and performance observation [7]. Scaled self-assessment asked the students to "rate their own competency development based on a pre-determined scale" [7]. In this study, due to the projected small sample size, we adopted a binary scale, "yes/no" paired with open-ended questions for self-assessments. Reflective writing provided space for the students to respond to "prompts reflecting on their competency development" [7]. Scenario/case test asked the students to respond to specific competency-requiring prompts after being presented with a case [7]. Performance observation in this context refers to the evaluation of the students' sustainability competencies in the process of carrying out their capstone project. It leverages the strengths of each to overcome the weakness of the others.

5. Knowledge and Competency Development Around Sustainability

Most of the students (65%) responded that they benefitted from the inclusion of reflective assignments in the course. As participant #11 noted, "Reflective assignments provided a valuable space for self-examination and improvement. They prompted introspection on personal growth, critical thinking, and course insights. This process enhanced my understanding, allowing me to apply theoretical knowledge in practical contexts. The assignments fostered self-awareness and deepened my connection to the course content". They are beneficial in terms of expanding their knowledge (59%) and understanding (56%) of sustainability concepts and thinking more critically (53%) about them (Table 1). A small portion of the students (26%) reported that the reflections increased their ability to integrate or implement sustainability concepts.

Table 1. Counts of responses to closed questions.

Questions *	# Yes	# No
Did you find the reflective assignments beneficial?	22	12
Did reflective assignments help you to <i>remember</i> sustainability concepts?	20	14
Did reflective assignments help you to <i>understand</i> sustainability concepts?	19	15
Did reflective assignments help you to <i>think critically</i> about sustainability concepts?	18	16
Did reflective assignments help <i>integrate</i> sustainability concepts <i>into your work</i> ?	9	25
Did the reflective assignments benefit your <i>ability to implement</i> sustainability concepts?	9	24

* Note: One participant did not respond to the last question. Since the sustainability modules were implemented as reflective assignments, all of the questions refer to this practice as "reflective assignments".

The following subsections present how students benefitted from reflecting on the sustainability modules across three levels: a base level of knowledge and comprehension, a mid-tier level focused on critical thinking, and a higher level of integration and implementation.

5.1. Knowledge and Comprehension

At the foundational level, the students reflected on the examples and stories from the modules and connected the concepts to their own projects, academic experiences, or personal lives. Such connections and storytelling make the learning more relatable, helping most of the students to better remember or understand sustainability concepts.

“They help me understand [sustainability concepts] because they had stories in them (i.e., the water contamination in indigenous communities)”. —Participant 30

“In one of the reflective assignments, I had to connect my project to the sustainability concept. This made me better understand the concept as I was applying it to something I had a deeper knowledge about, and made the concept more relatable, and easier to understand”. —Participant 14

“It helped me to keep the concept of sustainability on the top of my head, and noticing things around me that are linked to sustainability”. —Participant 8

“Reflective assignments have helped me understand sustainability concepts by making me connect them to real-life situations. For example, analyzing case studies by writing about what worked and what didn’t for sustainable businesses helped me understand systems thinking and the importance of balancing environmental, social, and economic factors”. —Participant 28

This echoes previous research, which identified reflective assignments supporting various cognitive processes, such as retaining information and analytical reasoning [43,44]. This is because the reflective writing provides them with a space to derive meaning in their own terms [45]. This study confirms that reflecting on sustainability examples and connecting to their own GIS capstone projects help students retain knowledge on sustainability concepts. However, cognitive processes alone are not a panacea for sustainability pedagogy. While reflective assignments can and do support these skillsets, they have several limitations. For example, they are difficult to apply in certain systems such as outcome-driven ones that focus on deliverables [44].

5.2. Critical Thinking

At the critical thinking level, the students mentioned that the reflective assignments provided a space where they could think about sustainability from different perspectives, the connections between different SDGs, and self-examine what they learned in connection to practical contexts. Their critical thinking was in synergy with the foundational level, as most of the students felt that they improved their ability to remember concepts from the modules, especially when provided with an opportunity to critically reflect and think deeper.

“Some of the articles cited in the module are critical analyses that allow us to think about sustainability from a different perspective”. —Participant 5

“I think the reflective assignments definitely helped me think more critically. I think in the process of trying to formulate an answer for the reflection I really had to analyze the concept and try to apply it to the course overall and our individual project. Further, reading and analyzing other responses to the assignments helped me see the concepts through a different lens which expanded my understanding giving me a more holistic view about the topic”. —Participant 4

These quotes highlight how reflective assignments can support analyzing complex issues from multiple perspectives. As students gain self-awareness through reflecting on their own experiences, they also extend that awareness beyond, questioning how different groups of people are facing the same issue. In addition, the findings of the reflections helped

the students to form a holistic view that draws interconnectedness to the interdisciplinary dimensions of sustainability and analyze the complex environmental-socio-ecological systems, which are consistent with other studies [46].

“Reflective assignments allowed me to reflect upon my own work which is imperative in order to have some form of progress. By understanding what you have done, you can even learn from your experiences and others through reflections”. —Participant 17

By providing space, time, and structured prompts, the students were able to collect their thoughts, analyze them, and then externalize their thoughts into reflections that supported critical thinking and metacognition. One previous study similarly found that reflective assignments supported higher-order cognitive processes by providing space for students to engage in critical thinking [43]. This is supported by other research, which found that connecting personal experiences to learned concepts is a key benefit of reflective assignments [46]. Students deepen their critical thinking by relying on lived, personal experiences, where they translate concepts beyond the classroom [46]. Furthermore, the students were able to draw connections between different SDGs and comment on how strategies to achieve different sustainability goals may be complimentary, mutually beneficial, or even antagonistic to each other.

“The reflective assignments do help me to think critically on the SDGs including how can we measure the goals and how can we achieve one goal without affecting the progress of another goal”. —Participant 2

Through reflections, the students were able to think beyond simply working toward a single goal, and they instead began to reflect on how the SDGs were measured and how strategies might impact other goals that are connected. Without accurately measuring the problems or current status, we are not able to manage problems or achieve goals [47]. Recognizing the importance of geospatial information in measuring the problems or goal achievements, the United Nations Economic and Social Council established the United Nations Committee of Experts on Global Geospatial Information Management in 2011. Fourteen global fundamental geospatial data themes were identified and integrated into multiple institutions such as mapping agencies and statistical offices as an effort to help governments make informed decisions to support the SDGs. Our results show that integrating sustainability reflections into GIS education also enhanced students’ GIS&T competencies such as critical thinking, analytics and modeling, and domain application [48].

5.3. Integration and Implementation

Fewer students found that the reflections enhanced their ability to integrate or implement sustainability concepts in their work or life. This does require the students to transfer their knowledge and skills and apply them at a much higher level. For the students who did reach this level, they applied their GIS skills in solving problems encountered in other fields such as environmental science, or they integrated sustainability concepts into their projects or other professional endeavors.

“The articles from the sustainability modules booklet help me better understand how to incorporate my GIS skills into SDG goals and it really benefited my other project from my ENV course, which I feel I can take this advantage and touch upon more different data interpretation and analysis”. —Participant 11

This demonstrates that through reflections, the students were able to draw connections between geospatial thinking or GIS technical skills and achieving sustainability goals. Other research has found that reflective assignments are useful for reducing knowledge fragmen-

tation and connecting between different classes [49]. This required the students to think about and actively relate the different concepts and methods to different course outcomes.

“I was able to discuss how sustainability is important in our project and the benefits it would bring to people and stakeholders. I was able to incorporate some of the concepts in the reports we wrote”. —Participant 30

“Reflective assignments facilitated the integration of sustainability concepts into my work by encouraging a systematic evaluation of environmental implications. For instance, reflecting on project decisions highlighted the importance of eco-friendly practices, leading to the integration of sustainable strategies in subsequent work. This approach improved my ability to seamlessly incorporate sustainability into various professional endeavors”. —Participant 7

“Reflective assignments helped integrate sustainability concepts into my work by providing opportunities to connect theory to practice. Through the process of reflection, I was able to critically assess how sustainability principles apply to my projects and ensure they were embedded in my decision-making”. —Participant 29

This is one of the first studies to show the effectiveness of helping students to achieve integration and implementation levels of sustainability competencies [50]. It is also the first study in the context of a GIS course that measured this achievement. Since the GIS projects were acquired from multiple partners in diverse sectors, including agriculture, transportation, health, ecosystems, and energy, the students could map GIS to different domain applications. As students typically struggle with conceptualization of abstract concepts and applying geospatial knowledge when solving problems [48], the integration of sustainability into their projects provided another opportunity for the students to practice abstract conceptualization.

However, our data suggest that the reflective assignments provided only modest benefits at this level, as the students largely did not feel they made meaningful progress compared to lower-level benefits. The reflections supported a few students in integrating and using sustainability concepts into their real-life experience. Compared to other cognitive-dimension-only progress [18], it went a step further. However, it only supported very few students, suggesting room for improvement in implementing reflections as a pedagogical tool for building sustainability competencies, especially the key ones that can support the transmission and application of sustainability concepts into problem-solving frameworks. Nevertheless, key barriers for students to achieve this were identified in this study. First, a few students did not see a direct connection between their GIS projects and the SDGs due to a limited understanding of the scope of these goals. Second, the students viewed themselves as analysts instead of action-drivers in their capstone projects. This overlooks the power of accurate analysis or modeling as a first step in addressing sustainability problems [33]. Third, the students did not think they had any control over external partners' final implementation plans. Further interventions could focus on these disconnections.

In summary, from the students' perspectives, the reflective assignments helped them to consider the complex and dynamic nature of sustainability problems. By visualizing the issues through maps and geospatial analysis, it helped the students to better understand the problems and therefore devise solutions. By supporting the students in acquiring sustainability knowledge, critically analyzing different perspectives, and synthesizing information into action, the reflective assignments reinforced transformational approaches to sustainability solutions [33]. At the lower tier of a foundational comprehension of sustainability concepts, the students connected previous knowledge to new content. At the intermediate tier, the students developed critical thinking and metacognition. At the

upper tier, the students integrated the sustainability concepts learned in sustainability modules in their GIS projects or personal life. In addition to these tiers, the students also reported that they developed general research skills, communication skills, collaboration skills, and personal introspection. Some of them fit into the inter-personal and intra-personal competencies [10] that are important in both sustainability education and GIS education [48].

6. Sustainability Competencies in Capstone Project Implementation

By grading and analyzing the students' reflective assignments and their GIS project implementations, the instructor observed that about half of the students demonstrated systems-thinking and strategies-thinking, and about a quarter of the students demonstrated futures-thinking and values-thinking. Such competencies benefited the students in integrating sustainability design into their projects.

6.1. Systems-Thinking

The following responses were categorized into systems-thinking according to the sustainability competency framework [9,10,51,52]: identification of spatial interconnections; the interactions between the economic, environmental, and socio-cultural aspects; the importance of a life-cycle analysis of products; the connections between different spheres; and the importance of interdisciplinary collaborations.

For example, some students initially overlooked the connections between local and global events. Reading examples in the modules helped them to realize that pollution may not be contained at one location but could be mobilized to other places. Even though the students had learned about this connection and highlighted its importance after the reflective practice, they did not take the initiative to incorporate this change in their project assessing the impact of air pollution. A few reasons can potentially explain this lack of action. First, the students had fixed milestones to achieve, and incorporating changes may have delayed their process. Second, it required more effort for the students to learn skills beyond what they deemed necessary, and this acted as a learning barrier for them. For example, it required the students to collect data from neighboring regions, which may be organized in a different schema, as well as applying some spatial analysis taking distance decay into consideration. Nevertheless, the reflections did raise the students' awareness that they would need to take a further step.

"Our local project is connected to a global system because although we are mapping the spatial distribution of pollution data and seeing its impact on the Peel Region, pollution does not remain in our region. Due to weather patterns (wind) this pollution starts off in a local area (Peel), moves into regional area (ex Dufferin) and then enters the global system. . . In class I have generally ignored this sustainability concept because I didn't really think of it, I was so focused on the Peel Region I did not consider that air pollution is mobile and eventually enters regional and global systems". —Participant 6

In contrast, other students integrated what they learned from the modules into their GIS project. For example, beyond their project goals, the students further assessed whether their objectives to increase the crop yield and enhance the economic growth would have socio-cultural or environmental consequences. To avoid negative impacts, they suggested strategies to maintain awareness of traditional practices by consulting their mentor, who had contact with local farmers. Such practices ensured that their spatial model and algorithm design respected the cultural and environmental context of stakeholders. It also demonstrated that the students were mindful of impacting other SDGs when trying to achieve one goal.

“In our project, we have carefully assessed the potential sociocultural and environmental consequences. We understand the need to balance technological and economic growth with environmental preservation and cultural preservation. For example, in developing our tools for agricultural monitoring, we took into account the potential effects of how climate resilience strategies may affect traditional practices and livelihoods. Our goal is to ensure that the models we aim to develop do not disrupt local food systems or cause further environmental degradation. Instead, we aim to contribute to sustainability by providing tools that enhance resource efficiency while respecting and supporting the cultural and environmental context of the stakeholders who choose to use the algorithms. . . . Our mentor’s direct communication with local farmers allows us to adapt our algorithms to their needs. This ensures that economic growth does not come at the expense of their land, culture, or health”. —Participant 30

Reflecting on different modules also helped the students to move away from blind spots or superficial reasoning to drawing deeper connections such as using a life-cycle analysis. At the beginning of the term, some students were not able to identify any relationship between their projects and sustainability. For example, some students commented that investigating patterns of air pollution had nothing to do with sustainability. Later, they were able to associate their project with the SDG of reduced inequality. By visualizing the map showing air pollution patterns, green space distribution, and socio-economic status, the students found that socio-economically disadvantaged groups were more susceptible to air pollution and had less green space around them. A few other students initially drew superficial connections, such as the reasoning that providing infrastructure for electric vehicles is equal to promoting sustainability. After reflecting on the modules, the students were able to think more critically and analyze the life-cycle of a product. For example, the students started to investigate the source of electricity in California and found that a large portion was converted from thermal and non-renewable energy such as natural gas, defeating the purpose of the end products. Other students applied the life-cycle analysis to guide their assessment matrix design.

“The project we have is about finding the cheapest electricity rates in the region for lowering commercial electric vehicle operation costs. This can be connected to the global system from different perspectives, such as energy sources, the production of EVs as well as waste management. For example, if the energy provider used non-renewable energy such as fossil fuels to produce electricity, it will add more CO₂ emissions to the global system which will be meaningless for the transition to EV in transportation industry, more research should be done on renewable energy”. —Participant 3

“When we analyze the environmental impact of a regional sea cucumber farm, although the impact of the farming industry on the water environment is spatially limited, the final product is marketed worldwide and with the involvement of various downstream industries, a small sea cucumber farmed in Panamanian waters enters the world food industry with global economic, environmental and socio-cultural impacts. . . . When analyzing the carbon footprint or environmental impact of a company, industry or product, each stage of its life cycle should be considered and analyzed using different methods and strategies”. —Participant 2

Some modules prompted the students to identify how changes in one sphere (i.e., biosphere) impact another (i.e., hydrosphere) in the context of their own projects. For example, in a project where the students investigated the spatial patterns of an invasive species, phragmites, they identified that removing these plants may enhance water quality

as well. Although the students did not extend their analyses into a different sphere due to the project scope and timeline, such connections could benefit them if they oversee more complex projects in the future.

“I believe that our project has an indirect positive impact on the hydrosphere because it assists in removing and preventing containments in the Credit River watershed and consequently the global watershed”. —Participant 25

“Furthermore, our project also has indirect effects on the hydrosphere and, consequently, the food web, primarily through its focus on agricultural monitoring. By using satellite data to monitor soil moisture, crop health, and evapotranspiration, we aim to optimize water usage in farming. Additionally, effective water management reduces the risk of over-irrigation and water waste, which can benefit the hydrosphere by protecting water supplies and lowering the danger of contamination from agricultural runoff. This could sustain the larger food web and preserves the integrity of nearby water systems”. —Participant 30

By working with their external partners and reflecting on a module focusing on the university–city collaboration, the students highlighted the importance of interdisciplinary collaboration in addressing sustainability issues.

“If I were to initiate collaboration with universities, governments, or corporations to achieve my goals, I would take inspiration from factors outside geography, demographics, and politics like interest in sustainability, individual and collective competencies in sustainability, and sustainable actions. I would focus on reciprocity as a rule of thumb for fostering collaboration between different institutions. Acknowledging what each stakeholder can bring to the table and what each lacks invites more meaningful partnerships and development. Expanding on this, by isolating points of weakness in competencies across stakeholders—between universities and governments, for example—stable collaboration and the building of diverse teams is vital”. —Participant 24

In another study where the students were engaged in mental mapping and reflections, they developed basic systems thinking such as viewing the urban environment as a complex unit with interacting components and identifying feedback-loops and cause–effect relations [51,52]. This confirms the effectiveness of the spatial component of GIS in helping students establish spatial interconnections. The reflections on events or impacts along different dimensions fosters thinkings on cause–effect relationships and cascading effects. With GIS, students or professionals may create maps showing the spatial covariations of different attributes. Caudill et al. (2024) further proposed to integrate the Western scientific approach and indigenous knowledge systems through geospatial technology to leverage complementary perspectives, knowledges, and capacities to obtain a holistic understanding of political, philosophical, psychological, emotional, relational, anthropological, and ecological dimensions [53,54].

6.2. *Strategies-Thinking*

Some students focused on their use of GIS to produce accurate maps and take different strategies in communicating data to audiences, such as developing algorithms and performing hot spot analysis. The visual analysis aligns with step 1—problem analysis in complex problem handling according to the four methodological frameworks for transformational sustainability research [34,55]. Developing algorithms to model future outcomes aligns with the foresight stream that projects the problem into the future to depict plausible future states [33]. Although both employ methods in the descriptive-analytical family, which do not directly translate into solving the problem, they do provide a helpful first step [33].

“We can utilize available data such as remote sensing images when evaluating how sea cucumber farms affect the environment to minimize the energy used during on-site data collection. We will need to consider if our procedures can replicate for most existing sea cucumber farms. Such as further developing an algorithm storing the analytical process to reuse and reproduce in further evaluations”. —Participant 5

“In order to show where the highest levels of violations, inspections, and accidents take place, we will also perform a hotspot analysis to determine in which areas they are happening”. —Participant 20

Some students addressed the importance of maintaining objectivity while producing maps and ensuring the replicability of their approach. Some also became aware of the inaccuracies in acquired data and the associated bias or uncertainty. Studies show that different methods of representing geographical information can shape the discussion of sustainability, therefore influencing the implementation of solutions [55]. If the students were to make maps for stakeholders or become professionals who produce visualizations for decision makers, it is important for them to be strategic in curating data and creating maps so that information is not misinterpreted.

“In my opinion, if I want to show the message objectively, then I need to consider the purpose of a map that is based on the user’s demands, not expressing my personal message and opinion”. —Participant 16

“I will try to compare data from multiple sources because it is important to see whether the data across different sources are consistent among each other and the results are not skewed in any form”. —Participant 26

“Furthermore, Alberta’s transportation data may not account for informal or non-conventional transportation methods such as community-run shuttles or carpooling networks. These gaps could introduce biases in our analysis, making certain regions appear more isolated than they are in practice. We will ensure that various transportation options are considered, incorporating a multi-layered approach that provides an in-depth analysis. For example, we will explore different modes such as public buses, trains, and bike-sharing systems or walking paths”. —Participant 29

Other students further analyzed scenarios using different parameters to model real-world situations, assisting stakeholders in implementing their projects. Testing viable strategies for interventions is considered as an important aspect of strategies-thinking competence [10].

“To overcome these challenges... We plan to run multiple “what-if scenarios” using the OD Cost Matrix and Location-Allocation tools to simulate various transit improvements. This will help us understand how our proposed solutions will perform under different conditions, such as varying travel demand or future road improvements”. —Participant 29

It is evident that the students applied different strategies gained from different courses in the GIS program, including foundational GIS concepts, cartography, and spatial data science. The integration of sustainability provided further opportunities for the students to transfer these skills into different contexts and close the gap in knowledge and skill fragmentation.

6.3. Futures-Thinking

Fewer students demonstrated futures-thinking competency. For the students who did, they evaluated possible outcomes based on past events, which further guided their decisions or analyses, and they reasoned how actions might develop in the future.

“This is important for us to consider when conducting our analysis because while we’re trying to determine a potential solution for this remote indigenous community, we also need to keep in mind the previous environmental issues they have faced and how we need to develop a plan that would maintain as much sustainability as possible”. —Participant 26

“By showing comparisons between this year’s data and the data from the past twenty years, this can start the discussion on why trends in mine workplace violations, inspections, and accidents are changing”. —Participant 20

GIS has been used in depicting future scenarios or states in multiple research or educational interventions, and it has proved to be effective in identifying areas for interventions or solutions [56]. The fact that very few students demonstrated futures-thinking could be due to the project goals set by the partners, most of whom were more interested in the current states. Incentives like bonus marks could potentially encourage students to take extra steps in generate future scenarios.

6.4. Values-Thinking

A few students were able to identify the conflicting interests of varying groups and understand different societal demands. While acknowledging the current issues and status, the students were trying to make progress in their project. The ability to deal with disputes and conflicting goals is a key competence in tolerating ambiguity and frustration [57]. Equally important is the ability to put oneself in other people’s position and to accept diversity.

“In the end, while mining is not a sustainable process, we understand that current societal demands prevent us from shifting away from a heavy reliance on it. Our bigger goal hopefully leads to a safer work environment for those in the force, at least until we figure out better alternatives so that we as a society can start to move forward towards more sustainable resource practices and away from mining”. —Participant 12

Some students openly shared their own values or valued participation and support from the public in promoting sustainability. It is important to note that educated citizens are an important foundation for a sustainable future. However, individuals can easily become overwhelmed if they are burdened with many responsibilities [57]. Realizing that sustainability is a collective mission can help students to alleviate burdens.

“Taking sustainability into account in real-world projects ensures a long term, positive influence on society, the environment, and the economy. These are things I value and therefore, in my opinion, it becomes exceedingly crucial during project implementation. What attracted me to working with Sofvie is the project’s strong focus on sustainability via community well-being. Utilizing GIS to emphasize mining accident hotspots serves a dual purpose: protecting the well-being of workers as well as a valuable tool for advocating for sustainable mining practices to prioritize the safety and health of workers who quite likely live in communities nearby”. —Participant 19

“Thirdly, public support and participation are important for cities and can be encouraged by crowdsourcing data with open GIS platforms. This would allow

for public engagement at a level that can inform larger stakeholders like the city, who benefit from public support for sustainability projects”. —Participant 24

In summary, integrating reflective assignments into the GIS capstone project course helped about half of the students to implement systems-thinking and strategies-thinking in their projects. Since such interventions have not been applied in any other GIS courses, we were not able to draw comparisons with other studies in the field. A study in a different field that integrated reflections in a service-learning course used a combination of surveys, reflections, and concept maps to assess outcomes, also reporting successful enhancement of student sustainability competencies in systems thinking and action-oriented competences [50]. Similarly, they reported less success in helping students to achieve futures-thinking competence.

Students’ or future professionals’ holistic analysis and modeling through GIS tools and mapping may help stakeholders make informed decisions and take actions to make real-world changes. Combining reflections with external collaborations, this course built an environment where students had opportunities to analyze such “wicked” problems. This created non-traditional approaches to integrate sustainability learning into GIS education [16], where both qualitative and quantitative methods provided space for diverse problem-solving across dynamic societal spheres [12,58].

7. Limitations of Integrated Reflections and Recommendations

Integrated reflective assignments do have limitations. The primary impediment is the time commitment required by the instructor or instructional team. Carefully designing modules that are relevant to students’ learning experience takes significant effort, and grading reflections is also time consuming. Such barriers may make it hard to adopt these methods in large classes. Nevertheless, reflection has been proven to be an effective educational pedagogy to support learning outcomes related to sustainability [50]. It has also been widely adopted in service-learning or experiential learning courses. Such action-oriented learning, even in a short course, has been demonstrated to support students in developing a wide range of sustainability competencies [59]. Therefore, it is worthwhile to invest in helping students to develop these competencies and solve complex problems.

Reflections alone have a few weaknesses, such as the challenge of interpretation, students’ limited understanding of competencies, and the impact of the incentives to engage [7]. To overcome these limitations, we combined ungraded surveys to incorporate students’ perspectives and observed their performance from the instructor’s view to objectively assess their ability to integrate sustainability in their projects. In addition to their own projects’ problems, the students also reflected on a few cases or scenarios in modules or from their peers’ projects.

The analyses of the students’ reflections and survey responses showed that some did not take the reflections seriously. Some held a negative attitude towards the reflections and deemed them as useless in terms of achieving their project goals, while others only provided superficial reflections. Such attitudes make the reflective practices less meaningful. We observed that the students who held negative attitudes toward the reflections did not develop or had marginal development towards sustainability competencies. As such, the results we observed represent a lower magnitude of effect compared to what we would have observed if all students had practiced meaningful reflections. To encourage meaningful reflections, motivations at the beginning of the term can be incorporated. Prompting students to think about what constitutes a good reflection, like what Migliorini and Lieblein (2016) did, can be considered [59].

Higher education continues in transforming existing pedagogy to support the next generation in solving sustainability problems. GIS education can potentially play a sig-

nificant role in this transformative change. The next generation of students needs to be exposed to new learning strategies that integrate and connect concepts across entrenched knowledge gaps [1,9]. Current frameworks are failing at providing novel strategies for students to bridge these gaps [6,7], lacking the tools to make conceptual learning grounded in sustainable real-world practices. We presented a case study that integrated sustainability in GIS capstone projects where students address complex real-world problems in collaboration with external partners. Although this new model has some limitations, the evidence shows that the students developed sustainability competencies at different levels.

8. Conclusions

This case study shows that through reflections on sustainability modules and completion of their capstone projects, students developed systems-thinking and strategies-thinking, as well as futures-thinking and values-thinking to a lesser extent. The students developed competencies at different levels: (1) remembering and understanding sustainability concepts; (2) critically analyzing complex sustainability issues; and (3) implementing or integrating sustainability solutions in their projects or personal life. As most studies have focused on the cognitive dimensions of sustainability education, this study fills the important gap of helping students to develop action-oriented competencies. This is also the first study that integrates sustainability reflections into GIS education.

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