

Space Mission Ecology: Making Connections Among Science Disciplines Through the Lens of a Unique Plant

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Abstract

With this case study, we aim to increase awareness of essential services plants provide to society, as well as the importance of fundamental aspects of ecology for other disciplines and the interconnectedness among different fields of science in general. The case study was designed to be implemented in two 75-minute class periods in an introductory university-level ecology course. This case study provides an interdisciplinary perspective by defining learning goals at the nexus of science and society, explicitly emphasizing (and embracing) the interconnectedness among different fields of science via student exploration and how an often under-appreciated sub-discipline of biology—plant science—is useful for other disciplines. We use plants from the family Lemnaceae (duckweeds or water lenses) as a hook to introduce what is needed to create a self-sustaining ecosystem in a habitat on the surface of a moon or planet, in orbit, or during long-duration crewed spaceflight. Following the 5E model of curriculum design, students explore their chosen scientific literature before presenting their findings. The structure of the case study and student presentations facilitate making connections between scientific practices, peers, and ecological concepts, enhancing understanding of science's interconnected nature and the importance of plants. After implementation of this case study in a Principles of Ecology course, students felt more comfortable interacting with, and making claims about, scientific material, better recognized the interdisciplinary nature of science, and were more aware of essential services plants provide for humans.

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Learning Goals

Students will be able to identify, evaluate, communicate, and value:

- ◊ essential services plants provide to human society.
- ◊ important fundamental aspects of plant science relevant to other disciplines.
- ◊ the interconnectedness among different fields of science in general.

In engaging with these content goals, students will develop and/or practice:

- ◊ evidence-based reasoning.
- ◊ effective communication of complex scientific content.
- ◊ respectful collaboration and integration of different perspectives.
- ◊ appreciation for the dynamic, interdependent nature of biological systems.
- ◊ From the Ecology Learning Framework
 - » How do organisms mediate the movement of matter and energy through ecosystems?
 - » How do organisms obtain and use matter and energy to live and grow?
 - » How are living systems interconnected and interacting?
 - » How do humans depend on ecosystems for their health and well-being?
- ◊ From the Plant Biology Learning Framework
 - » How do plants interact with the living and non-living environment?
 - » How do matter and energy move through an ecosystem?

Learning Objectives

Students will be able to:

- ◊ develop confidence in their ability to evaluate evidence and make evidence-based claims.
- ◊ describe how plants are essential to support life.
- ◊ articulate how ecology and other sciences (natural, physical, and social) are inextricably linked.
- ◊ accurately extract information from graphs, illustrations, and text.
- ◊ communicate with brevity, clarity, and persuasion.

INTRODUCTION

Interdisciplinarity is needed to solve increasingly complex and interconnected problems (e.g., COVID-19 vaccine development, wildfire mitigation, coral reef restoration, etc.; [1]). Thus, it is critical for students across science, engineering, and social science fields to develop as interdisciplinary thinkers. For example, biologists must harness knowledge from various disciplines because their field intersects with engineering and systems development as exemplified in disciplines like restoration ecology, astrobiology, and health science innovation. Moreover, integration is needed between science and other fields, such as humanities and policy, to address socio-scientific issues (e.g., food insecurity, climate change, genetically engineered organisms, etc.) through equitable solutions for the public. Notably, interdisciplinarity and the associated skills are broadly valued and together are a core competency in the document *Vision and Change: A Call to Action* (2, 3) and in subsequent work based on this document (4, 5). This body of work suggests scientists should apply the scientific method, tap into the interdisciplinary nature of science, and practice collaboration and scientific communication, and educators should design learning experiences incorporating interdisciplinary “real-world” science applications.

Although benefits of interdisciplinarity and cross-curricular skills are broadly recognized as valuable, interdisciplinary content can be challenging to teach. Building interdisciplinary learning opportunities for students requires time for developing collaborations and exchanging expertise among faculty from different disciplines (6). These undertakings require significant planning from educators who must also meet the standards of their curriculum. Since building interdisciplinary learning opportunities takes extra time and careful consideration, such opportunities have yet to be widely implemented. However, there are successful models of interdisciplinary learning in higher education environments that employ collaboration, communication, and connection-building across academic disciplines (7). Interdisciplinary or cross-curricular work challenges students to look at an issue through a wide variety of lenses and to use deep thinking, analysis, and application of knowledge to new scenarios (8, 9). We present an interdisciplinary case study that draws on the tenets of the work above for use in a range of different classrooms.

The case study described here challenges students to identify what is needed to support a long-duration, crewed space mission or space habitat through design of a regenerative life support system. Students must use ecological principles to support design of a small-scale, self-sustaining regenerative

system modeled after the key components of an ecosystem, with a single plant species—duckweed—as the primary source of energy-rich, health-supporting food and oxygen also capable of recycling CO₂ and other human waste. This case study allows students to problem-solve using different lenses and disciplines (e.g., ecology, engineering, biomedical science), thus leading to a deeper, more holistic understanding of the topic.

The open-ended structure empowers students to choose a science, technology, engineering, and mathematics (STEM) discipline they are interested in to create an interdisciplinary presentation focused on sustainable long-term crewed space missions via building a regenerative “ecosystem in space.” We provide students with a bank of peer-reviewed scientific publications in the areas of ecology, evolutionary biology, genetics, environmental science, plant science, plant microbiomes, medicine, agriculture, engineering and environmental design, and space sciences (see Supporting File S1) as well as allow use of any other peer-reviewed STEM article they might themselves find online. Students choose their topic, select a paper within that topic, examine it, and present their findings in small groups to their peers. Peer-sharing incorporates the interdisciplinary nature of the case study. Students hear from at least two other groups and then are asked to reflect on their topic within the context of what they learned from their peers. Additionally, the topics themselves often require knowledge from multiple fields, further emphasizing the interdisciplinary nature of the case study. For example, building a growth chamber in space integrates engineering and biology. Examples of other interdisciplinary topics that students might address include the design of plant growth conditions to maximize nutritional quality of duckweed and minimize required energy input, as well as the psychological benefits of plants in space.

Integrating plants into the framework of a regenerative life-support system for extended crewed space missions not only engages students with the material, but also establishes connections between plant science and various scientific disciplines, with a human-centered approach. By exploring the intersection of plant science with other fields, students develop a better understanding of plant services for human society, including roles of plants in their own lives. This integrated approach is particularly relevant when considering the gap between the importance of plants to society and general understanding and acknowledgement of these roles, as highlighted by the concept of plant awareness disparity (PAD; [10]).

PAD describes a lack of human appreciation for, or awareness of, plants (10). Despite their fundamental role in sustaining life on Earth (e.g., via production of food and oxygen, recycling of animal waste, and sequestration of CO₂ and the associated role in climate control), plants are often overlooked and undervalued by STEM students (11–13) and the broader public. This effect can be further exacerbated by a lack of plant representation in media and textbooks (11, 12, 14) and student perception that plants are boring (15, 16). However, actively drawing attention to plants can increase interest and reduce PAD (13). Activities encouraging student engagement with plants, including education modules (11, 17), can spark interest in plants and reduce PAD. Furthermore, an intriguing plant species—like duckweed—can further promote interest in

plants (18) and reduce PAD. For more detail on duckweed’s unique and exciting features, see Supporting File S2.

To support the development of interdisciplinary skills, this case study includes an emphasis on problem-solving, real-life relevance, collaboration, and communication. It also leverages student choice to build on existing student interests and drive deeper topic exploration. When learning feels relevant and applicable, students are more likely to actively deepen their understanding by creating connections to their own lives (19). Additionally, this case study is taught using small-group work as a pedagogical tool, which allows different students to weigh in with diverse perspectives and opinions (20, 21), propelling students to achieve a comprehensive approach informed by multiple views. Evaluating the future of sustainable long-term space missions requires students to consider factors supporting ecosystems on Earth, which broadens the case study’s scope to include exciting real-world problems on larger scales.

To support student learning and engagement, this case study incorporates multiple components, particularly within plant science and interdisciplinary STEM studies. It promotes application of skills learned in class to real-world scenarios (22), allows students to consider multiple perspectives and disciplines when analyzing a problem (23), and provides relevant examples that can increase student engagement and promote student learning (24). The text below further details the case study and evidence of student learning from our initial iterations in an undergraduate *Principles of Ecology* course.

Intended Audience

This case study was designed for an introductory *Principles of Ecology* course at the University of Colorado Boulder taken mainly by second and third-year science majors. Additionally, we believe this case study can be modified to fit well into other introductory biology courses or to meet the needs of students in an advanced high school classroom (see the *Teaching Discussion* section below for suggestions).

Required Learning Time

We developed this case study to cover two 75-minute class periods. However, it could be modified into three 50-minute class periods or one longer block period (see *Teaching Discussion* for recommendations on alternate timelines).

Prerequisite Student Knowledge

Students should have a basic understanding of principle physical and biological factors that support an ecosystem. Furthermore, students should have some practice reading and interpreting scientific literature, including tables and figures. Additionally, this case study allows students to refresh and build upon these skills. This case study is relatively open-ended and designed to be one of the semester’s final activities that enables students to apply skills and knowledge they have learned.

Prerequisite Teacher Knowledge

Before teaching this case study, instructors should feel confident in searching for, reading, and interpreting scientific literature and associated figures. We do not expect instructors to have read all scientific papers included in this case study (Supporting File S1), but they should feel comfortable supporting

students in reading scientific literature. Instructors should also have a cursory understanding of the basic principles of how plants support life within ecosystems. Instructors should review the instructor guide (Supporting File S2) and the slides (Supporting File S3) to prepare the case study.

SCIENTIFIC TEACHING THEMES

Active Learning

This case study is scaffolded such that students grapple with complexity, but do so in a structured, supportive environment (25). Class begins with an interactive lecture, and time allocated to a think-pair-share activity (26), in which students think about any plant they want to bring on a long trip into space, talk to neighboring peers about their plant, and report their ideas to the class. After the instructor presents some additional information, students are asked to revisit their previous answers and either revise or defend their original suggestions. After this lecture component, students transition to group discussions and collaboration. Students are asked to identify a topic and then collaborate with others to explore that topic. They create and eventually present a slideshow to the other groups. Through these presentations, students participate in a jigsaw-like activity (27), where they first become experts on a topic within their small groups before presenting to other groups who have explored distinct but complementary topics.

Assessment

Pre- and post-assessments (Supporting File S4) are used to assess learning from this case study. These assessments are given outside of class before and after the case study. Pre- and post-assessments consists of 18 and 19 questions, respectively. Questions vary in format, including Likert scale questions (for example, answers scaled with five options ranging from 1 – “strongly disagree” to 5 – “strongly agree”) and short written-answer questions. All questions are tied to a specific learning objective (see Supporting File S2 for a more detailed explanation). Objectives, assessment questions, rubrics for assessing student learning, and an exemplar of a Claim Evidence Reasoning paragraph (CER; [28]) are included in Supporting File S2.

Inclusive Teaching

A hook is used in education to increase student interest—with an engaging hook making lessons particularly meaningful by connecting personal interest to class topics, providing a powerful pedagogical tool (29). Allowing students to choose personally relevant material can increase student interest in the topic (30) and make learning more personal through a student-driven framework (31). Leveraging students’ interests and encouraging use of prior knowledge can also support student retention in STEM (32). Furthermore, using multiple modes of interaction with the material—reading scientific literature, developing and sharing a presentation, peer reviewing, and writing answers—increases accessibility for students with differing learning styles (33).

Group projects support educational and emotional needs by promoting discourse, building connections, and engendering a sense of community among students (34, 35). Collaborative projects also address learners’ educational and emotional needs by promoting student discourse, equity, and connection

(34). Furthermore, group work can promote equity in learning by supporting students to benefit and learn from their peers’ organization and foundational skills (36). Group work can thus lessen the achievement gap among students (37). Additionally, this case study supports classroom cohesion and encourages community through peer teaching (36) about complementary topics. Peer teaching is an effective strategy for meeting the social-emotional needs of learners and promoting collaboration and communication (38).

To provide all students with an opportunity to think about concepts, be engaged, and reason through concepts in a large lecture hall, we used multiple strategies from the twenty-one strategies for inclusive teaching (26). The first was to integrate a think-pair-share activity into the lecture (described above). This activity was enhanced by including open-ended questions (Supporting File S3, slides 2 and 4) presented without judgment of the student response on part of the instructors. By practicing wait time and an approach termed multiple-hands-multiple voices, the instructors allowed ample time for students to reflect. Specifically, the instructors waited for multiple students to volunteer responses before continuing. These strategies help elicit numerous opinions from the class and promote class discussion during the interactive part of the interrupted lecture (26).

LESSON PLAN

This case study follows the Biological Sciences Curriculum Study 5E (engage, explore, explain, elaborate, and evaluate) instructional model (Table 1; [39]). The student worksheet (Supporting File S5) is structured to help guide students and instructors through each section. This case study style provides an opportunity for active student participation and exploration. Furthermore, the inquiry-based template promotes critical thinking, motivates students, and facilitates discovery. Students are actively engaged in problem-solving and collaboration, supported in developing their active learning, and encouraged to draw conclusions based on evidence. Each phase—as well as the associated portion of the case study—is briefly described below.

Engage

In the Engage phase, we present students with a problem that captures their attention and encourages them to tap into their prior knowledge. Utilizing surprising or unusual examples, as in this case study, can enhance student interest in the subject (40). Through a brief lecture (Supporting File S3), we first ask students to brainstorm with their peers to identify a plant they think would be best suited for growth on a long-term space mission. After the introduction of more background and discussion about the benefits of plants to human society, we ask students are asked to either revise or defend their initial choice of plant.

We introduce students to duckweed as a novel model crop and potential component of a regenerative life-support system for a space mission (more information about duckweed and our rationale for why duckweed is an ideal organism for this instance is included in Supporting File S2) as well as to multiple lenses through which students can explore this topic (Supporting File S3, slide 9). Then, we ask students to choose a topic related to duckweed for further exploration. To try and alleviate any

frustration that may come with the expectation for students to “discover” information on their own (41), we provide a list of potential topics and scientific articles from which to choose (Supporting File S1), while also offering the option to identify articles on their own. By the end of the engage section, students will pick which topic and specific paper to explore further.

Explore

In the Explore phase, students participate in investigations and create a presentation that allows them to develop their understanding. Working in small groups (3 to 4 students), students delve deeper into their chosen topic and associated scientific article to create a short (~5 min) presentation about the article. For their presentation, we ask students to explore the definitions of vocabulary words relevant to their topic, explore key concepts involved and how these relate to ecology, look for relevant figures or schematics in their chosen article if applicable, and note any questions that come up during their research. Designing such a presentation requires and demonstrates a deep level of cognitive effort (9). Furthermore, preparing such presentations allows students to show creativity in their learning while thinking about relevant scenarios (31).

Explain

In the Explain phase, students refine and deliver presentations that establish connections between their own experiences and the material they explored. Peer teaching plays a crucial role here because it actively involves students in their learning and enables them to gauge their understanding (42, 43). In this section, groups of students present to each other and provide constructive and supportive peer feedback. Creating and presenting a topic challenges students to reflect on and communicate scientific content in their own words by paraphrasing what they read. This further supports learning for student presenters and those listening (44). With this approach, students practice not only scientific investigation but also communication.

While one group presents, the other groups listen and we encourage them to respond to the case study questions in the *Explain* section to provide peer feedback on presentations they watch (see Supporting File S5). We give students guidelines on how groups should provide positive and respectful feedback to each other in the case study, including guiding questions and a rubric. Instructors also ask questions to students and use their knowledge to draw out particularly salient aspects of student presentations.

Elaborate

In the Elaborate phase, students apply concepts they learned, deepening their understanding, and creating a meaningful learning experience. We ask students to connect their chosen topic to complementary topics presented by their peers. Questions included in this section (Supporting File S5) prompt students to reflect on their learning and assess how their new knowledge connects to their prior understanding of the material. Explicitly connecting multiple facets of a larger topic and reflecting on their learning helps students identify meaningful relationships and promotes scientific literacy (45).

The questions in this section ask students to connect to real-world applications of ecology, fostering a sense of relevance to the case study material. This approach also provides additional opportunities for peer collaboration both within their

small group and among groups. Sharing diverse perspectives enriches the overall learning experience by allowing students to appreciate the value of different points of view and how individual strengths contribute to the group's collective strength, which are key benefits of scientific collaboration and interdisciplinary research.

Evaluate

Finally, in the Evaluate phase, students demonstrate their understanding of concepts learned. The summative assessments (Supporting File S4) are detailed in the *Assessment* section above. We provide students and instructors with a detailed rubric (Supporting File S2) of how their final case study can be scored. It is important to note that these pre- and post-assessments are not necessarily testing for correct answers based on content knowledge. Rather, this evaluation focuses on student-reported growth and confidence in interacting with scientific material, appreciation of plants, and reflections on the interconnectedness of science. To further help students evaluate their own learning, students could be encouraged to compare or edit their CER paragraphs from the pre- to the post-assessment. In addition, instructors may review students' responses to the reflective writing portion of the case study and assess the individual's participation during group work (see the *Teaching Discussion* for our suggestions).

Logistic Information

The case study materials were shared with students virtually through a link posted on our class website. However, instructors could encourage students to fill out the case study on paper and create a scientific poster to convey their learning instead of a digital slideshow. During the *Explore* section, we allowed students to form their own groups; instructors could alternatively group students based on shared interests. To structure the mixed-group presentations in the *Explain* section, each group received a random colored sticker, and students with matching stickers congregated in designated areas. Alternatively, instructors could group presentations thematically based on the topics' similarities or differences.

TEACHING DISCUSSION

This case study is designed to engage students in solving real-world problems through interdisciplinary learning, practice engaging with and understanding scientific literature, and address plant awareness disparity. Through a combination of collaborative group work and student choice, this case study aims to enhance student engagement and critical thinking, as well as promote understanding of how biology and other disciplines within and beyond STEM fertilize and support each other. We found that students (i) gained confidence in their ability to interact with and understand scientific literature, (ii) improved their knowledge about and attention to plants, (iii) improved their ability to draw conclusions based on information presented in scientific literature, and (iv) developed and honed their ability to recognize and appreciate the interconnectedness of various scientific and other fields.

Results from Pre- and Post-Assessments

Unless otherwise noted, all data reported here are from the Fall 2022 semester ($n = 162$ students). For questions associated

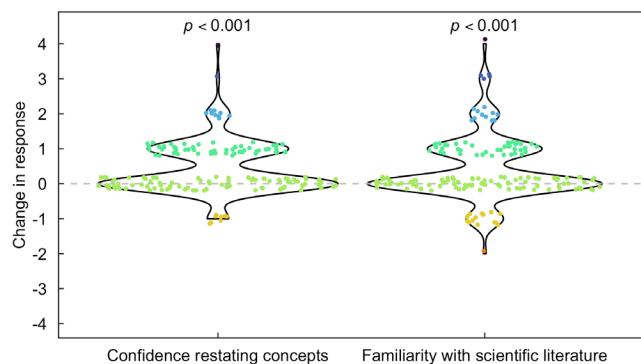


Figure 1. Change in student score from pre- to post-assessment for questions associated with objective 1, student confidence interacting with scientific materials. Symbol color denotes the change in student response, with green to blue colors representing positive shifts in response and yellow to red colors representing negative shifts in response (olive-green points exhibited no shift). Each point represents one student ($n = 162$).

with objectives 1 and 2, we used a paired t test to identify significant changes in student responses from pre- to post-assessment. A positive score indicates stronger agreement with the statement. No change in score indicates the same response on both pre- and post-assessments. A negative score indicates stronger disagreement. Each data point in the plot represents one student. For questions associated with objectives 3, 4, and 5, we used qualitative codes (further described in each section) to gauge changes in student thinking from pre- to post-assessment, followed by analysis of any changes in responses with a paired t test.

Objective 1: Develop Confidence in Their Ability to Evaluate Evidence and Make Evidence-Based Claims

To measure change in students' confidence interacting with scientific literature, we used Likert scale-based questions in pre- and post-assessments (Supporting File S4, questions 1 and 2). After implementation of the case study, students reported feeling more confident in their ability to restate concepts described in a scientific paper ($p < 0.001$, Figure 1) and were overall more comfortable interacting with scientific literature ($p < 0.001$, Figure 1).

On the post-assessment (Supporting File S4, question 19), most students "agreed" (49%) or "strongly agreed" (31%) with the statement, "This case study helped me increase the confidence I felt in evaluating and making claims from a scientific paper." Overall, after implementing this case study, we observed that students felt more confident in their ability to read and understand scientific literature, thereby meeting learning objective 1.

Objective 2: Describe How Plants Are Essential to Support Life

To assess if students met objective 2, we used questions from the "Knowledge" and "Attention" sections of the Plant Awareness Disparity Index (PAD-I; [13]). A paired t test was used to detect significant changes in student PAD from pre- to post-assessment (Supporting File S4, questions 3–12).

For the "Knowledge" section of PAD-I (Figure 2A), students more strongly agreed at post- versus pre-assessment with statements that plants are an important source of food ($p < 0.05$) and plants are an important source of new medicines ($p < 0.05$). Students also tended to more strongly agree with the statement that plants are important because they are a source of oxygen, although this change was not statistically significant ($p = 0.065$).

All three statements in which we observed positive changes were associated with topics heavily represented in the case study and student presentations. The class discussed that, on a long-term space mission, plants could serve as a critical component of a bioregenerative life-support system producing oxygen and serving as a continuous food source for the crew. Additionally, the importance of nutrition from a whole-food source was discussed, and many students focused on the nutritional and medicinal aspects of plants in their presentations. The fact that 98% of students already "agreed" or "strongly agreed" on the pre-assessment with the statement "Plants are important to ecosystems" may explain the large number of students that showed no significant change in response despite numerous connections to ecology made during this case study.

For the section of PAD-I focused on attention to plants (Figure 2B), students agreed more strongly with three out of four statements associated with attention to plants on post- versus pre-assessment. Specifically, students agreed more strongly with statements after the case study about noticing crops ($p < 0.001$), noticing individual plants in a wooded area ($p < 0.05$),

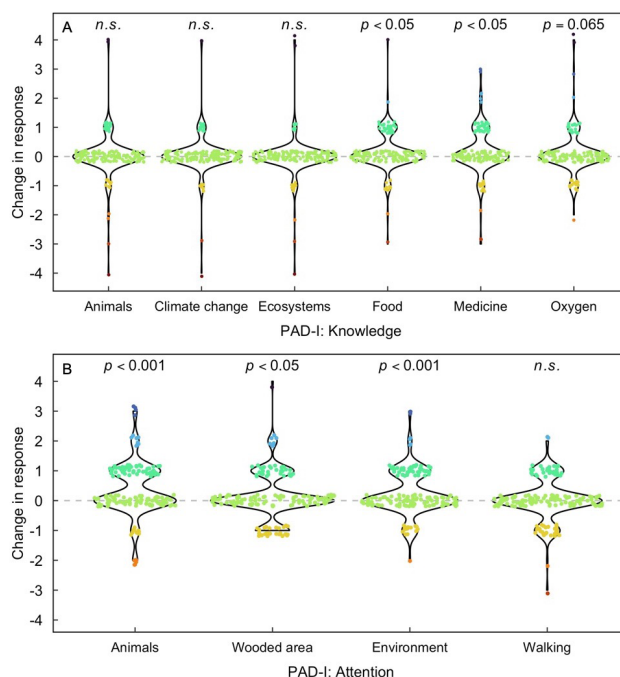


Figure 2. Change in student response from pre- to post-assessment for questions from the category of PAD-I (A) Knowledge and (B) PAD-I Attention. Symbol color denotes the change in student response, with green to blue colors representing positive shifts in response and yellow to red colors representing negative shifts in response (olive-green points exhibited no shift). Each point represents one student ($n = 162$).

and noticing all plants in the environment, not just food plants ($p < 0.001$). The fact that there was no significant change in student response to the statement about noticing plants while on a walk could again be due to a ceiling effect because most students already agreed or strongly agreed with this statement during pre-assessment.

Overall, this case study helped reduce PAD among students in the PAD-I “Attention” and “Knowledge” sections. After participating in the case study, students on average exhibited improved knowledge of the importance of plants for humans and started to pay more attention to plants in their environments, thereby meeting objective 2.

Objective 3: Articulate How Ecology and Other Sciences (Natural, Physical, and Social) Are Inextricably Linked

To measure changes in skills and attitudes addressed by objective 3, we used qualitative coding to analyze students’ thoughts about the interconnectedness of scientific disciplines specifically involving ecology (Supporting File S4, questions 13 and 14). First, we asked students to respond to the prompt, “How, if at all, do scientific (natural, physical, and social) fields inform each other? List any examples you can think of.” On the post-assessment, more students recognized connections and provided examples of scientific fields supporting each other compared to pre-assessment ($p < 0.05$, Table 2). On the pre-assessment, 13 students (8%) responded that there were no connections between scientific fields or could not provide an example. However, on the post-assessment, all students recognized a connection between ecology and other scientific disciplines, and only seven students (4%) recognized a connection but did not provide an example of different scientific fields supporting each other.

Notably, we identified a source of student confusion in the question listed in quotes in the previous paragraph. In the question, we asked how different scientific fields inform each other. The word “inform” led several students to respond with answers based on the word’s literal meaning by stating how different fields provide information through avenues like scientific conferences or literature. Instead, we were interested in how different fields can support work in other fields. In the assessment included here, we have changed the wording to read, “How, if at all, do scientific (natural, physical, and social) fields **support the work done** in other scientific fields?” We suggest this wording for future use of this question.

Additionally, we wanted to evaluate whether students were making specific connections between ecology and other STEM disciplines based on the case study. A key concept we aimed to reinforce was ecosystem services (*i.e.*, ecosystems’ benefits to people, including water and air purification, recreation, food production, stress reduction, etc.). We asked students to respond to the prompt, “Do you think having plants on a space shuttle may provide ecosystem services? Please explain why or why not.”

On the pre-assessment, approximately 85% of students identified that plants could provide ecosystem services on a space shuttle, and 81% of students provided an appropriate

example of an ecosystem service plants could provide on a space shuttle. The post-assessment revealed an increase to 97% of students identifying that plants could provide an ecosystem service on a space shuttle and 91% of students providing an appropriate example of such an ecosystem service. The difference from pre- to post-assessment response was highly significant ($p < 0.001$). Even with a potential ceiling effect, more students thus recognized and made connections between key concepts in ecology. Moreover, recognizing that shuttles are utilized for delivery of crew and/or cargo from one point to another on trips of short-duration, on which a bioregenerative system is not practical, we revised the question to read, “Do you think having plants on a **spacecraft during a long-term crewed mission or in a space habitat** may provide ecosystem services? Please explain why or why not.” We suggest this revised wording in future use of this question.

Objectives 4 and 5: Accurately Extract Information From Graphs, Illustrations, and Text and Communicate With Brevity, Clarity, and Persuasion

Unlike the results under the other objectives above, the results presented in this section are from the Spring 2023 semester ($n = 73$ students). After evaluating preliminary results from Fall 2022, which did not show substantial gains in graph interpretation, we modified instruction surrounding understanding of scientific figures and figures included in the assessment questions to better support students. In the initial assessment of the case study, we used figures directly from a scientific paper without support of the corresponding text of the article, which caused students to have trouble understanding complex axis labels on figures. In the subsequent semester, we revised these figures by making their labels more self-explanatory. In addition, we added a new component to the lecture that explicitly addressed how to interpret figures and identify key information. The revised version of the questions (Supporting File S4, questions 15–18) and slides (Supporting File S3) are included in the supporting files, and results presented below are from the revised version.

After implementing the case study, we saw learning gains associated with objectives 4 and 5, indicating increased student ability to interpret, and communicate about, scientific figures (Table 3). To measure changes in student interpretation of, and communication about, scientific figures, we asked students to review three graphs from a figure focused on duckweed growth (46) and make a single claim about each graph before ultimately writing a CER paragraph about the entire figure. For information about the structure of a CER paragraph, the rubric for scoring, and the figure included in the assessment, see Supporting File S2.

It is worth acknowledging that the type of graphs used in the assessments may have influenced students’ performance in making claims. Graph 1 is a line graph that could be initially difficult to interpret. However, during the implementation of the case study, students were exposed to various graph types. On the post-assessment, we saw significant improvement in students’ responses to claim 1 ($p < 0.001$) compared to the pre-assessment. Graphs 2 and 3 are bar graphs that compare two groups, and this structure is likely more familiar to students. However, students compared two groups in graph 2 that looked somewhat different but without a statistically significant difference. This scenario led to students claiming (technically

incorrectly) that there was a difference between the groups on both the pre- and post-assessment ($p = 0.083$). In contrast, the two groups being compared in graph 3 both look different and are statistically different. This latter graph format led to a high correct response rate for claim 3 ($p = 0.159$) on both the pre- and post-assessment, and a potential ceiling effect. For improved utility of such assessment and deepened understanding in the future, we added an additional slide about interpreting statistics in the materials included here (Supporting File S3, slides 11 and 12) and encourage instructors to add examples of figures with relevant statistics related to their material into the slideshow for practice.

Additionally, our post-assessment revealed significant improvements in the quality of evidence ($p < 0.05$) and reasoning ($p < 0.001$) students employed to support their claims about each graph. This was also reflected in the overall improvement of the CER paragraph scores ($p < 0.001$). These positive outcomes can likely be attributed to additional practice students received during the case study where they presented a scientific figure from their chosen paper and explained it to their peers. This hands-on approach effectively reinforced their scientific understanding and communication skills, contributing to their overall growth in these areas.

Observations from Formative Assessments

In addition to analyzing student responses to pre- and post-assessments, we reviewed written student responses to the *Elaborate* section of the case study (Supporting File S5). The *Elaborate* section was designed to support students in making connections among various small-group presentations and applying what they learned to broader ecology principles discussed in class over the semester before the case study. Students working in their groups ($n = 91$ groups) were asked to respond to four questions to encourage identification of connections between scientific topics and promote reflective writing. We used qualitative codes to identify differences in student responses and categorize their thinking into broader categories.

Case Study Responses: Interconnectedness of Science

The first prompt asked students to describe how their presentation and those they watched connected to what they had learned in the earlier portion of the *Principles of Ecology* course leading up to the case study. On average, students listed four to five different connections between their topic, the presentations they watched, and ecological principles or examples they recognized after completing the case study. This outcome demonstrates interdisciplinary scientific thinking specifically in the context of ecology.

The second prompt asked students to imagine giving their presentation to NASA and to identify other scientific disciplines they would want represented in their presentation. On average, students wanted to include representation of three to four scientific disciplines in a proposal to NASA (Figure 3, blue left circle). Human health and engineering were the two most common disciplines mentioned after botany. Since students could choose a topic of personal interest, those choices likely reflect topics our students are passionate about as well as the applicability of both subjects to human space missions.



Figure 3. Responses to questions 2 (blue, left) and 3 (pink, center) from the *Elaborate* section of the case study as well as the sum of responses to both questions (purple, right). The size of each word represents how many times that category was mentioned in student responses. We used qualitative coding to identify different scientific fields mentioned in student responses before summing the categories.

The third prompt asked students to reflect on their knowledge about the interconnectedness of ecology to different scientific disciplines before the case study, to identify whether their opinions had changed after completing the case study, and to explain their thinking. Most groups (77 or ~85% of the groups) agreed that this case study changed their thinking about connections between ecology and other disciplines. Twelve groups (~13%) said that their original thinking was not necessarily changed but was enhanced and improved after implementing the case study. Students often replied that they were previously unaware of the complexity and intricacies arising from the interconnected nature of science. Many groups replied that, before the case study, they already thought that ecology could be used to support other life sciences but were surprised that ecology could support space sciences because these fields are so different. Only two groups said their knowledge and opinions stayed the same after this case study, citing an already high understanding of the interconnectedness of sciences and topics at hand.

For analyzing student responses to the third prompt, we categorized the various scientific disciplines students included in their explanations. On average, students included two to four scientific disciplines when explaining how different fields of science are interconnected. Space science and broader impacts (including implications for the public, policy, education, and applications) were the most recognized categories beyond ecology and botany (Figure 3, pink center circle).

Case Study Responses: Plant Awareness Disparity

The fourth and final prompt asked students to reflect on their prior knowledge about how plants support climate, human health, and ecosystems and report whether their thinking had changed after completing the case study as well as elaborate on why or why not. Most groups (83 groups, ~91%) responded that this case study had positively changed or enhanced their understanding of the benefits of plants to human society. Again, groups who said that this case study did not improve their knowledge of the benefits of plants (8 groups, ~9%) cited an already high initial understanding of the importance of plants.

We evaluated the categories of PAD students included in their explanations. The most frequently included category was knowledge about how plants support humans (78 groups, ~86%)

followed by responses associated with the attention category of PAD (32 groups, ~35%). These statements are further supported by the change in knowledge and attention categories from pre- and post-assessment questions. Additionally, some groups identified an increased interest in plants (18 groups, ~20%), although this was not a PAD category tested in the pre- and post-assessment.

Suggestions for Improvements and Adaptations to Other Courses

Alternative Timelines and Audiences

We recommend the following adjusted outline for teaching this case study in three 50-minute class periods. Instructors can use the first class to introduce the topic and have students identify a paper they want to explore. Students complete their research and start their presentations during the second class period. In the final class period, students finish, practice, and present their research findings, as well as finish the case study worksheet. If completion of pre- and post-assessment were desired, students should complete these outside of class. Additionally, it would be feasible to complete the entire case study in a single 3-hour lab period.

For high school classrooms, we recommend adding an additional class period to the case study to provide further practice for students to understand scientific literature and interpret scientific figures and statistics. We also recommend encouraging students to focus on specific parts of scientific literature that may be easiest to interpret (e.g., the abstract, parts of the introduction, or a conclusions section of the discussion) and to pull out the main ideas from the text before creating their presentations. Depending on students' prior familiarity with scientific literature, we may also suggest emphasizing reviews written for broader audiences and non-peer-reviewed publications in the topic list and supporting references (Supporting File S1). Additionally, sentence starters for figures and statistics-heavy sections, such as "This [is/is not] a statistically significant difference," can help students communicate their findings more effectively.

Assessments

While the pre- and post-assessments included here provided valuable insights into how students engage with scientific literature and the significance of plants in their lives, this understanding can be further enhanced by prompting students to delve deeper into the "why" aspect of their responses, *i.e.*, the rationale behind them. While the case study questions allowed us to gather valuable group-level data, incorporating more nuanced inquiries could yield invaluable individual-level insights into how students perceive changes in their knowledge and confidence following case study implementation.

For an additional form of assessment, instructors can modify the rubric used for evaluating student presentations to include

a component for feedback about group dynamics and group members' levels of participation, as well as other aspects of desired peer cooperation. Such additions may encourage students to engage in group work actively and can provide valuable insights into individual contributions. Additionally, because of the anxiety students typically face around presentations, we ensured that full credit was given for group presentations to all students in the group, and we applauded each group after their presentation to promote a sense of community. However, for students already practiced in giving presentations, the rubric associated with presentations could be more structured to encourage them to provide more concrete and constructive feedback to other presenting groups.

Topic List, Supporting References, and Extensions

This case study was designed to easily fit into a range of science and engineering classrooms because of the flexibility with respect to the large number of topics for students to choose from (Supporting File S1). To implement this activity in any classroom, instructors can edit the topics and references, either by shortening the number of topics to create a narrower focus or by changing the papers included to best fit the needs of their classroom. The topic list and supporting references provided here focuses on resources from STEM fields. Instructors could modify it easily to include articles from the popular press and literature from outside of STEM fields. Moreover, the resources serve as extension activities for students who want to learn more about their topic or a topic they learned about in the presentations. This adaptability ensures that the case study remains a versatile and effective tool for educators and students across various disciplines.

Institutional Review Board (IRB) Approval

After review by the University of Colorado Boulder IRB Office, this work was classified as exempt with IRB protocol number 23-0124.

SUPPORTING MATERIALS

- S1. Space Mission Ecology – Topic List and Supporting References
- S2. Space Mission Ecology – Instructor Guide
- S3. Space Mission Ecology – Slides
- S4. Space Mission Ecology – Assessments
- S5. Space Mission Ecology – Student Case Study

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Table 1. Timeline of instruction and student activities.

Activity	Description	Estimated Time	Notes
Before Class – Instructor Preparation			
Prepare materials	Review the materials for class, including the slides, case study materials, and assessments. Because this is an activity that takes place over multiple class periods, identify ways to support groups if students are absent on one or both days, and decide whether to include the graphing and statistics practice slides.	30 min	Make any adjustments to the materials that you need to best fit your class. This case study was developed to be entirely digital, but you could print copies of the case study for each group of students for your class. Supporting Files S1–S5.
Review topics	Choose topics that best fit your class. Decide if you want to further adapt the case study to address specific class learning goals by selecting literature that aligns with your objectives. The topic list is broken into 9 categories. You can include all the categories or, if you want students to focus on specific topics that best meet the needs of your class, narrow the number of categories to the topics that you want students to focus on.	30 min	This case study was designed so that students have a choice in deciding which topic they are interested in and want to explore more. However, if assigning topics would work better for the structure of your class revise questions 2 and 3 in the case study. Supporting Files S1 and S2.
Before Class – Student Preparation			
Pre-assessment	Students answer 12 Likert-like questions to report feelings about plants and interacting with scientific literature. Students answer 2 short answer questions to elaborate on interconnectedness of science and 4 short answer questions to build a Claim, Evidence, Reasoning (CER) paragraph.	15 min	This activity is optional depending on the instruction. If your goal is to measure changes in learning and self-reported feelings about scientific processes, include this entire pre-assessment. Supporting File S4.
Part I – Engage			
Introductory lecture	Present the included slides (or similar slides) to students at the start of class to provide a brief overview of why we think duckweed is a versatile and interesting future crop as well as the objectives of the case study. Once the instructor reaches slide 4, students can use the space in case study question 1 to brainstorm their ideas. After some time for brainstorming, the instructor should lead the class in a think-pair-share.	30 min	Supporting Files S3 and S5.
Part II – Explore			
Group and topic selection	After students have had the opportunity to brainstorm with their peers, they should choose the groups they want to work with. Once in groups, students choose the lens through which they want to explore duckweed. The instructor should have groups sign up for their topic. You can create a virtual or physical sign-up list so that students do not choose the same paper to present.	10 min	A student could complete this individually. However, we encouraged students to work in groups of 3 or 4. Supporting Files S1 and S5.
Case study	Students start working through the case study parts I and II to create their presentations. The instructor should be moving around the room to check on students and answer any questions that might arise. While doing this, encourage students to make clear connections between their chosen topic and the subject of the class, as well as their prior knowledge.	35 min	Students do not need to finish their presentation by the end of the first class. However, students should feel comfortable with their paper and okay with finishing the presentation within 20 min during the next class. If not, students should finish reading their chosen paper for homework. Supporting File S5.

Activity	Description	Estimated Time	Notes
This is the end of the first 75-min class period			
Part III – Explain			
Case study	Students continue working through the case study and creating their presentation about using duckweed to support life on a space mission in the context of their topic and ecology. While students are working the instructor should start forming groups of small groups. There should be three to four small groups in each large group. By the end of this time, students should have a near-complete draft of their presentation.	20 min	Creating larger groups will help the case study run more smoothly. The instructor may also consider creating and structuring groups based on different topic clusters to ensure a well-rounded presentation of interdisciplinary concepts. Supporting File S5.
Practice presentations	Students should practice and edit their presentations with their small group. The instructor should encourage students to practice their presentations out loud to their small groups. This will help alleviate student stress and keep the presentations on time.	10 min	Student presentations should be about 5 min long, so students have an additional 5 min to make any small edits needed to their presentations.
Part IV – Elaborate			
Presentations	Students should meet with the other groups in their larger group. The rubric for peer feedback is included in the case study so that students can see what they will be evaluated on. The small groups should then take turns presenting to each other within their large group. Groups that are not presenting should be listening quietly, working on the peer feedback portion of the case, and prepare to ask any clarifying questions. The instructor should be checking in with the various groups and listening to portions of the presentations. Each presentation will take ~5 min; groups should be back in the classroom within 25 min of the start of presentations.	25 min	Because several groups will be presenting at once, it is nice if students are allowed to leave the room and present to each other in a quiet space. We have also included the rubric as in the instructor guide if you want to print them out so that each group has one. If you are completing this activity in a smaller class, you may have time for each group to present individually to the whole class. Supporting File S5.
Presentation reflection	Students should make connections between their own presentation and the presentations from other students they watched before finishing the case study. In Part IV of the case study, students are asked four questions to elucidate student thinking about the interconnectedness of science and how plants are related to a host of topics.	20 min	After class, save three to five presentations from the class submissions. If a student was not able to attend the in-person presentations, they can still complete the elaborate portion of the case study using the saved presentations. You may also want to offer times that groups can come and present to you if they were unable to present in class due to extenuating circumstances or absences. Supporting File S5.
Part V – Evaluate			
Case study wrap up	Students complete a post-assessment to measure learning objectives after completing the case study. The CER paragraph could be collected for an additional assessment grade.	20 min	If time, review answers to evaluation questions and discuss with students as a class. This can also take place outside of class if time is limited. Supporting Files S4 and S5.

Table 2. Table of the number of student responses (and percentage of the class) in each category in response to the prompt “How, if at all, do scientific (natural, physical, and social) fields inform each other? List any examples you can think of.”

Student Response	Pre-Assessment	Post-Assessment	Difference
Student recognizes connection and provides an example	117 (72%)	128 (79%)	+ 11 (7%)
Student does not recognize a connection or does not provide an example	13 (8%)	7 (4%)	- 6 (4%)
Student mentions sharing information through journals/conferences	32 (20%)	27 (17%)	- 5 (3%)

Table 3. Number of students who scored full points on each section of the rubric as well as percentage of the class makeup (in parentheses). For claims, only one point was available. For statements about evidence and reasoning, up to two points were available, and for the entire paragraph, up to five points were available. For a detailed version of the rubric, see Supporting File S2.

Question Evaluated	Pre-Assessment	Post-Assessment	Difference	<i>p</i> Value
Claim 1	27 (37.0%)	39 (53.4%)	+ 12 (16.4%)	< 0.001
Claim 2	31 (42.5%)	37 (50.7%)	+ 6 (8.2%)	= 0.083
Claim 3	69 (94.5%)	71 (97.3%)	+ 2 (2.8%)	= 0.159
CER Claim	40 (54.8%)	45 (61.6%)	+ 5 (6.9%)	= 0.058
CER Evidence	33 (45.2%)	42 (57.5%)	+ 9 (12.5%)	= 0.028
CER Reasoning	33 (45.2%)	47 (64.4%)	+ 14 (19.4%)	< 0.001
CER Total Score	24 (32.9%)	36 (49.3%)	+ 12 (16.7%)	< 0.001

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