CASE STUDY PEDAGOGY

# Improving Student Learning Through an Interdisciplinary Case Study: Exploring Eutrophication in Lake Erie

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ABSTRACT This pedagogical project examined how embedding an interdisciplinary case study in an undergraduate ecology course impacted student learning outcomes. Specifically, we examined learning outcomes following participation in a group-based case study project, which asked students to adopt the role of an expert phycologist, microbiologist, agronomist, or limnologist in order to jointly investigate the problem of eutrophication in Lake Erie. We examined student learning outcomes on exam questions that tested students' knowledge of eutrophication compared to their performance on exam questions that tested knowledge of course content taught using traditional lecture-based methods. We also examined how students' recognition of the value of interdisciplinary approaches to solving science problems changed across the semester, as well as changes in students' views of the ways in which the skills and knowledge of their major could contribute to solving eutrophication problems and the complex problem of climate change. Results indicated significant increases in student understanding of eutrophication through comparisons of pre- and posttest scores, and dramatic twofold increases in student learning on the eutrophication exam questions relative to the content taught using traditional instructional methods. Interestingly, at the end of the course, the non-science majors in the course were more likely to endorse interdisciplinary approaches for solving complex science problems than were the science majors in the course. Implications for educational practices for both major and nonmajor science courses are discussed.

## INTRODUCTION

Undergraduate teaching in the biological sciences is rapidly evolving in response to research demonstrating that active learning techniques are more effective at furthering student learning than traditional lecturing to a passive audience [1, 2]. The recent meta-analysis by Freeman et al. [3] presented a compelling case for active learning in the science/technology/engineering/mathematics (STEM) classroom, noting that students in lecture-based classes are 1.5 times more likely to fail than students in classes that incorporate active learning practices. Science content delivered in lecture format can be particularly difficult for non-STEM major students, who may lack interest in STEM fields and fail to see the relevance of STEM content to their daily lives [4]. Thus, non-STEM major students may benefit even more than STEM-majors from an applied, active-learning approach to science content.

The traditional model of university teaching keeps disciplines strictly siloed, which can have some advantages in terms of delivering specific kinds of content efficiently and encouraging collaboration among faculty and students within disciplines. However, the twenty-first century workplace is increasingly requiring collaboration and cooperation across disciplines as well as across geographic and cultural boundaries [5, 6]. Additionally, familiarity with disciplines outside their personal expertise helps students become informed citizens and consumers of knowledge. Therefore, it is imperative that university teaching evolve to include more opportunities for students to practice interdisciplinary thinking and collaboration.

The Vision and Change in Biology Education Report [7] emphasizes that biological concepts are best learned when they are presented in societal context and applied to problems that are relevant and important to the learn-

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ers. Case studies can be a particularly effective vehicle for incorporating active learning pedagogy while also demonstrating the relevance of environmental issues in a broader, interdisciplinary context through a specific example. Case studies are a form of problem-based learning; case studies present students with a real-world, complex problem and challenge them to identify the methods, tools, and stakeholder engagement they need to solve the problem [8]. For environmental issues, this is likely to require integration of methods from different scientific disciplines as well as information from non-science disciplines and the perspectives of multiple stakeholders. Thus, we propose that engagement with this form of problem-based learning naturally leads to increased interdisciplinary thinking.

The literature indicates that engagement with interdisciplinary problems can contribute to meaningful learning gains for students, including expanding students' perspectives and raising their awareness of the disciplinary biases they may hold [9] as well as helping students learn to synthesize divergent expert opinions into a complex, multidisciplinary solution to a complicated problem [10]. We suggest that interdisciplinary work may be particularly important for non-STEM majors in science classes because such exercises highlight ways in which the students' own interests and majors connect with real-world problems that the students once perceived as personally immaterial. This may motivate non-STEM majors to learn the science and increase their perceptions of themselves as relevant and necessary team members in solving these problems.

The Interdisciplinary Eutrophication Case Study (IECS) was developed by L.J.A. with input from J.R.Y. and S.L.B. as part of a project funded by the Andrew W. Mellon Foundation to S.L.B. and J.R.Y. to create teaching and assessment tools designed to enhance interdisciplinary thinking for undergraduates at Ohio Wesleyan University. The IECS was specifically created for a large, introductory ecology and environmental science class *Ecology and the Human Future* (EHF) and focused on the issue of toxic algae blooms in Lake Erie, a consequence of the process of eutrophication.

Eutrophication is defined as the fertilization of surface waters with nutrients that were previously scarce, and while the slow transition of lakes from a nutrient-poor system (oligotrophic) to a nutrient-rich one (eutrophic) is a natural process that can occur over centuries or millennia, the process of cultural eutrophication, stemming from nutrient run-off due to human activities such as agriculture, can happen within a few years and is a water pollution problem with a global scope [11]. Cultural eutrophication manifests with abundant growth of short-lived algae, eventual loss of oxygen from the water column as large amounts of algae are decomposed by the aquatic microbial community, and the decline of various forms of aquatic life due to the low oxygen levels. Biodiversity, food webs, fisheries, aesthetics, water recreation and tourism can all be negatively affected. Water quality for human consumption can also decline when certain algal species become abundant and release toxins into the water, a phenomenon known as a harmful algal bloom (HAB) [12]. Eutrophication in Lake Erie was recognized as a significant problem in the 1970s and was reduced with aggressive management of nutrient inputs into the lake, but has been on the rise again over the last two decades, as evidenced by increased algal biomass correlated with increased loading of soluble reactive phosphorus [13], more incidents of hypoxia in the lake hypolimnion [14], and more incidents of HABs [15]. The water quality problems in Lake Erie entered national news in 2014 when residents of Toledo, Ohio, USA, were unable to drink their tap water for several days due to algal contamination [16]. This event led to greater potential for eutrophication to be a highly relevant case study topic for students at Ohio Wesleyan, which is located in central Ohio, about 3 h south of the shores of Lake Erie. Other authors in this journal have also recognized the importance of this topic and developed case studies focused on teaching about eutrophication in this region [17].

The pedagogical goals of the IECS were to (1) help students place science and ecological issues in a broader societal context, (2) empower non-majors to see themselves and their expertise as effective agents in solving environmental problems, (3) increase active learning pedagogy in EHF in order to improve student engagement with the class material, and (4) improve student understanding of the ecological interactions involved in the process of eutrophication. Specific research questions that arose from these goals were: Does an interdisciplinary, active-learning, case-based approach to teaching eutrophication (1) enhance student learning of science content relative to material presented in a lecture-only format? (2) Does it improve student learning of science content for non-STEM majors more than for STEM majors? (3) Does it enhance interdisciplinary thinking for all students?

## METHODS

### *Class Information and Context*

L.J.A. is the sole instructor of EHF, which is offered annually and enrolls large numbers of non-science majors across all class years (Table 1). The class is a core requirement for the university's Environmental Studies major, and serves as a popular general education requirement for the natural sciences. The class consists of two 80-min lecture periods per week; there is no lab component. Learning goals for the class as presented on the syllabus in Fall 2015 are presented in the Supporting Information (page 14).

EHF was developed by L.J.A.'s predecessor prior to her arrival at Ohio Wesleyan in 2001 and has a long history in the Ohio Wesleyan curriculum. It has generally been taught using traditional methods, with students listening to lectures, completing out of class textbook reading assignments, and being assessed using in-class exams. L.J.A. has been gradually phasing in more active learning exercises and assignment diversity over time. EHF now includes an in-class experimental design exercise for pairs of students, frequent small group discussions of primary literature and in-class videos, and an out-of-class assignment to build a web page on an environmental or ecological topic. However, lecture-based instruction and exams are still a major focus of the class (see lecture schedule from the syllabus in the Supporting Information, pages 13–14).

**TABLE 1.** Characteristics of students enrolled in Ecology and the Human Future from Academic Year 2011/2012 through 2015/2016.

| Student trait | Percentage of students |
|---|---|
| **Gender** | |
| Female | 63 |
| Male | 37 |
| **IPEDS ethnicity** | |
| 2 or more ethnicities | 2.5 |
| Asian | 2.9 |
| Black or African American | 8.0 |
| Hispanic | 4.2 |
| International | 4.6 |
| Unknown | 2.9 |
| White | 74.8 |
| **Class year** | |
| First year students | 9.2 |
| Sophomore | 31.1 |
| Junior | 23.5 |
| Senior | 36.1 |
| **Major** | |
| STEM majors | 9.2 |
| Undeclared | 26.9 |
| Non-STEM major | 63.9 |

Notes: A total of 237 students attended the class during this period. Class sizes ranged from 45 to 53 students. IPEDS, Integrated Postsecondary Education Data System; STEM, science/technology/engineering/mathematics.

### *Research Design*

The IECS was used in both the Spring 2015 and Fall 2015 sections of EHF. The methods for each section were the same. Students received an extensive written handout with instructions for completing the IECS before they received any in-class instruction on the topic of eutrophication (see Supporting Information pages 1–6). Students were required to complete an online pretest outside of class at the start of the assignment, and took the same test, with an additional question about their impressions of the assignment, at the end of the assignment as a posttest (Table 2). Completion of the pre/posttest was linked to a portion of the student's grade on the interdisciplinary assignment (5% for each) but students were allowed to opt out (without penalty) of having their data used in this study by checking the appropriate box on the pre- and posttest forms. Students who opted out were removed from the data set before scoring any responses.

The IECS involved the following steps:

1. L.J.A. provided an overview of the ecological interactions involved in eutrophication using a lecture with figures and text presented in PowerPoint after the students had completed their pretests. This lecture took one 80-min class period.

2. The entire class read the primary literature article "Record-setting algal bloom in Lake Erie caused by agricultural and meteorological trends consistent with expected future conditions" by Michalak et al. [15], and a New York Times article by Michael Wines [16] reporting on drinking water problems in Toledo, OH, linked to eutrophication. The instructor then divided the class into Eutrophication Research Teams of four students. Each student in a team assumed the role of a scientific expert on one component of the eutrophication processes discussed in the article by Michalak et al. (2013) [15]. Each group had

    - A phycologist (algae specialist) researching the algae genera *Microcystis* and *Anabaena*

**TABLE 2.** Pretest and posttest questions and scoring rubric.

Question 1. What does the word "interdisciplinary" mean to you? Answer in one to five sentences.

| Score | Score explanation |
|---|---|
| 1 (novice) | The answer is brief, vague, and may use the term to define the term, or the student may not know what the term means. Example: "It means using many disciplines." |
| 2 | The answer is clear and correct, but brief and general. Example: "It means to approach a problem from many different perspectives." |
| 3 | The answer is clear, correct, and provides some specific insights about the term. Example: "Interdisciplinary means to use the tools and ways of thinking from many different fields of study to explore or solve a problem." |
| 4 (expert) | The answer is clear, correct, and shows understanding of the potential for synthesis and creativity in interdisciplinary situations.<br>Example: "Interdisciplinary means to combine tools and ways of thinking from many different fields of study to explore or solve a problem and possibly create new ideas, products, or solutions that arise from the synthesis of diverse perspectives." |

Question 2. Why is an interdisciplinary approach important for solving environmental problems? Answer in one to five sentences.

| Score | Score explanation |
|---|---|
| 1 (novice) | The answer is brief, vague, and does not provide a strong argument for using an interdisciplinary approach. The answer may just restate the prompt. Example: "You need different approaches to solve environmental problems." |
| 2 | The answer is brief, but <u>provides one reasonable justification</u> for using an interdisciplinary approach. Example: "Environmental problems are multi-faceted so diverse tools and approaches are needed to develop solutions." |
| 3 | The answer provides <u>one reasonable and detailed justification</u> for using an interdisciplinary approach. Example: "Environmental problems are multi-faceted so diverse tools and approaches are needed to appropriately address the different components of the problem. A single discipline may not recognize and be ready to address all the components." |
| 4 (expert) | The answer provides <u>more than one reasonable and detailed justification</u> for using an interdisciplinary approach, or provides examples of how different disciplines might contribute. Example: "Environmental problems are multi-faceted so diverse tools and approaches are needed to appropriately address the different components of the problem. A single discipline may not recognize and be ready to address all the components. Also, environmental problems involve many stakeholders and a single disciplinary approach may not address the needs of all the stakeholders." |

Question 3. How can/does your major discipline(s) contribute to solving the problem of climate change? Answer in one to five sentences.

| Score | Score explanation |
|---|---|
| 1 (novice) | The answer is brief, vague, and does not provide a strong case for the possible contributions of the student's discipline, or denies that the discipline relates to climate change. Example: "The skills of an English major could be used to communicate better about climate change." |
| 2 | The answer is brief, but provides a reasonable case for the possible contributions of the student's discipline. This score is also appropriate for double majors that see connections with climate change for one major but not the other. Example: "Communicating science to the public is necessary for broad understanding of climate change and the skills of an English major could facilitate this communication." |

**TABLE 2** *Continued*

| | |
|---|---|
| 3 | The answer provides a detailed, reasonable case for the possible contributions of the student's discipline, with at least two concrete examples. Example: "Communicating science to the public is necessary for broad understanding of climate change and the skills of an English major could facilitate this communication through newspaper articles and briefs for policy makers." |
| 4 (expert) | The answer provides a detailed, reasonable, and sophisticated case for the possible contributions of the student's discipline, with at least two arguments and two specific examples. Example: "Communicating science to the public is necessary for broad understanding of climate change and the skills of an English major could facilitate this communication through newspaper articles and briefs for policy makers. Scientists may also need help editing their work to make it more understandable to the public and to fellow scientists and the skills of an English major could help here as well." |

Question 4. Explain, in your own words, the ecological interactions and processes involved in eutrophication.

| Score | Score explanation |
|---|---|
| 1 (novice) | The student does not know what eutrophication is. |
| 2 | The student can define eutrophication, but the majority of ecological interactions are not correctly explained or not mentioned. |
| 3 | The student can define eutrophication, and correctly explains the majority of interactions, but has some omissions or errors. Some discussion of hypoxia (low oxygen) must be included to earn this score. |
| 4 (expert) | The student can define eutrophication and gives a complete and correct description of the ecological interactions. The roles of fertilizer run-off, algae blooms, and aquatic decomposers and hypoxia must be correctly explained to earn this score. |

Question 5. (Posttest only) Do you feel this assignment improved your understanding of eutrophication and/or your capacity to think from an interdisciplinary perspective? Provide any comments or feedback on the assignment you wish to.

Open response – not scored formally

- A microbiologist researching the decomposer community of freshwater lakes
- An agronomist (farming specialist) researching agricultural practices
- A limnologist (lake specialist) researching patterns of lake turnover and mixing

3. Each student independently studied sources relevant to their expert topic in order to answer questions assigned by the instructor about their topic (see Supporting Information pages 3–5 for more details). The instructor provided links to web-based, reliable information sources for the students relevant to their assigned topic. The students were expected to delve beyond the level of detail presented by L.J.A. in her overview lecture.
4. Each student then prepared a 5-min "mini lecture" based on these questions and presented their findings to their small group of four in a class in order to demonstrate how their expert topic related to the problem of eutrophication as described in the readings. Each student also prepared a short (1–2 pages) written summary on their assigned expert topic that served as notes for their mini lecture; this summary was also handed by L.J.A. for evaluation.
5. Each group of four students also filled out a peer evaluation form at the end of class to indicate how effective each expert was at presenting and teaching other students about their topic. This teaching effectiveness score was incorporated into the student's grade for the first phase of this assignment.

6. Each group of four students then discussed and prepared answers to a group worksheet in response to “Focus Questions” on the assigned primary literature paper and New York Times article (see Supporting Information, pages 7–8). These were questions designed by L.J.A. to prompt the students to examine particular figures and concepts covered in the readings.

This first phase was completed in one 80-min class period. The second phase was carried out in the next class period and consisted of the following steps:

1. All students read “Long-term and short-term interdisciplinary work: Difficulties, pitfalls and built-in failures” by Sverre Sjölander [18], and the “Lake Erie Binational Nutrient Management Plan” [19].

2. Each student prepared a short essay (1–2 pages) on how their own major(s) can contribute to managing nutrient inputs to Lake Erie, and discussed, at the end of the essay, whether the Nutrient Management Plan included the approaches outlined during discussion in Phase I and was sufficiently interdisciplinary.

3. Each group of four people assembled again in class and each person had 5 min to present to their group the ways in which their major(s) can and should contribute to nutrient management in Lake Erie, and whether the Binational Nutrient Management Plan includes these approaches.

4. The group then discussed focus questions on the readings (see Supporting Information, pages 9–10), and prepared a group worksheet with their responses.

*Scoring and Data Analysis*

Data were prepared for scoring by project assistant M. Witkovsky-Eldred. Student names, the status of the responses as pretest or posttest, and the semester of the response were removed from the data file, the responses were randomly sorted, and assigned an identification number. Any students who did not give permission for their responses to be used in the study were removed from data set, leaving a total of 154 responses; these anonymized responses were given to L.J.A. for scoring. L.J.A. scored the data using the rubric provided in Table 2, and J.R.Y. also scored the last 31 student responses in the same data file (20% of the responses) to test rubric reliability. L.J.A. and J.R.Y. had 100% concordance (scores for the same response identical or adjacent) on Questions 2–4 and 90.3% concordance on Question 1, therefore the rubric was considered reliable. Upon completion of the scoring, L.J.A. was given access to the non-anonymized data and removed any students who had completed only a pretest or only a posttest. This left a total of 65 students with complete information across the two semesters (total enrollment for the two classes combined was 94, 46 for Spring 2015 and 48 for Fall 2015). The scores for these students were matched with information about their class year, their declared major at the time of the class, and their overall letter grade in the class as measured on a traditional 0–4 scale, with 4 = A, 3.7 = A–, 3.3 = B+, 3.0 = B, 2.7 = B–, 2.3 = C+, 2.0 = C, 1.7 = C–, 1.3 = D+, 1.0 = D, 0.7 = D–, and 0 = F. Since students did not self-report gender or ethnicity, we did not include this information in our analyses. Students were assigned a code number for analysis by L.J.A. in order to keep data anonymized for the other researchers, since the data included student grades.

To compare student learning of eutrophication with similar ecological concepts taught by L.J.A. in the same class using traditional teaching methods, L.J.A. recorded point deductions she took on questions asked about the nitrogen cycle and compared these to deductions on questions on eutrophication on the first in-class exam given in Spring 2015. The nitrogen cycle was selected for comparison because (1) it had a similar level of ecological complexity to the process of eutrophication (unlike the phosphorus cycle, for example, which is relatively simple), (2) appeared on the same exam as eutrophication, and (3) the exam questions had similar point values (Table 3). L.J.A. scored the tests as usual, but recorded the scores for these individual questions separately, in addition to the overall exam grades.

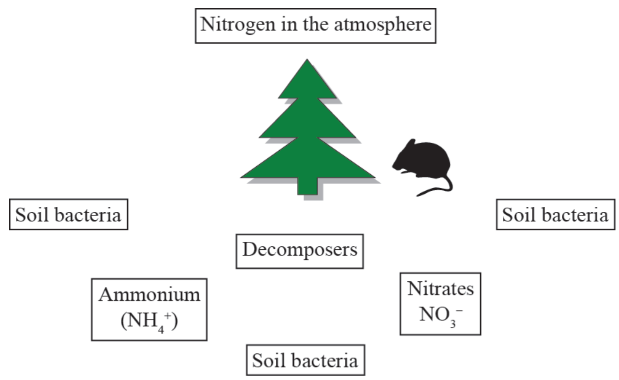
Data were analyzed using the Statistical Package for the Social Sciences. Pre- and posttest scores were compared separately for Questions 1–4 using paired-samples t-tests. Multiple linear regression was used to assess the influence of class year, status as an STEM major or non-STEM major, and pretest score on the posttest score to explore the relative effects of these factors on posttest performance. Finally, paired t-tests were also used to compare student performance on nitrogen cycle questions vs. eutrophication questions on Exam 1.

**TABLE 3.** Questions on the nitrogen cycle and eutrophication from Exam 1 during the Spring 2015 section of EHF.

Exam Questions 9 and 10 on the nitrogen cycle:
9. Briefly define/describe the steps of the nitrogen cycle on the lines below. The first one is done for you to serve as an example. These steps are not presented in a particular order. (2 pts each)

A. nitrification Bacteria convert the ammonium ion ($NH_4^+$) to the nitrate ion ($NO_3^-$)
B. nitrogen fixation ____________________________________________
C. ammonification____________________________________________
D. denitrification ____________________________________________

10. Use labelled arrows (for example, use an arrow labelled "denitrification" that goes from one box to another) to add all the steps above into the diagram below to create a reasonable pathway that a nitrogen atom could follow from the atmosphere, through the ecosystem, and back to the atmosphere. You should involve the plant, the herbivore, decomposers, and soil bacteria of various kinds in this pathway. Make annotations and additions to the diagram as needed. Use your knowledge of the nitrogen cycle figure presented in lecture in this answer. (10 pts)




Exam Question 12 on eutrophication
12. Explain the connections between farming, nutrient loading, algae blooms, aquatic decomposers, lake stratification, and water quality and fisheries problems in Lake Erie. Stated another way, explain the ecological interactions involved in the causes and consequences of eutrophication in Lake Erie. Be sure to use the chemical equation describing respiration in your answer. (15 pts)

Note: The scores of these two questions were compared using a paired t-test to measure differences in student learning for ecological material taught using the intensive case study method (eutrophication) vs. traditional methods only (nitrogen cycle)

## RESULTS

Prior to running any descriptive or inferential analyses, we first examined whether there were semester-level differences between the Fall and Spring 2015 courses on the variables of interest. Thus, we conducted t-test analyses on the change scores (posttest - pretest) across these two semesters. There were no significant differences between semesters on Question 1 ($t(62) = -1.71$, $p = 0.09$), Question 2 ($t(62) = -1.64$, $p = 0.11$), Question 3 ($t(60) = -0.21$, $p = 0.84$), or Question 4 ($t(62) = -0.51$, $p = 0.61$); therefore, we collapsed the data across semesters.

According to comparisons of mean pre- and posttest scores across the questions, students were least familiar with the process of eutrophication (Question 4) at the start of the term, but they also displayed the highest level of average performance on this question on the posttest (Table 4). Importantly, as the scoring scale ranged from 1 to 4, it appears that the level of question difficulty on the pre- and posttests was appropriately challenging but not overly so. Paired samples t-tests comparing student performance between pretest and posttest assessment points revealed significant improvements on Question 1 ($t(63) = -4.03$, $p < 0.001$), Question 3 ($t(61) = -4.24$, $p < 0.001$), and Question 4 ($t(63) = -12.00$, $p < 0.001$), with a marginal improvement in performance on Question 2 ($t(63) = -1.90$, $p = 0.06$, Table 4).

Bivariate correlations between pretest and posttest responses indicated consistent positive correlations between scores on Questions 1 through 3 at both the pretest and posttest time points (Table 5). Question 4 scores were less consistently related to the scores on other questions asked at the same time point, which makes good conceptual sense, as Question 4 asked specifically about students' knowledge of the eutrophication process, which is in contrast to the broader, interdisciplinary focus of Questions 1 through 3.

We conducted a series of multiple regression analyses to test whether a student's class year (i.e., first-year, sophomore, junior, senior) or status as a natural science/environmental studies major (or not) predicted posttest performance, controlling for the students' pretest level of understanding (Table 6). The models predicting performance on Question 1 ($F(3, 61) = 0.21$, $p = 0.89$) and Question 4 ($F(3, 61) = 1.47$, $p = 0.23$) were not significant, but there were significant relationships between the predictors and posttest performance on Question 2 ($F(3, 61) = 2.78$, $p = 0.049$) and Question 3 ($F(3, 59) = 2.99$, $p = 0.038$, Table 6). These models revealed that while class level did not significantly predict performance on either question, non-science majors outperformed science majors or environmental studies majors on both these questions at the end of the semester. We also conducted an exploratory analysis to look at whether major predicted overall class performance. This analysis indicated that there was a significant difference between these two groups ($t(46.67) = 2.20$, $p = 0.03$): science majors outperformed non-science majors in their final grades in the course.

Finally, we examined whether there was a difference in exam performance between the questions that tested students' knowledge of the nitrogen cycle ($M$ = 48.77%, $SD$ = 28.60%) and performance on questions that tested students' understanding of the eutrophication process ($M$ = 81.37%, $SD$ = 17.50%). There was a significant difference in student performance on these two sets of questions ($t(47) = -8.53$, $p < 0.001$), such that students demonstrated dramatically higher performance on the eutrophication-based questions, which were taught using the case-based approach described above, relative to the nitrogen cycle-based questions, which were taught using a traditional, lecture-based approach.

**TABLE 4.** Testing Pre- and Posttest Differences for Questions 1–4.

| Question | Pretest mean (SD) | Posttest mean (SD) | $t$ | $df$ | $p$ |
|---|---|---|---|---|---|
| 1 (define interdisciplinary) | 2.02 (0.97) | 2.64 (0.84) | −4.03 | 63 | <0.001 |
| 2 (interdisciplinary approaches to environment) | 2.36 (0.86) | 2.63 (0.85) | −1.90 | 63 | 0.06 |
| 3 (your major and climate change) | 2.39 (1.00) | 2.98 (0.78) | −4.24 | 61 | <0.001 |
| 4 (describe eutrophication) | 1.52 (0.71) | 3.20 (0.84) | −12.00 | 63 | <0.001 |

**TABLE 5.** Correlations between pretest and posttest scores.

| Variables | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| 1. Pretest Q1 | 1.00 | 0.64** | 0.50** | 0.40** | 0.07 | 0.18 | 0.23 | 0.17 |
| 2. Pretest Q2 | | 1.00 | 0.52** | 0.42** | 0.09 | 0.14 | 0.02 | 0.29* |
| 3. Pretest Q3 | | | 1.00 | 0.28 | 0.09 | 0.33** | 0.24 | 0.31* |
| 4. Pretest Q4 | | | | 1.00 | −0.16 | −0.02 | −0.09 | −0.05 |
| 5. Posttest Q1 | | | | | 1.00 | 0.46** | 0.44** | 0.15 |
| 6. Posttest Q2 | | | | | | 1.00 | 0.56** | 0.38** |
| 7. Posttest Q3 | | | | | | | 1.00 | 0.27** |
| 8. Posttest Q4 | | | | | | | | 1.00 |

Note: ** $p < 0.01$, * $p < 0.05$. Q, Question.

**TABLE 6.** Regression models examining predictors of posttest question performance.

| Predictor | $\beta_{\text{Question 1}}$ | $\beta_{\text{Question 2}}$ | $\beta_{\text{Question 3}}$ | $\beta_{\text{Question 4}}$ |
|---|---|---|---|---|
| Pretest question performance | 0.07 | 0.29* | 0.24 | −0.11 |
| Science/EnvStud major or not | −0.08 | −0.31* | −0.30* | 0.23 |
| Class year | −0.04 | −0.09 | 0.09 | −0.13 |

Note: *$p < 0.05$.

## DISCUSSION

This study provides compelling support for the use of case-based approaches in the teaching of complicated ecological concepts such as eutrophication. Our data indicate substantial improvements in student learning on content taught using an interdisciplinary, case-based approach relative to content taught using a traditional lecture-based approach, consistent with previous work [3]. In addition, we found that the use of this teaching approach enhanced students' understanding of and value placed on interdisciplinary thinking and learning, an especially important perspective for people entering today's workforce.

Non-science majors were particularly likely to show improvements in interdisciplinary understanding, relative to science majors. There are several reasons this may have happened. First, as this was a natural science course, it is possible that the science majors were primed to think more narrowly about the content than their non-science major counterparts. In contrast, the non-science majors were taking a course outside of their disciplinary expertise and were likely engaging more interdisciplinary thinking in their interaction with the course material. A second, but less likely, explanation is that the science majors who took this course were less academically skilled, on average, than the non-science major students. This is a course that fulfills the University's natural science distribution requirement for non-majors and is known to be taught at a more introductory level than courses frequented by science majors. However, as the science majors earned higher overall grades in the course than did the non-science majors, this explanation lacks support. A third possibility is that the open-ended, essay format questions on interdisciplinary thinking in the posttest were targeted more to the academic skills of students majoring in humanities or social sciences (where more discussion and argument in writing may be expected of students), and therefore they showed higher performance on these questions than science majors. Regardless of the mechanism, this work indicates an important future direction for the teaching of natural science courses, which is to help students understand the inherent collaborative and interdisciplinary nature of the scientific enterprise itself, as well as its connections to other disciplines, particularly in the context of environmental problems.

Integrating this case study into the course required a high level of planning as well as time and resource allocation, which necessarily required that less course content was covered. The struggle between content breadth and depth of coverage is a constant one, and seems to be a particular tension in areas of study, such as the natural sciences, where there is a clear expectation that lower-level courses prepare students for upper-level course work. Our findings, however, suggest that using an interdisciplinary, active learning approach to deeply engage students with scientific skills and ways of thinking not only enhances learning of the course content but also helps students recognize the value of interdisciplinary thinking about complex, real-world scientific problems. This finding is consistent with the recommendations of the Vision and Change Report [7], which state that content in biology courses should be reduced and replaced with more experiential activities that involve students in the scientific process in order to maximize learning and engagement.

We expect that the characteristics and qualities of the case, in addition to focusing student attention on interdisciplinary thinking, will allow for transfer of knowledge and skills from the context of the EHF course to their other courses. The National Research Foundation report "Education for Life and Work: Developing Transferable Knowledge and Skills in the 21st Century" [6] laid out six features of effective teaching for transfer. This case employs several of these six, particularly engages the strategies of "encouraging elaboration, questioning, and self-explanation", "engaging learners in challenging tasks with supportive guidance and feedback", and "teaching with examples and cases". This case makes wide use of formative assessment (in addition to the summative grading), another characteristic of teaching for transfer. The use of problem-based learning is one of the features that promotes transfer across problems, courses, and situations.

The case particularly seems to have engaged the strategy of "priming student motivation" with interactive activities, providing multiple ways for learners to practice skills in the setting of the case, providing timely relevant support and allowing learners to understand their learning in the context of their prior knowledge [6]. While many of the students in the course were non-majors, they were able to apply their prior knowledge from their own majors to this problem in a way that was prescripted in form, but not in content. This is a significant strength of this case and was perhaps the key to get non-majors engaged with the material and to facilitate strong learning gains in these students.

The data collected here indicate that a carefully constructed, interdisciplinary case can improve students' disciplinary learning and increase their engagement in and appreciation of interdisciplinary thinking. While science students were still able to generate higher overall grades, the interdisciplinary case approach significantly raised the understanding and learning of students from majors outside the sciences. By engaging in real-world problems, the students at our liberal arts institution were able to see how their disciplines can inform and contribute to environmental issues that are of increasing concern to society.

## AUTHOR CONTRIBUTIONS USING CREDIT TAXONOMY

| | |
|---|---|
| Conceptualization | L.J.A. and J.R.Y. (equal) |
| Methodology | L.J.A. and J.R.Y. (equal) |
| Investigation | L.J.A. (lead) and J.R.Y. (supporting) |
| Data curation | L.J.A. |
| Formal analysis | S.L.B. (lead) and L.J.A. (supporting) |
| Funding acquisition | J.R.Y. and S.L.B. (equal) |
| Writing original draft | L.J.A. and S.L.B. (equal) and J.R.Y. (supporting) |
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## COMPETING INTERESTS

The authors have declared that no competing interests exist.

## SUPPORTING INFORMATION

Case Study on Eutrophication in Lake Erie and the Power of Interdisciplinary Thinking. Materials distributed to students.

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