On the Symbiotic Nature of Science, Sustainability, and Systems Thinking in an Introductory Course on Sustainability Concepts

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Papadopoulos endeavors to orient his research and teaching activities around advancing, peace, socialequity, justice, and human wellbeing. In the words of Roberto Clemente, anytime when you have the opportunity to make a difference in the world, and you don't do it, then you are wasting your time on earth.

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I'm Krystal Colón Rivera, a doctoral student in the School Psychology Program at the Mayagüez Campus of the University of Puerto Rico (RUM), where I completed my master's degree in School Psychology in the summer of 2024. Previously, I earned a bachelor's degree in Sociology with a double concentration in General Psychology at the University of Puerto Rico in Cayey. During my undergraduate studies, I was a member of two student organizations: the Sociology Association (ASOCI) and the Association of Psychology Students (Psy-chi). Additionally, I worked as a research assistant on two projects: the Resilience and Medical Helpseeking project in Cayey (2019-2021) and the Negotiating Dementia project (2021-2022), both under the supervision of Professor Patria López de Victoria. Currently, I am involved in two research projects at RUM. The first is the Sustainable Engineering (ISOS) project, directed by Dr. Christopher M. Papadopoulos, and the second is the project on the relationship between executive functions and academic performance in university students (ESFERA), under the direction of Dr. Cristina Perea and Dr. Mary Moreno. I am also a member of the Association of School Psychology Students (AEPE) at RUM. I volunteered in the community program Aula en la Montaña. My research interests cover a wide range of topics, including the role of play in early childhood cognitive development, mindset, social support, behavior, learning, and physical activity. Additionally, I have a particular interest in studying executive functions, with a special emphasis on planning.

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Keywords: sustainability education, earth systems, systems thinking, science and math literacy

1. Introduction

A new minor in Sustainability Engineering (SE) is being developed at the University of Puerto Rico, Mayagüez which is open to all students enrolled in an engineering degree program[1]. The minor provides an introduction to fundamental principles and frameworks of sustainability, with design, scientific, economic, and socio-political components, while emphasizing synthesis of information and interrelationships across these domains. The minor also provides extracurricular opportunities for students to explore topics of interest, in conjunction with mentoring and participation in a community of practice. Through this instruction, mentoring, and peer support, the minor establishes sustainability as an overarching context for the study of engineering, serving as a compass to guide students to consciously integrate sustainability principles and practices throughout their academic programs and career pathways.[2] Taken as a whole, the minor supports students to develop a comprehensive sustainability mindset [2] that will prepare them as engineers for the 21st century.

A hallmark of the minor is that, while open to all engineering students, it is particularly designed to admit first-year students. The principal reason for this is to enable students to begin the process of developing the sustainability mindset at the very outset of their studies, allowing maximum opportunity to embed sustainability thinking in their studies, and to undertake academic, research, and professional opportunities that embed sustainability. With support of a grant from NSF, a scholarship is currently available to support approximately 12 first-year students each year, although many more (from any level) can enroll in the minor without the support of the scholarship.

A commonly accepted notion of sustainability is associated with the Brundtland Report from 1987 [3], which defines "sustainable development" as "development which meets the needs of current generations without compromising the ability of future generations to meet their own needs". The report further recognizes ecological limits, social equity, and new economic models, thereby suggesting what are now recognized as the "three pillars" of sustainability, "Equity, Environment, and Economy" or "People, Planet, and Prosperity" (which is an adaptation of

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[1] The minor is part of a larger initiative in Sustainability Engineering at UPRM to develop a new Bachelor's degree program, Master's program, and professional certificate program. See www.uprm.edu/isos.

[2] The literature on the decontextualized nature of engineering education is well established. Contextualized approaches, including around sustainability, have potential to improve learning outcomes and to prepare graduates to address grand challenges. [1]

Elkington's Triple Bottom Line [4], [5]). Grasping these three dimensions and their interrelationships is a key outcome of the minor.

However, beyond the three pillars, it is well accepted that a core element of sustainability thinking, mindset, or competency is systems thinking [6], [7], [8], [9]. Moreover, a basic understanding of sustainability must include a scientifically literate conceptualization of the underlying earth systems and the corresponding natural biogeochemical cycles that govern the flow of energy and matter through these systems, as a baseline from which to understand the human impacts that typify the Anthropocene [10], [11]. Since earth systems themselves constitute a complex system, learning about them is symbiotic with learning systems thinking.

The focus on admitting first-year engineering students provides further opportunity for applying and contextualizing courses such as pre-calculus, calculus, chemistry, and physics. Courses such as these have long been "gatekeeper" courses, emphasizing problem-solving in a well-structured but decontextualized manner. Typically, these courses steer students to learn about the "trees" rather than the "forest". Therefore, while a goal of the minor is to learn about sustainability through the lenses of math and science, equally a goal is to use sustainability as a means to drive learning of and curiosity about math and science, ultimately to "see the forest for the trees".

To explore how learning sustainability, science, and systems is symbiotic, this article describes an introductory course called "Creating a Sustainable World", which is the gateway course for the SE minor. As will be discussed, this course provides a component of scientific and quantitative reasoning, which entwine with the goal of also introducing students to systems thinking. A selected set of activities are evaluated to show both the progress and limits of scientific learning in the class. An end-of-class survey, based on the Student Assessment of their Learning Gains (SALG) [12], is conducted, showing that students have generally positive impressions of their growth in science, math, and systems thinking.

2. Description of Course "Creating a Sustainable World"

The course "Creating a Sustainable World" is designed to be an introduction to principles, frameworks, and essential topics of sustainability, with no prerequisites, so as to be open to students of all levels, especially first-year students. As with the SE minor as a whole, the principal reason for this is to provide students with a grounding – both academically and motivationally – that can contextualize their studies, both in their major field of study in engineering and in the SE Minor. As per the focus of this article, this includes contextualization of scientific and mathematical reasoning, which primarily relates to pre-calculus and chemistry.

The course provides an introduction to sustainability through the following themes: (1) sustainability definitions and frameworks, including a brief history of the UN meetings and treaties; (2) earth systems cycles and planetary boundaries; (3) energy; (4) materials usage patterns and circular economy; (5) water, agriculture, and land use; (6) career planning and development from a sustainability perspective; and (7) selected topics. Running throughout these topics is an attempt to promote systems thinking, critical thinking, and communication skills. Scientific and mathematical reasoning are most emphasized in topics (1), (2), and (3):

(1) The topic on sustainability frameworks and principles begins with a brief history of the major UN meetings and treaties, including the aforementioned Brundtland Report definition and the notion of the “three pillars”. Students read excerpts from this and the introductory chapter from Garren & Brinkman [13] to gain an overview of the global sustainability landscape.

These notions are then followed with short videos from the Natural Step, which explicitly link the ‘environmental’ pillar with the scientific notions that the earth is an open system with respect to energy flow and (very nearly) a closed system with respect to material flow. In particular, the notion that “matter is neither created nor destroyed, but may change form” is presented. Two early qualitative examples are given to begin making this idea concrete: (1) the process of washing dishes or clothes, which is essentially a constant cycle of material items, but which requires energy to drive (although a richer version could include flow of water and soap); and (2) the notion of a (nearly) constant atmospheric temperature is related to equilibrium of incoming and outgoing radiation.

(2) With this basic conceptualization introduced, the course proceeds to introduce Earth systems, with a focus on the hydrological, carbon, and nitrogen cycles. Building off of the idea that “matter is neither created nor destroyed, but may change form”, students are encouraged to learn about the cycles as ‘detectives’ following the basic elements as they change form throughout various ecological processes. The chemical equations for photosynthesis and respiration are discussed, indicating the exchanges of CO_2, O_2, and H_2O, and also showing similarity to cellular respiration of carbohydrates to combustion of hydrocarbons. Although there is some expectation of doing basic stoichiometry, which is like “a tree in a forest”, to understand “the forest”, questions such as “from where is the principal material of a plant derived?” provoke thought to understand the physical exchange of matter between the atmosphere and biosphere.

Integrated in this material are some key points in geological history, which help to further contextualize the history of CO_2, O_2, and H_2O, and in so doing, scientific notation is (re)introduced in the context of how to make measurements across short- and long-term time scales (along with the idea that the very notions of long/short, big/small, etc. inherently require bases for comparison). With this background, an overview of the research on planetary boundaries is given, which allows students to apply what they have learned about earth systems to the problems of climate change. A key reading is "Earth beyond six of nine planetary boundaries" [14].

(3) Although energy is implicitly introduced with the equations of photosynthesis and respiration, it is subsequently introduced more systematically. First, 'common everyday' notions of work and energy are solicited, before proceeding to the common definition that "work = force times distance". Students then read "Human domination of the biosphere: Rapid discharge of the earth-space battery foretells the future of humankind" [15], which introduces a second, less common definition, which is that (potential) energy is a measure of the "distance of a system from equilibrium". From this, the notion of different forms of energy is presented, together with a discussion of how to measure energy and power with different units, and how to do unit conversions.

The discussion then shifts to global overviews of energy consumption and generation. Two summaries are given: (1) a history of energy consumption by source (which returns to prior ideas of carbon storage in biomass and fossils), and (2) the global "energy value chain", which traces primary energy produced, across different sectors, through conversion and distribution to end use (services), showing that utilized energy is significantly less than primary production. Resources to quantify carbon intensity of energy consumption are also presented. This culminates with a qualitative introduction of the second law of thermodynamics, and returns to the example if incoming vs outgoing radiation through the earth's atmosphere (although in equilibrium, incoming solar radiation is of higher quality than outgoing heat – "its like $100 bills incoming vs pennies outgoing," to borrow the analogy explained by a colleague who teaches physics). The notion of the final equilibrium state of the universe ("heat death") is presented.

The notion of systems thinking is cultivated through two primary means: (1) as a direct result of studying earth systems cycles; (2) through repeated class discussion on how to make connections between topics (including cross-referencing information).

The course has been offered by the first author (Papadopoulos) four times since Fall 2022. This article evaluates results from Fall 2024, which enrolled 22 students, 7 women and 15 men. Of these, 12 students were first-year, 7 were 2nd-3rd year, and 3 were 4th year or later. The second author (Jensen) provided Assignment 3, based on his course "Ecology, Environment, & the Anthropocene" at Pratt Institute.

3. Methods

Two research questions are investigated in this study: (1) How do students express scientific and mathematical reasoning in the context of an introduction to principles of sustainability?; and (2)

How do students develop and express systems thinking? To answer these questions, two end-of-class reflections and two assignments are qualitatively assessed (coded) to determine emergent themes. In addition, a detailed survey, based on the Student Assessment of their Learning Gains (SALG) [12] was administered, which includes closed and open format questions. The text of the assignments and the corresponding evaluation rubrics are provided, as well as the text of the survey instrument, are provided in the Appendices.

4. Results

4a. Analysis of End-of-class Reflections. The purpose of this analysis is to identify potential markers that can point to progress in scientific and quantitative reasoning. The two general markers are "depth" and "curiosity", ranked on a 0-3 point scale. "Depth" refers to the level at which a student expressed something meaningful about a scientific or quantitative concept, based on the class discussion. "Curiosity" refers to the level with which a student expressed a point of curiosity, including by posing questions for future inquiry, or being surprised. The results of the analysis are in Table 1.

Table 1. Assessment of Depth and Curiosity of End-of-class Reflections

	Sept 5		Oct 29	
Rating	**Depth**	**Curiosity**	**Depth**	**Curiosity**
3	3	8	6	11
2	7	3	10	3
1	5	4	2	4
0	0	0	0	0
Average	**1.87**	**2.27**	**2.22**	**2.39**
Total Responses	**15**	**15**	**18**	**18**

A possible pattern that emerges from this evaluation is that students are able to express curiosity more strongly than depth of the idea. This is encouraging to the extent that curiosity is widely understood as a driver for learning [16].

4b. Assignment 3: Mapping Earth Systems Cycles. Systems thinking skills are a crucial element of sustainability science curricula [17], but frequently both teachers [18] and students [19] struggle to develop these skills. Concept (or cognitive) mapping has been suggested as a learning tool that can be used to effectively foster systems thinking skills [20], [21], [22], [23]. Concept maps have been used to promote and explore systems thinking, including among primary and secondary students [24], undergraduates [22], and sustainability experts [25]. Research in primary and secondary education suggests that concept mapping activities that are computer-based and highly directed are most successful in fostering systems thinking [24].

The immediate goals of this assignment, which are assessed here, are to have students develop understanding of the basic science of earth systems cycles (particularly carbon, nitrogen, and water), and in so doing, to develop skill and understanding of systems thinking by understanding interactions and feedbacks within the earth spheres and cycles. Works were evaluated for (1) Content, including components of the earth and the earth spheres; and (2) Systems Thinking, including ecological flows, ecological interactions, and interrelationships. Each of these categories is evaluated on a 0-3 point scale: Fully achieved (3), Achieved (2), Emerging (1), and Missing (0). The broader goals, which are not yet assessed, are to promote and inspire further interest and success in first-year chemistry, as well as to build a "sustainability mindset" in which the basics of earth systems, and systems thinking in general, might influence how work in other classes is approached. A complete description of the assignment and the evaluation rubric are in Appendix B. The results are provided in Table 2.

Table 2. Evaluation of Assignment 3, Concept Mapping of Earth Systems.

Assignment ID Items	A3_1	A3_2	A3_3	A3_4	A3_5	A3_6	A3_7	Averages
Components of the Earth	2	1	1	3	2	3	2	2.00
Earth Spheres	1	1	0	1	1	1	0	0.71
Content Average	**1.50**	**1.00**	**0.50**	**2.00**	**1.50**	**2.00**	**1.00**	**1.36**
Ecological flows	1	1	0	2	1	2	1	1.14
Ecological interactions	1	0	2	3	1	3	0	1.43
Interrelationships	1	1	0	1	1	1	0	0.71
Systems Thinking Average	**1.00**	**0.67**	**0.67**	**2.00**	**1.00**	**2.00**	**0.33**	**1.10**
Total Average	**1.20**	**0.80**	**0.60**	**2.00**	**1.20**	**2.00**	**0.60**	**1.20**

As shown, students were most successful at representing Components of the Earth and Ecological Interactions (for example, see Figure 1). Students were moderately successful at depicting Ecological Flows, with some groups using arrows and/or words to effectively explain how matter and energy flow through ecosystems and some groups not depicting flows at all. Many groups did not seize on the potential to use arrows within their concept map to depict flows. A few groups used color to differentiate between the flows of different forms of matter; no group used arrows to show the flow of energy.

Overall the concept maps were least effective at depicting Earth Spheres and Interrelationships, with none of the groups of students reaching the "Fully Achieved" or "Achieved" levels. While some maps did explicitly include the atmosphere and many implied the existence of the hydrosphere, none effectively used a visual depiction system (such as color-coding or particular shapes) to differentiate between the atmosphere, hydrosphere, lithosphere, and biosphere within their maps. There was a strong tendency among student maps to depict the cycles of matter separately, even as many were clearly depicted, leading to no maps that effectively showed how these cycles are intertwined and interrelated. Students were modestly better at depicting the content of ecological systems (average score = 1.36) than at depicting concepts related to systems thinking (average score = 1.10)

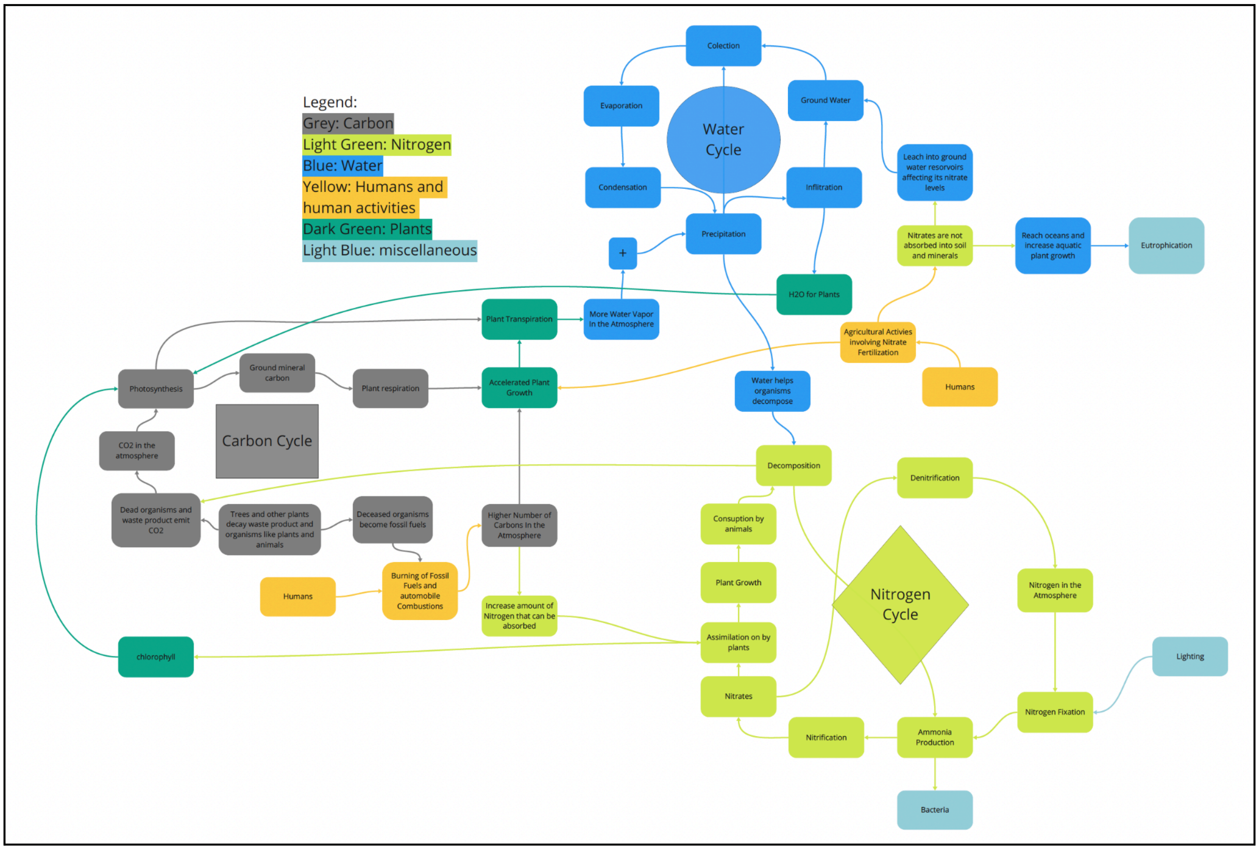

Figure 1. An example of a student concept map that fully achieved depiction of Earth components and ecological interactions, and achieved depiction of ecological flows.

Overall our concept mapping results suggest that engineering students working in an environmental science course – or in this case, as a module which is approximately 30% of the course – face a number of challenges in applying systems thinking to depictions of the way that matter and energy flows through ecological systems. These challenges include appropriately categorizing different components of these systems, depicting the cyclical nature of material flows, and most prominently integrating separate depictions of material cycles. They also struggle to break free of words as the chief means of depicting ideas.

We discovered that although the prompt was to make a concept map, many students reverted to other forms of depiction. Students produced entire paragraphs of explanation, most of which contained numerous concepts, and positioned these spatially within their maps (for example, see Figure 2). While often these verbal depictions were compelling and valuable, they prevented students from truly breaking apart ideas and reintegrating them into a coherent whole. It was clear from the concept map content that students had – by-and-large – done comprehensive research into each of the individual material cycles. But most groups struggled to convert their research-derived textual depictions into a comprehensive visual depiction. Limiting the amount of text that students can use in each "node" of their concept map might push them to rely less on words and more on conceptual depiction.

A related struggle emerged from the fact that many students relied heavily on images downloaded from the internet to "do the explaining" in their concept maps (for example, see Figure 2). While in some use cases these images enhanced their explanation, often they were used in lieu of a clear and compelling conceptual representation on their maps. For this reason, preventing students from using imported images – or at least limiting the kinds of images they use to single concepts – might improve their use of concept maps to convey their understanding.

Another problem that students encountered with imported images of cycles of matter (carbon, nitrogen, and water) was that these images tended to encourage them to represent these cycles in isolation (for example, see Figure 2). Educational images designed to represent the nitrogen, carbon, and water cycles – which are easily found with an online image search – generally endeavor to separate out components of each cycle from other ecological processes rather than to integrate them. This depiction serves one purpose – to foster understanding of the elements of a particular system – while making it harder for students to see how these systems are integrated. Again, limiting how students are allowed to use such "isolated cycle" images might improve their chances of discovering ways to represent these systems in an integrated manner.

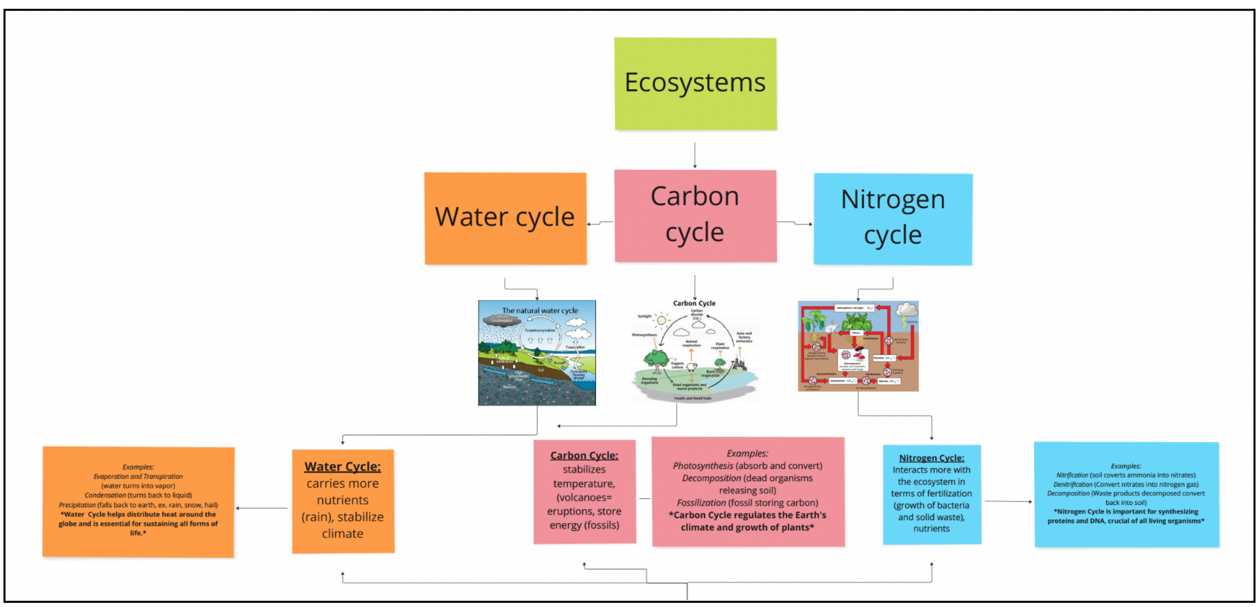

Figure 2. An example of a student concept map that was based on solid research but used excessive text rather than concepts, leaned heavily on imported images, and treated each material cycle as isolated.

Curiously, some students did create concept maps, but set them up in ways that did not necessarily serve the assigned task. A good example of this was to assign a concept to represent one of the material cycles, a design decision that makes it hard to show how multiple different components of ecological systems interact to produce these cycles (for example, see Figure 3). Generally, for this assigned task, it is valuable to create concept map nodes that represent reservoirs (such as a plant, the ocean, the soil, or the atmosphere) and concept map connectors that represent flows of matter and energy. Some students intuit this, allowing them to better depict the interrelationship of these ecological flows. But other students make different design decisions — such as creating venn diagrams, flowcharts, or otherwise using connectors to show similarities and differences between Earth system components — that make it harder to tackle this particular challenge. Students may need better initial orientation into how to effectively use the basic components of a concept map to optimize the value they get from this classroom activity; this insight will inform revisions of the course and how it is delivered, particularly in regard to selection of background materials and discussion of the challenge of this activity.

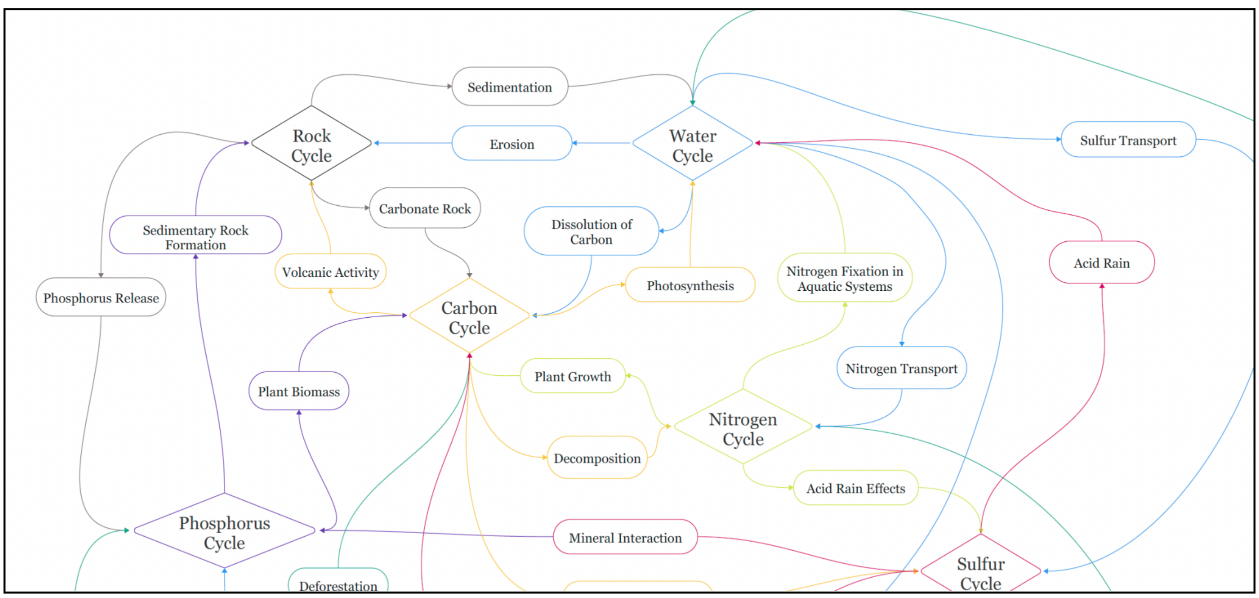

Figure 3. An example of a student concept map with strong connectivity and clear use of nodes, but where cycles were represented as single nodes and connectors were not labeled to explain the meaning of connections.

Interestingly, none of the seven student groups effectively incorporated the flow of energy in their maps, with only a few groups even mentioning the role of energy (mostly through the process of photosynthesis). This omission may stem from the resources students encounter in their research for this assignment: they are far more likely to find visual inspiration for depicting material cycles than they are to discover clear depictions of how energy moves through ecological systems. This is a loss, especially for engineering students whose work is so focused on energy, suggesting the need for ways to scaffold their depiction of energy in these diagrams.

Overall, our results suggest that students are most likely to struggle with depiction of ecological flows when doing so requires abstraction. Energy flows are more abstract than material flows, and the concept of "Earth spheres" requires an abstract assignment of categorical belonging that is not needed to identify and depict components of the Earth system. To fully understand how these cycles of matter and energy are interrelated, students must conceptualize how ecological interactions such as photosynthesis or consumption mediate the simultaneous flow of water, carbon, nitrogen, and energy. To fully equip students to apply systems thinking to Earth systems, we need to find ways to promote this conceptualization and depiction of more abstract ideas.

Our findings also suggest that in order to gain the most out of these mapping exercises, students need more practice (or at least guidance) in how to most effectively use a concept map to show flows of carbon, nitrogen, water, and energy. While some groups did intuit that concept map "nodes" should be used to depict reservoirs in Earth systems into and out of which material and energy flow and that "connectors" (i.e. arrows) should be used to depict these different flows, not all groups discovered this on their own, limiting their potential to think deeply about the interrelated nature of these flows. Future work of this sort should begin with a basic orientation to the use of concept maps to show flows between different reservoirs.

4c. Assignment 4: Energy Calculations. The energy assignment was designed to engage students in performing a combination of quantitative analysis, research, and interpretative analysis, to better understand energy use and related greenhouse gas emissions. The quantitative aspect involved basic algebra to calculate average rates (e.g., carbon emissions per unit of energy generated) and stoichiometry (e.g., to calculate the carbon emissions from combusting 1 liter of octane, as a proxy for gasoline); the research aspect was primarily to look up key data; the interpretive aspect included making useful comparisons (e.g., comparing overall emissions per unit of energy generated with that of octane) and to propose reasons for variability. The three criteria can be viewed as a pyramid (Figure 4), with the most well-structured activities at the base, and the least well-structured at the pinnacle.

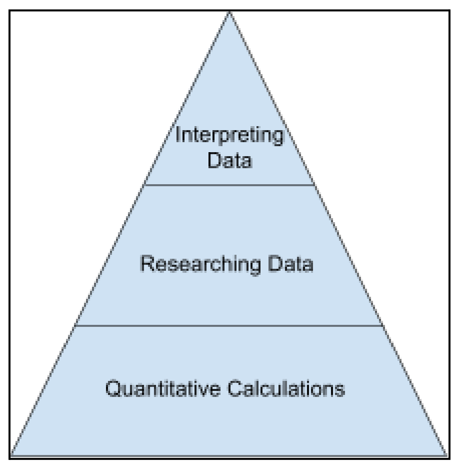

Figure 4. Hierarchy of Criteria for Assignment 4.

Six team assignments were evaluated. Similar to Assignment 3, these were evaluated for (1) Content, including ability to perform and justify calculations, and data research; and (2) Systems Thinking, including interpretative and consistency checks of information. Each of these categories is evaluated on a 0-3 point scale: Fully achieved (3), Achieved (2), Emerging (1), and Missing (0). The results of the evaluation of Assignment 4 are in Table 3.

Table 3. Evaluation of Assignment 4, Energy Calculations.

Assignment ID Item	A4_1	A4_2	A4_3	A4_4	A4_5	A4_6	Averages
Quantitative Reasoning	2	3	2	2	2	3	2.33
Research Quality	3	1	1	1	1	3	1.67
Consistency and interpretation	1	1	1	0	1	2	1.00
Total Average	**2.00**	**1.67**	**1.33**	**1.00**	**1.33**	**2.67**	**1.67**

As can be observed, all students performed relatively strongly on quantitative reasoning. This is not surprising since they are all engineering students, and the level of skill required in the assignment is at or below their current coursework levels. Even though it might appear trivial to rate students on their ability to perform basic algebra, past experience has shown that engineering students are often not methodical with unit conversions ("do I multiply or divide by the conversion factor?"), and that they also confuse direct unit conversions (e.g., 1000m/km) with relational rates (e.g., 1 mol C_8H_{18}/8 moles CO_2, or 0.064 kg CO_2e/1 MJ energy generated). In this sense, the students appear to be generally doing correct and well justified calculations. Indeed, unlike what is often observed in a 'regular' introductory math or chemistry class, instead of writing a scramble of calculations with various levels of organization, here, all six assignments presented calculations with detailed written explanations.

It is also intended that by doing these 'basic' problems, students will gain an initial window into the orders of magnitude of some important energetic quantities, such as the average metabolic power requirement (~100W) vs what is in practice consumed (~10,000W in affluent countries), per capita carbon footprint (~15 GT/person in the US), etc., and can thereby build fluency and a basis of expectations that can be used in future situations (see below).

Not surprisingly, as the task becomes less 'routine' or 'objective', students were not as successful. The notion of doing research is often absent in traditional STEM classes, due to the very deductive, well-structured nature of the material and problems presented in labs and class activities. Requiring students to answer questions by first seeking data requires them to engage in the context by implicitly learning about platforms and agencies that archive and present data. Although most assignments contained sufficient data, in most cases, insufficient citations were given, a phenomenon which has been observed elsewhere in evaluations of STEM work [26].

As a further step away from well-structuredness, the final criteria for the assignment is the ability to interpret and compare results - sometimes when prompted, and other times when not prompted. Interpretive reasoning (a form of critical thinking) can mean many things, but one particular focus here builds off of the research criterion. That is, in addition to being required to research data, a skill to be developed is to find multiple sources of information and compare them. With the initial question about global energy consumption, all students reported a correct answer, some cited it properly, but few provided more than one source to verify the answer, even though this practice was discussed frequently in class. Moreover, sometimes when there were multiple sources or pieces of data, inconsistencies went unnoticed. Table 4 provides examples of excerpts to give an idea of the quality of the work and how it was evaluated.

Table 4. Excerpts of Student Work on Assignment 4.

Item	Excerpt	Comments
A4_1	By taking that the annual energy consumption per year is 94.3 EJ and due to previous calculations, the annual per capita consumption is 277.356 GJ/person. We divide this number by the number of days in a year being 277.356 / 365 which would give us a result of an approximate of 0.76 GJ/person a day. Stated by an article on *MedicalNewsToday* the average amount of calories a human with a moderate or light amount of physical activity would need a day are just below 3,000 kcal (kilocalories). For men these would be approximately 2,700 kcal/ per day and for women it would be approximately 2,200 kcal / per day. …. The average kcal between 2,700 and 2,200 is 2,450 kcal. We get to this conclusion by dividing the sum of both numbers by two. After this we can convert the kcals to joules to make the comparison easier. …, we can convert this by multiplying … 2450 kcal between 4184 joules/kcal is 10,250,800 joules. They are equal to 10 MJ. To better compare both results we can change 0.76 GJ to MJ by multiplying 0.76 by 1000. This gives us 760 MJ which is the average consumption of energy per person every day in the US and the amount of energy for dietary consumption is 10 MJ. The average human consumes about 76 times the amount of energy that they would need dietary consumption daily.	This excerpt meets all criteria corresponding to level 3. The calculations are correct and justified. The primary data is cited. And the final sentence gives an interpretation of the result.

A4_2	How much CO2 is released from this combustion process? Is the amount of CO2 emitted, greater than, equal to, or less than the amount of input fuel on a mass basis?
	
	- **Step 1:** Use octane(C_8H_{18}) as an approximation for gasoline in this combustion process. The balanced reaction for the combustion of octane is:
	$\mathbf{C_8H_{18} + 12.5\ O_2 \rightarrow 8\ CO_2 + 9\ H_2O}$
	
	- **Step 2:** For each mole of octane burned, 8 moles of CO_2 are produced. Let's calculate the mass of CO_2 generated from burning 1 mole of octane.
	  - Molar mass of octane (C_8H_{18}) = 114g/mol
	  - Molar mass of CO_2 = 44 g/mol
	  - **Therefore, 1 mole of octane produces:**
	  8×44 g = 352 g of CO_2
	
	- **Step 3:** We calculate how many moles of octane are in 1 liter of gasoline. Assuming gasoline has a density of about 0.75 kg/L, the mass of 1 liter of gasoline is approximately: 0.75kg = 750g. Number of moles of octane in 750 g:
	750 g divided by **114 g/mol ≈ 6.58 mol**
		This excerpt shows a detailed quantification that would meet level 3 standard for quantification.

	- **Step 4:** Multiply the moles of octane by the CO_2 produced per mole to find the total mass of CO_2 generated from burning 1 liter of gasoline: 6.58 mol × 352 g CO2/mol ≈ 2316 g CO2. Therefore, burning 1 liter of gasoline releases approximately **2316 grams (or 2.316 kg) of CO_2**.	
A4_3	**In terms of EJ's for the year consumption, the United States consumed approximately 93.59 quadrillion BTUs, equivalent to about 98.6 Exajoules (EJ) of energy.** This total reflects energy use across transportation, electricity generation, industrial processes, and residential and commercial activities. With one of the highest per capita energy consumptions globally, this translates to approximately **277,500 terawatt-hours (TWh)**. The data emphasizes the extensive energy demand required to support the U.S. economy and lifestyle.	This excerpt would meet level 2 standard for research because the data is accurate, but the citation is missing. The conversion to TWh probably was conceived correctly, but it has an error (the accepted result is about 27,000 TWh). Repeated errors of this nature would reduce the quantitative rating from 3 to 2.
A4_6	What is the total amount of greenhouse gas ("GHG") emissions? Be careful to express this in terms of a meaningful unit. - To calculate the total amount of GHG emissions, we must remember that the total energy consumption was 27,431 TWh. **Which is also equal to $27{,}431\times10^9$ kWh.** - According to the EIA, typical GHG emissions go around 0.4 kg CO2e per kWh. **(0.4 kg CO2e/kWh)($27{,}431\times10^9$ kWh) = 1.097×10^{13} kgCO2e.** What is the average per capita greenhouse emission? - To find the average per capita, we must do the same equation that was previously used. Since the population is 334.9 M people, the average GHG emission is **32,756.05 kgCO2e.** What is the average "GHG intensity" of energy consumed in the US? That is, how much GHG is emitted per unit of energy consumption? - To find the GHG intensity, we must divide the GHG emissions per capita, per how much energy is consumed (which we know is $27{,}431 \times 10^9$ kWh). Doing this calculation, we would find that the GHG intensity, which is **1.19×10^{-6} kg CO2e/kWh.**	This excerpt represents good procedure, but there are some inconsistencies with confusing the role of total vs per capita data, thus leading to a result that is not of the correct order of magnitude.

4d. SALG Survey Results. A survey in the format of the SALG was administered to understand the student learning experience in the course. Whereas it is common to administer an end-of-semester survey such as a "faculty course evaluation", in which a primary emphasis is on the teaching qualities of the instructor, the SALG focuses on student learning gains. The questions in the SALG were also designed to map results according to a framework of Knowledge, Skills, Behaviors, and Attitudes (KSBA) [2]. To date 7 of the 22 enrolled students have completed the survey, with the available results reported in Tables 5 and 6.

Table 5. Summary of Closed form Responses from SALG Survey.

Closed-formed Questions related to Understanding, Skills, Attitudes and Qualities, and Integration and Synthesis. (N = 7 respondents). Aggregate averages per category appear at the top of each box. Blue items directly relate to the goals of this pedagogical inquiry project.	**Average Rating**
3. As a result of your work in this class, what gains did you make in your **understanding** of each of the following?	**3.57** **3.57**
[General definitions and frameworks of sustainability]	4.00
[History of sustainability frameworks]	3.57
[Frameworks and methods to define and monitor sustainability progress]	3.57
[Earth Systems and Biogeochemical Cycles]	3.71
[Planetary Boundaries]	3.71
[The reason that increased carbon dioxide in the atmosphere causes global warming]	3.57
[The different sources of energy generation]	3.57
[The different sectors of energy consumption]	3.71
[The relation between energy generation and carbon emissions]	3.43
[The production and flow of materials throughout the economy]	3.29
[The meaning of a circular economy]	3.57
[How food consumption (diet) and production relate to sustainability]	3.14
4. As a result of your work in this class, what gains did you make in the following **skills**?	**3.68** **3.55**
[How to synthesize, compare and cross-check information from multiple sources]	3.43
[How to write clearly and concisely, and in an organized manner]	3.71
[How to create visual objects and graphics to communicate information]	4.00
[How to appropriately document and cite information]	3.43
[How to create your own critical questions that build off of topics discussed in class]	4.00
[How to lead your own learning about sustainability outside of the class]	3.57
[How to search for career opportunities that will allow you promote sustainable causes and practices]	3.43
[How to perform stoichiometric calculations (mass balance in chemical equations)]	3.29
[How to use scientific and exponential notation]	3.86
[How to perform conversions between physical units]	3.29
5. As a result of your work in Creating a Sustainable World, what gains did you make in developing the following **qualities and attitudes**?	**3.90** **3.64**
[Confidence to learn and read about sustainability topics in an informed way]	3.86
[Confidence to write and speak about sustainability topics in an informed way]	3.86
[Confidence to ask a potential employer about their sustainability practices and goals]	4.00
[Confidence to apply principles from math and science to understand phenomena that relate to sustainability]	3.57
[Sense that approximations and estimates are often more useful than precise calculations]	3.71
[Motivation to make personal lifestyle changes to live more sustainably]	3.57
[Motivation to continue studying and researching sustainability concepts and applications]	4.00
[Motivation to seek a job or career path where you can play a role to advance sustainability]	4.00
[Feeling that you are part of a community of other students and faculty who are committed to sustainability]	4.00
6. As a result of your work in Creating a Sustainable World, what gains did you make in **integrating and synthesizing ideas and information**?	**3.77**
[Identifying how and where sustainability concepts and questions appear in other courses that you are taking]	3.43
[Identifying how and where sustainability concepts and questions appear in real-world situations]	3.57
[How sustainability relates to your discipline of engineering]	4.00
[Realizing how several elementary ideas combine into a larger complex system]	4.00
[Realizing that there can be more than one solution method for a given problem]	3.86

Table 6. Summary of Open form Responses to the SALG Survey, with Selected Comments.

Questions (N = 7 respondents)	Comments
1. What surprised you about this class? 2. What, specifically, is different about you now than at the beginning of the class? What are the most important ideas, concepts, skills, habits, ways of thinking, etc. that you have acquired that you think are important in your future studies and career?	2 total responses referring to “science” and “natural cycles”. “You have to think of the whole and how one part affects the other” “What I liked most is the way of thinking that Sustainability has taught me. It's like a strategy game where you have to think of the whole and how one part affects the other to make a true positive impact, with systems thinking.”
8. Which [course activity] was the most useful or the least useful?	1 student mentioned the Energy Assignment, and 1 mentioned the mapping Assignment as highlights. 1 student mentioned the Energy assignment as ‘confusing’
9. What did you specifically learn about mathematics, chemistry, and more generally about scientific and quantitative reasoning?	2 mentioned unit conversions, 2 mentioned scientific notation, 2 mentioned energy, and 3 mentioned chemistry and natural cycles “I noticed how something simple as photosynthesis and cellular respiration processes can be used for bigger understanding and impacts.” “I learned new tricks about exponential notation and operations to make mental math easier, and more about the chemical background of the Nitrogen, Oxygen, and Water cycle. … By calculating specific data about things like energy consumption (per capita, per country, per year, etc.), it helped me put into perspective where we stand in terms of sustainability in the energy sector and how much more we have to improve.”
10. What did you specifically learn about oral and written communication?	5 students referred to researching information and making proper citations “I learned how to search for information to write my work in an understandable form, but at the same time, dense with information and evidence.”
11. Can you describe at least one example when you compared different sources of data to check if they were consistent? 12. Can you describe at least one example in which you actively compared or combined an idea, skill, or question from this class with that of another class?	2 mentioned the Energy assignment, no one mentioned Assignment 3, and 2 mentioned other assignments. 5 mentioned chemistry or thermodynamics, one mentioned English, and no one mentioned math. “I feel that this class and my chemistry class could be combined in the point where we were doing the earth system concept map assingment.”
13. Did you start doing anything different in your life related to sustainability? For example, different approaches to buying products? Consumption of energy, water, etc.? Dietary habits? Conversations with family and friends? Etc.	Comments were about being more conscious of products (energy, water, and food), reducing plastic bottles, and starting conversations with friends and family. Some suggestions for the course were to slow down and have some hands-on activities.

14. Please leave any final comments … including suggestions of how to improve the experience.	

The particular closed form items that directly correspond to this article are colored in blue in Table 5. As can be seen, students generally rated their learning gains very highly, but with a slight lag for the results that correspond to the quantitative reasoning and systems thinking of the course. Although these results appear to be subjective, other work has demonstrated that results of the SALG can reliably indicate learning gains [27]. Therefore, despite the fact that the evaluations of Assignment 3 and 4 revealed some weaknesses in students' progress, the survey results suggest that students are at least aware and receptive to the importance of scientific understanding in their pursuit of learning about sustainability, leading to the possible outcome that continued learning will occur.

The results of the open questions also reveal positive trends (Table 6). In Questions 1 and 2, which opened the entire survey (and so there were no prompts at this point to steer the respondent to think about any particular topic), 3 of 7 respondents mentioned the importance of scientific or systems thinking. One student commented, *"What I liked most is the way of thinking that Sustainability has taught me. It's like a strategy game where you have to think of the whole and how one part affects the other to make a true positive impact, with systems thinking."*. Similarly, 3 respondents noted the usefulness of Assignments 3 and 4 among all of the course assignments. In the responses to Question 9, which did contain direct prompts, several students articulated specific details of what they learned or practiced scientifically. One student commented, *"I learned new tricks about exponential notation and operations to make mental math easier, and more about the chemical background of the Nitrogen, Oxygen, and Water cycle. … By calculating specific data about things like energy consumption (per capita, per country, per year, etc.), it helped me put into perspective where we stand in terms of sustainability in the energy sector and how much more we have to improve."* In answering Question 12, another student wrote *"I feel that this class and my chemistry class could be combined in the point where we were doing the earth system concept map assignment."* Also of note, in Question 10, the predominant response was that learning to use citations was important, even though this practice was often omitted in Assignment 4. One student commented, *"I learned how to search for information to write my work in an understandable form, but at the same time, dense with information and evidence."* For reference, the other salient outcomes of the open questions were that students really liked the discussion-oriented format of the course, and the activities that involved the reverse job interviews and mock consultations.

5. Conclusions

Scientific literacy, quantitative reasoning, and systems thinking are essential components of developing a sustainability mindset, and thus should form elements of introductory courses in sustainability so that such mindsets can be cultivated from the outset of a student's academic studies, particularly in engineering. Several teaching practices can be employed to foster holistic learning across these domains, such as those highlighted.

The results of the evaluations of selected student works suggest that engineering students demonstrate proficiency with basic quantitative skills and other well-structured activities, such as finding information, but as the activities become less well prescribed, they need to develop more practice to do “higher order” tasks, such as interpreting, cross-checking, citing, and communicating ideas outside of their routine.

The results of the student self-assessments are generally positive, and suggest that students are aware of the need to achieve the higher order expectations. The results of the open questions, in particular, indicate that several students authentically learned scientific and quantitative elements of sustainability thinking, as evidenced by their articulation of specific details about systems thinking, chemistry, and mathematics.

Future work can explore how improved instructional design, explanations, and prompts can lead to improved learning outcomes in the higher order tasks. Future work can also include longitudinal evaluation of the cohort to to understand the degree to which scientific ideas are retained and used by students in subsequent coursework.

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Appendix A. End of Class Reflections (Annotated)

Frequent end-of-class reflections were conducted during the last 2-5 minutes of class, or in some cases, to be completed after class within 24 hours. These reflections are designed to provide the instructor to "check the pulse" of the class based on what students are thinking and questioning; promote meta-cognition; and provide a brief space for individualized feedback.

1. **End of Class Reflection September 5, 2024:** Briefly reflect on any of the following after today's class: what new insights you have and/or what you found confusing, inspiring, curiosity-provoking.

   Context: This reflection was conducted after the lecture on September 5, after discussing the Natural Step framework for Sustainability science, in which the notion of the earth as a system open to energy exchange, and (very nearly) closed to mass exchange. A portion of a separate topic on sustainability jobs and careers was also discussed that day.

2. **End of Class Reflection October 29, 2024:** Give a recap on 1-2 ideas that you have learned about energy (covering the last 3 lectures), or that surprised you, and then 1-2 questions that are not clear.

   Context: This reflection was given as a summative reflection on three class periods that covered the notion of energy and power, as described in Section 2.

Appendix B. Text and Evaluation Rubric for Assignment 3

Assignment 3 : The Inter-relationships Between Ecological and Earth Systems Cycles

This assignment is from Prof. Christopher Jensen, from his course "Ecology, Environment, & the Anthropocene" at the Pratt Institute.

Objectives of this Activity

1. Consider how cycles of matter (carbon, nitrogen, and water) and flows of energy are inter-related in ecosystems;

2. Do appropriate web research to better understand how these cycles/flows are inter-related;

3. Construct a concept map — designed to teach others — that explicitly shows how these cycles/flows are inter-related; and

4. Present your concept map to the rest of the class so that we can:

   a. discuss how these ecological flows are interrelated; and

   b. compare and contrast different ways of representing information on a concept map.

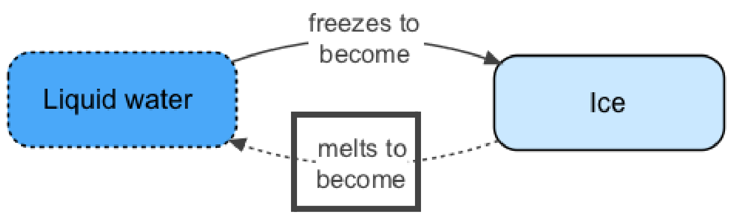
Instructions

1. Discuss in your group how cycles of matter (carbon, nitrogen, and water) and energy are inter-related in ecosystems.
2. Based on your discussion, identify any questions or confusion you have about the inter-relationship of these cycles.
3. As needed, do web research to answer questions and clear up confusion. Make sure to take note of the source of all information you gather.
4. Using MIRO, construct a concept map that is capable of teaching someone else how these cycles/flows are inter-related. At the very least, your concept map should:
   - 4.1. Represent the major biotic and abiotic components of the earth that relate to ecological cycling.
   - 4.2. Show how matter and energy flows through each of these cycles (in other words, there should be at least four identifiable "flows" in your diagram).
   - 4.3. Show how ecological interactions (e.g. predation, parasitism, mutualism, competition, or commensalism) and other ecological activities (e.g. photosynthesis, respiration, excretion/elimination, decomposition) are involved in these cycles.
   - 4.4. Clearly demonstrate where and how these cycles are inter-related.
   - 4.5. Label or otherwise demarcate which components on your map belong to the biosphere, lithosphere, hydrosphere, & atmosphere (please note that trying to represent these spheres as "nodes" won't lead to a successful concept map).
5. Where appropriate, indicate the source of information represented on the map. [See instructions for creating a concept map in Miro on the next page.]

How to create a concept map with MIRO:

★ Concept maps include two basic elements, nodes and connectors. **Nodes** are open shapes that can be filled with text; you can use color variations in text, fill, and line to signify commonality and difference between nodes. **Connectors** are lines that connect nodes and can be labeled with text; you can use arrowheads/tails, color, and stroke differences to create different meanings in your connectors.

★ Nodes should be used to represent a concept: an idea, entity, or phenomenon. The best nodes are very simple; if you find yourself writing a paragraph inside a node, you probably are trying to jam multiple ideas into a single node. It is better to create multiple nodes than to represent complex ideas within a single node.



★ Connectors should be used to show relationships between nodes. For example, I might create two nodes, one called "liquid water" and another called "ice". I could connect these two ideas with two connectors. An arrow moving from "liquid water" to "ice" could be labelled "freezes to become". Notice how this connector creates a relationship between the nodes, and can be read as a simple sentence. An arrow moving in the opposite direction could be labelled "melts to become". Selecting arcing connectors allows these two relationships to be represented side-by-side:

★ The best concept maps use spatial arrangement to effectively convey relationships between ideas (nodes). Connectors can help you to decide which ideas belong nearer to each other: when there are many connectors between a series of nodes, they will look better (and make more sense!) if they are placed closer to each other. Nodes that are not directly connected will end up further apart. This spacing tells us something about the relationships between the various ideas on your map.

★ Although *MIRO* may seem like a relatively simple program, it is very powerful for creating concept maps. Take advantage of the ability to create arrows with different shapes (straight, arcing, or s-curved) and directionality (no arrowheads, single arrowhead, dual arrowhead) to make your maps easier to read and understand. Use differences in the color of fonts, fills, and strokes to signify commonality and difference. Also use MIRO's power to rearrange your map to optimize spacing and location of different nodes on your map.

Table B1. Evaluation Rubric for Assignment 3.

Score ➡	3	2	1	0
Category ➡	**Fully Achieved**	**Achieved**	**Emerging**	**Missing**
Content				
Components of the Earth	Concept map represents all of the major biotic and abiotic components of the earth that relate to ecological cycling	Concept map represents most of the major biotic and abiotic components of the earth that relate to ecological cycling	Concept map represents some of the major biotic and abiotic components of the earth that relate to ecological cycling	Concept map represents none of the major biotic and abiotic components of the earth that relate to ecological cycling
Earth Spheres	Concept map shows where all components belong to the biosphere, lithosphere, hydrosphere, & atmosphere	Concept map shows where most components belong to the biosphere, lithosphere, hydrosphere, & atmosphere	Concept map shows where some components belong to the biosphere, lithosphere, hydrosphere, & atmosphere	Concept map does not show where components belong to the biosphere, lithosphere, hydrosphere, & atmosphere
Systems Thinking				
Ecological flows	Concept map comprehensively shows how matter and energy flow through each of the cycles	Concept map predominantly shows how matter and energy flow through each of the cycles	Concept map partially shows how matter and energy flow through each of the cycles	Concept map does not show how matter and energy flow through each of the cycles
Ecological interactions	Concept map comprehensively shows how ecological interactions and other ecological activities are involved in these cycles	Concept map predominantly shows how ecological interactions and other ecological activities are involved in these cycles	Concept map partially shows how ecological interactions and other ecological activities are involved in these cycles	Concept map does not show how ecological interactions and other ecological activities are involved in these cycles
Interrelationships	Concept map comprehensively demonstrates where and how these cycles are interrelated	Concept map predominantlly demonstrates where and how these cycles are interrelated	Concept map partially demonstrates where and how these cycles are interrelated	Concept map does not demonstrate where and how these cycles are interrelated

Appendix C. Text and Evaluation Rubric for Assignment 4

Assignment 4: Energy

This activity is a team activity.

1. Find data for the total energy consumption and the corresponding carbon emissions for **the US in 2023**.

    a. What is the total energy consumption in units of TWh and EJ for the year? Provide an explanation of why the two numbers are equivalent.
    b. Calculate the average annual per capita energy consumption (per person).
    c. Calculate the average per capita energy consumption per day. How does this compare to an average metabolic (dietary) requirement?
    d. What is the corresponding average per capita power (rate of energy consumed)? Remember that P = E/t.
    e. What is the total amount of greenhouse gas ("GHG") emissions? Be careful to express this in terms of a meaningful unit.
    f. What is the average per capita greenhouse emission?
    g. What is the average "GHG intensity" of energy consumed in the US? That is, how much GHG is emitted per unit of energy consumption?
    h. Are any of these results directly comparable to data reported in the article "Human Domination of the Biosphere"?

2. Calculate your Carbon Footprint using this and this. How do the results compare with the corresponding results in Question 1? What might explain the differences? What might be some examples of energy consumption that you are responsible for, but which might not be included in the online calculators?

3. Consider the energy and corresponding emissions from burning a liter of gasoline, using octane as the reference fuel. You can use this video for reference.

    a. How much CO2 is released from this combustion process? Is the amount emitted, greater than, equal to, or less than the amount of input fuel on a mass basis?
    b. How much energy is liberated from this combustion process?
    c. What is the GHG intensity of this process? Compare to your answer in 1(g).

    Hints: Also think about equivalences between volume, mass, and mols.

4. Compare the cost of energy from the following sources:

    a. Food
    b. Gasoline
    c. Electricity

Table C1. Evaluation Rubric for Assignment 4.

Score ➡	3	2	1	0
Category ➡	**Fully Achieved**	**Achieved**	**Emerging**	**Missing**
Content				
Quantitative Reasoning	Calculations are correct and reasoning is completely justified and clearly presented.	Calculations are mostly correct, and/or with some occasional gaps in justification, giving confidence that there is no major conceptual barrier.	Calculations have frequent errors, and/or there are frequent instances where steps are missing, raising questions that an underlying weakness may be present.	Calculations are fundamentally poorly conceived or constructed.
Research	Data has been researched whenever necessary, and cited appropriately.	Most of the essential data has been researched, but with some gaps, and/or gaps in citations.	Some data is cited, but it is incomplete, and poorly cited.	Data and citations are fundamentally absent.
Systems Thinking				
Consistency and cross-comparison, and interpretation.	Multiple data and sources are presented, and are cross-checked for consistency, and/or other useful Interpretations are always made. Differences due to estimation or rounding are not confused with inconsistency.	Multiple data and sources are presented, but some inconsistencies are apparent, and/or there are some missing interpretations.	Even when essential data is given, a single source is relied upon, with few attempts to check for consistency.	Missing essential data that does not allow for useful interpretation or context.

Appendix D. SALG Survey

The questions that apply most directly to this article are in blue. Comments in pink are annotations that do not appear in the survey.

1. What surprised you about this class?

2. What, specifically, is different about you now than at the beginning of the class? What are the most important ideas, concepts, skills, habits, ways of thinking, etc. that you have acquired that you think are important in your future studies and career?

3. How much did the following aspects of the course help you in your **learning**? (Examples might include class and lab activities, assessments, particular learning methods, and resources.) [5-pt Likert scale: not helpful at all to greatly helpful]

- Participating in class discussions
- Writing end-of-class reflections
- Individual or small group discussions in office hours
- Reading assigned articles
- Reading the prepared Notes (slides) in Google Classroom
- Reading articles/watching videos linked in the Notes slides that were not assigned
- Finding your own articles, podcasts, videos or other resources to read, watch, or listen to, without being required
- Completing the assigned activities
- Reading and responding to feedback related to the activities
- Engaging with or interviewing an outside organization

4. As a result of your work in this class, what gains did you make in your **understanding** of each of the following? (Instructors insert those concepts that they consider most important.) [5-pt Likert scale ranging from No Gains to Great Gains]

3. As a result of your work in this class, what gains did you make in your **understanding** of each of the following?

- General definitions and frameworks of sustainability
- History of sustainability frameworks
- Frameworks and methods to define and monitor sustainability progress
- Earth Systems and Biogeochemical Cycles
- Planetary Boundaries
- The reason that increased carbon dioxide in the atmosphere causes global warming
- The different sources of energy generation
- The different sectors of energy consumption
- The relation between energy generation and carbon emissions
- The production and flow of materials throughout the economy
- The meaning of a circular economy
- How food consumption (diet) and production relate to sustainability

*This question corresponds to **knowledge***

5. As a result of your work in this class, what gains did you make in the following **skills**? (A sample of skills includes the ability to make quantitative estimates, finding trends in data, or writing technical texts.) [5-pt Likert scale ranging from No Gains to Great Gains]

- How to synthesize, compare and cross-check information from multiple sources
- How to write clearly and concisely, and in an organized manner
- How to create visual objects and graphics to communicate information
- How to appropriately document and cite information
- How to create your own critical questions that build off of topics discussed in class
- How to lead your own learning about sustainability outside of the class
- How to search for career opportunities that will allow you promote sustainable causes and practices
- How to compare and cross-check data from different sources
- How to perform stoichiometric calculations (mass balance in chemical equations)
- How to use scientific and exponential notation
- How to perform conversions between physical units

6. As a result of your work in this class, what gains did you make in developing the following qualities and attitudes? (The sub-items address **attitudinal** issues such as enthusiasm for the course or subject area.) [5-pt Likert scale ranging from No Gains to Great Gains]

- Confidence to learn and read about sustainability topics in an informed way
- Confidence to write and speak about sustainability topics in an informed way
- Confidence to ask a potential employer about their sustainability practices and goals
- Confidence to apply principles from math and science to understand phenomena that relate to sustainability
- Sense that approximations and estimates are often more useful than precise calculations
- Motivation to make personal lifestyle changes to live more sustainably
- Motivation to continue studying and researching sustainability concepts and applications
- Motivation to seek a job or career path where you can play a role to advance sustainability
- Feeling that you are part of a community of other students and faculty who are committed to sustainability

7. As a result of your work in Creating a Sustainable World, what gains did you make in integrating and synthesizing ideas and information? (The sub-items address how the students **integrated** information.) [5-pt Likert scale ranging from No Gains to Great Gains]

- Identifying how and where sustainability concepts and questions appear in other courses that you are taking
- Identifying how and where sustainability concepts and questions appear in real-world situations
- How sustainability relates to your discipline of engineering
- Comfort with combining several elementary ideas into a larger complex system
- Realizing that there can be more than one solution method for a given problem

8. In this class there were 6 main assignments: **(1) Sustainability Frameworks and Metrics,** (2) Reverse Company Interview, **(3) Concept Mapping of Earth Systems Cycles, (4) Energy Consumption,** (5) Materials Use and Management, and (6) the Final Project about consulting with an external organization. We also had four externally coordinated activities: (a) visit to 3A Press, (b) lecture of Carlos Lee about Mass Timber, (c) lecture of Dennis Miller and Josiah Hernandez about food and diet, and (d) the visit to the Tropical Agricultural Research Station.

Which of these were the most useful or the least useful? Please provide any specific highlights or lowlights that you remember from any of these activities.

9. What did you specifically learn about mathematics, chemistry, and more generally about scientific and quantitative reasoning?

10. What did you specifically learn about oral and written communication?

11. Can you describe at least one example when you compared different sources of data to check if they were consistent?

12. Can you describe at least one example in which you actively compared or combined an idea, skill, or question from this class with that of another class?

13. Did you start doing anything different in your life related to sustainability? For example, different approaches to buying products? Consumption of energy, water, etc.? Dietary habits? Conversations with family and friends? Etc.

14. Please leave any final comments if not previously addressed, including suggestions of how to improve the experience.