An Interactive Planetary Boundaries Systems Thinking Learning Tool to Integrate Sustainability into Chemistry Curriculum

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ABSTRACT

Sustainability has a molecular basis that suggests a central role for chemistry in addressing today’s challenges to Earth and societal systems, and this role requires educators to see chemical reactions and processes as integral parts of dynamic and interconnected systems. Despite this prospect, few accessible resources are available for students and educators to facilitate systems thinking in chemistry for sustainability. We have developed an interactive digital learning tool (https://planetaryboundaries.kcvs.ca) based on the Planetary Boundaries sustainability framework, that uses interactive visualizations to help users better understand Earth system sustainability challenges and helps chemists and educators connect substances, reactions, and chemistry concepts to sustainability science. The tool highlights the fundamental role that chemistry plays in regulating the individual biophysical Earth system processes and in determining their control variables. It incorporates key features of a systems thinking framework by illustrating the dynamic interconnections among the processes and their control variables and demonstrates change of the Earth system over time. Finally, the interactive tool provides educators with accessible entry points to support the integration of chemistry curriculum content with sustainability considerations.
INTRODUCTION

Chemistry, through its primary activities of analysis, synthesis, and transformation of substances, plays an important role in explaining and predicting the behaviour of matter, and controlling important aspects of material conversions. As a consequence, chemistry has a central but not yet sufficiently realized role in efforts to address the impact of the massive scale of anthropogenic transformation of materials, as the mass of these materials now exceeds the mass of all living biomass.\(^1\) This planetary scale transformation has unintended consequences that pose multiple and interconnected threats to the sustainability of all living systems, including human societies.\(^2-4\) The molecular basis of sustainability, which we have previously defined as “the ways in which the material basis of society and economy underlie considerations of how present and future generations can live within the limits of the natural world,” highlights the role for strong, overt, and urgent attention by chemists and educators to the ways in which fundamental knowledge of chemistry can contribute to sustainability science and to achieving sustainability goals.\(^5\) It is difficult to imagine how targets such as the United Nations Sustainable Development Goals can be achieved, and targets related to food
production and security, healthy air and water, and affordable clean energy can be reached, without substantial and visible contributions from the molecular sciences.

However, chemistry can only fully contribute to sustainability science if chemistry educators are willing and able to reimagine the way they teach. A substantial transition is required, from presenting chemical substances, reactions, and processes as isolated chunks of knowledge to articulating strategies that help learners see and understand the place of chemistry in dynamic and interconnected systems, especially those that provide the molecular basis for the sustainability of Earth and societal systems. More holistic approaches to chemistry education can better equip the diverse group of students who take foundational courses such as general chemistry with the understanding of the molecular/material basis of sustainability needed for specialization in fields that draw heavily on understanding the molecular world.

The Planetary Boundaries framework is a structure for understanding the many ways humans are influencing the Earth system, how those influences interact, and how they threaten sustainability. Chemistry plays a key role in monitoring and understanding the impacts and interactions of Earth systems processes on planetary health and human society and is fundamental to working towards solutions to the sustainability challenges identified by the framework. We describe here an interactive digital learning tool intended to help readers understand and explore the Planetary Boundaries framework, and to help chemists and educators connect substances, reactions, and chemistry concepts introduced in chemistry courses to sustainability science in a systems context.

**SYSTEMS THINKING IN CHEMISTRY EDUCATION**

Systems thinking in chemistry education provides an approach and tools to move beyond teaching isolated concepts to emphasize how components interact dynamically within a system, the emergent behaviours of a system, and how these behaviours change over time. When applied to chemistry education, systems thinking can help chemistry students deepen their critical thinking skills, wrestle with complexity, and meaningfully connect knowledge in chemistry with local and global environmental, social, and economic systems. Students who understand the interconnectedness of chemistry with Earth and societal systems are better equipped to address global
The past five years have seen considerable momentum building to emphasize systems thinking in chemistry education as a strategy to help move from a reductionist presentation to a more holistic view of chemistry, while enhancing student learning and understanding of how chemistry influences the emergence of a healthy and sustainable planet and societies. The exploration of systems thinking by chemistry educators builds on important features of systems thinking increasingly incorporated into green and sustainable chemistry and other STEM disciplines.

One of the first globally coordinated efforts to incorporate systems thinking in chemistry education to address global challenges was a 2017-2020 project by the International Union of Pure and Applied Chemistry (IUPAC) on “Learning Objectives and Strategies for Infusing Systems Thinking into (Post)-Secondary General Chemistry Education,” or STICE (Systems Thinking In Chemistry Education). The STICE project surveyed the literature for effective practices in the incorporation of systems thinking into other STEM disciplines, including engineering, biology, and environmental sciences.

STICE project outcomes, as well as initiatives in the green and sustainable chemistry education community were reported in the December 2019 special issue of the Journal of Chemical Education, which focused on: “Reimagining Chemistry Education: Systems Thinking, and Green and Sustainable Chemistry.” Building on the success of the STICE project, a second IUPAC project on “Systems Thinking in Chemistry for Sustainability: Toward 2030 and Beyond (STCS 2030+)” aims to empower educators and industry to incorporate systems thinking into chemistry to promote sustainability, linking to both the 2022-23 International Year of Basic Sciences for Sustainable Development and the United Nations Sustainable Development Goals (UN SDG). Three IUPAC STCS 2030+ project working groups on Systems Thinking are now taking steps to arrive at shared understandings of how systems thinking can best be described, how it can most helpfully inform chemistry and chemistry education, and the working groups are developing resources to equip educators and students to use systems thinking approaches.
The Planetary Boundaries framework, first published by an international interdisciplinary team of scientists in 2009, with a substantial update in 2015, is relatively unfamiliar to chemists and the chemistry education community, despite its many connections to chemistry and its influence in environmental policy discourses. The framework describes nine human-perturbed Earth system processes: biosphere integrity, climate change, novel entities (originally chemical pollution, re-designated in 2015), aerosols, stratospheric ozone, ocean acidification, fresh water, land use, and biogeochemical flows, that collectively describe quantitatively the state of the Earth system with respect to human development. The Planetary Boundaries framework can be viewed as giving a measure of the global health of the Earth in light of substantial changes to Earth system processes in the transition from the Holocene Epoch, a 12,000-year period of remarkable climate stability, to the Anthropocene Epoch defined by human-driven change.

The changes to each Earth system process in the Planetary Boundaries framework are monitored by changes over time of one or more control variables, which are thought to be representative of the processes of change in that Earth system process as a whole. This biophysical framework summarizes anthropogenic pressure on the Earth system as a dashboard of sustainability which helps tell the story of the state of our planet. The framework has often been represented by a static diagram similar to Figure 1, in which the colour of the process changes from a green “safe operating space” at the centre to orange and red when a control variable crosses the planetary boundary for that Earth system process, indicating progression over time to conditions of high risk to society. The deeper red of the biosphere integrity and biogeochemical flows of N and P Earth system processes indicates that the risks to society and the global ecosystem are very high with a large degree of scientific confidence. Since Figure 1 was created, substantial changes have occurred to the control variable for the climate change and chemical pollution/novel entities Earth system processes.
Many of the Earth system process control variables in the framework are measurements of chemical substances or indicators of processes based on chemical transformations, and the changes over time of these control variables demonstrate how chemistry both describes and regulates important features of planetary health. These include changes to the concentration of stratospheric ozone (for the perturbed Earth system process of ozone depletion) due to introduction of anthropogenic ozone depleting substances; the rapid changes in concentrations of atmospheric aerosols and gases (e.g., carbon dioxide, methane, CFCs, and other greenhouse gases – for the framework’s climate change and aerosols processes); changing ratios of aquated ions (e.g., hydronium, bicarbonate, and carbonate ions in the ocean – ocean acidification process); the stark increase in concentrations of reactive nitrogen and phosphorus species (biogeochemical flows process); and the nature and quantities of novel entities such as plastics, CFCs, and other anthropogenic pollutants introduced to the environment (novel entities process). When these control variables remained within definable boundaries, the Earth system as a whole remained in its stable interglacial condition; the global change science community has some confidence that this configuration of conditions defines a safe operating space for human activity. Once the planetary boundaries are crossed, there is a rising risk
that the Earth system will destabilize, resulting in abrupt and large-scale environmental changes. For example, climate change has two control variables: mean atmospheric carbon dioxide concentration, and the energy imbalance at the top of the atmosphere. The planetary boundary, which defines the safe operating space for atmospheric carbon dioxide concentration, is set at 350 ppm of carbon dioxide; concentrations much higher than this will lead to feedback-enhanced warming and related changes to the global climate. This boundary was crossed around 1990, and the concentration at present is more than 420 ppm and rising. This system is now at high risk for extreme climate events, and since climate change is one of two “core” Earth system processes, the entire planet is at risk of destabilization.

The boundaries and the concept of a "safe operating space" are designed to account for scientific uncertainty. While one set of values for a control variable may be clearly "safe", and another set of values is clearly "high risk", uncertainties in measurement and mechanisms limit the precision at which the boundary between “safe” and “high risk” can be determined. Further, it is often not even possible to define a single “transition point” out of the “safe” space. Earth system responses that mark the human-caused shift away from Holocene conditions tend to be continuous rather than sharply visible thresholds in the individual control variables. The quantified planetary boundaries have been selected to lie well back from the region of known high risk, so that a safe operating space can be determined with some confidence.

The Planetary Boundaries framework also illustrates the interconnectedness of the Earth system as a whole, making it a valuable demonstration of and a learning resource for systems thinking. Two Earth system processes, biosphere integrity and climate change, are core Earth system processes which operate at the scale of the whole system, and which are closely linked to all of the other Earth system processes, showing clearly the interconnectedness of the Earth system. For example, increased concentration of carbon dioxide in the atmosphere leads to increased ocean acidification, while changes in land cover, water use and biogeochemical flows all affect feedbacks between climate and the world’s living ecosystems. Figure 2 illustrates some of the important ways that climate change connects to each of the other Earth system processes. This information can also be viewed dynamically by accessing the “connections” tab on the interactive learning tool.
Figure 2. Examples of connections and interactions between climate change and all other Earth system processes. The “connections” view in the KCVS planetary boundaries learning tool shows the web of interconnections among all the Earth system processes.

THE KCVS PLANETARY BOUNDARIES INTERACTIVE LEARNING TOOL

We have developed and published on the King’s Centre for Visualization in Science website a free, interactive learning tool for exploring the Planetary Boundaries framework, seeing the impact of human activity on the state of the Earth system processes, and visualizing some of the many chemistry connections to those processes and to sustainability considerations. Box 1 gives examples
of high level ("big idea") learning objectives for the tool when used in foundational secondary or post-secondary chemistry courses.

**Box 1. Examples of High Level Student Learning Objectives ("Big Ideas") for the Planetary Boundaries Interactive Learning Tool in Foundational Chemistry Courses**

- Describe why the Planetary Boundaries framework is a useful tool for understanding the state of Earth’s systems and their implications for sustainability.
- Provide specific examples of why chemistry is important for understanding the Planetary Boundaries framework.
- Apply knowledge of systems thinking tools and approaches to connect chemistry curriculum to global problems and solutions through the Planetary Boundaries framework.
- Value the central contributions chemistry can make towards achieving global sustainability.
- Use the Planetary Boundaries framework to draw connections among concepts in the chemistry curriculum.

When launching the tool, users first see an interactive, stylized Planetary Boundaries framework diagram ("processes view", Figure 3) along with supporting text. The Planetary Boundaries diagram shows the status of each Earth system process relative to its boundary; markers and color changes indicate in which Earth system processes human activity has already breached the boundaries. As evident by comparing Figure 3 with Figure 1, we made several design choices in our interactive visualization to address misinterpretation of the framework by users. For example, in our diagram radial position only indicates the state of the process instead of encoding specific values of the control variables, in part because users often try to compare process states using the relative sizes of the wedges (e.g. the state of biogeochemical flows is "not as bad" as that of biosphere integrity). Users also sometimes read the earlier diagrams like a pie chart that implies each process is an equal fraction of the whole; the use of markers reduces this association. Supporting text presents the purpose of the framework, clarifies terms, and gives examples. Users can select an Earth system process to see more information about that process and its control variables.
As described earlier, scientific uncertainty and the continuous nature of the Earth system’s responses to process changes mean there is no way to assign a specific value that marks the transition from "safe" to "high risk" for a control variable, and so the quantified planetary boundaries have been set back from the region of known high risk, essentially suggesting a “safety zone.” The learning tool illustrates these features of the framework in the graphs of the control variables (Figure 4). The progression from "safe" to "high risk" is shown by colour gradients indicating uncertain transition regions. The line indicating the boundary is shown to be in the "safe" region just before it starts to shift into a "risk" colour.

Figure 3. The King’s Centre for Visualization in Science Planetary Boundaries interactive learning tool.
Figure 4. Example of a graph of control variable values over time, from the Planetary Boundaries interactive learning tool. This graph features the second of two control variables for the Climate Change Earth system process, the change in radiative forcing of our planet since 1750. The dashed line shows the numerical value of the planetary boundary for this control variable, and the bands of colour encode levels of risk and scientific certainty.

Change over time and inter-component connections are both key elements of systems thinking, so graphs for each Earth system process such as that shown in Figure 4 are presented dynamically, showing change over time of each control variables, starting in 1900. An animation in the “processes” view of the learning resource shows how these changes play out simultaneously in the Planetary Boundaries diagram, showing humanity’s growing impact on the Earth system and further emphasizing the interconnectedness of Earth system processes. To reinforce insight about interconnections among the Earth system processes, when a process is selected, its most closely-connected processes are highlighted in the diagram and explained further in the supporting text. The interactive learning tool thus facilitates deeper understanding of the nine Earth system processes in the Planetary Boundaries framework and how they interconnect, and how these embody key sustainability challenges.

Web of Earth System Process Connections (“Connections” View)

Users can also visualize the multiple connections among each of the Earth system processes in the learning tool by switching to the "connections" view, a network diagram that visualizes the web of Earth system process connections and briefly describes key Earth system connections to a selected process. Figure 5 shows an example of this view, featuring the interconnections between the ocean acidification Earth system process and the eight other Earth system processes. In this view, the nine Earth system processes (i.e., the system's components) are shown as elliptical markers, with lines drawn between them to represent important connections. An interactive force-directed graphing
technique has been employed to enable the user to interrogate the connections in the web of planetary boundaries. When an Earth system process is selected, it moves to the centre of the display, and descriptions appear on each connection; clicking on a description brings up more detail. Lines not connected to the selected process are faded, which reduces the visual clutter while keeping the whole Earth system context in the background. The force-directed graph updates the layout as selections are changed. Users can pan and zoom to explore the diagram, and individual connection paths are highlighted on hover for clarity.

Figure 5. Screenshot of the force-directed graph that highlights connections among Earth system processes in the Planetary Boundaries interactive learning tool, using the ocean acidification Earth system process as an example. The interactive graph can be explored at https://planetaryboundaries.kcvs.ca

Web of Chemistry Curriculum Connections (“Curriculum” View)

The Web of chemistry curriculum connections (“curriculum” view, Figure 6) view in the interactive resource, also uses a force-directed graph to help chemistry educators and students visualize interconnections among selected chemistry curriculum topics, aspects of Earth system processes, and
sustainability considerations. An ongoing project by a working group of the IUPAC STCS-2030+ task force is mapping chemistry curriculum topics to each of the Earth system processes in the framework. The curriculum web view currently published online is a preliminary version showing only a few of the many connections, and it will be updated online over the next 18 months as the IUPAC task force continues its work.

This view is also constructed with an interactive force-directed graph to visualize the web of curriculum connections that the chemistry education community can use to relate traditional curriculum topics in foundational courses to the web of Earth system processes. It has functionality similar to the web of Earth system connections view: users can select either an Earth system process or a curriculum topic to highlight important connections; clicking on a link line brings up more detail. Topics are organized into categories; selecting a category displays connections for those topics. To find a particular topic of interest, users can also select from a list. The preferred starting point for many
educators will be with the list of chemistry topics they teach, and the web of curriculum connections can help an educator identify one or several entry points to integrating sustainability considerations into a course without feeling the need to redesign an entire course. We are developing a set of educator resources that can be used in the classroom to facilitate exploring more deeply the connections between select curriculum topics and Earth system processes, and these will be updated on-line after obtaining peer review. Several examples of these resources are available in the online learning tool.

**APPLYING SYSTEMS THINKING WITH THE PLANETARY BOUNDARIES LEARNING TOOL**

The Planetary Boundaries interactive learning tool incorporates several generalizable key aspects of systems thinking, including identifying components of systems and their connections, seeing the system as more than the sum of its parts, and setting boundaries to explore more deeply a part of a system. The learning tool also explores flows and cycles, dynamic complexity, and causal and feedback loops, which provide an excellent starting point for further discussion on aspects such as system interactions and emergent properties.

Understanding a system in terms of its components and their interactions is an essential part of systems thinking offering a powerful approach for problem solving. The Planetary Boundaries framework provides a science-based analysis of the perturbation of the Earth system as a whole, and its nine processes should be considered as dynamically interacting and interdependent components of the Earth system. The interactive learning tool provides a structured, visual way to explore the individual processes, their interconnections, and the way humanity is altering them over time, both individually and as an integrated system.

Material flows and cycles have central roles in most of the Earth system processes, linking a variety of reactions across stages and between processes. Many of these can be seen as paths and closed loops in the "connections" view. This interactive view exemplifies a key feature of systems thinking – showing an entire system, and then setting boundaries around a portion of that system for deeper exploration. Considering the ocean acidification process in Figure 5, for example, carbon dioxide emissions are a main driver of climate change, and the carbon cycles govern the climate
through feedback loops on land and in the oceans on several different time scales. As another example, the process of biogeochemical flows follows the movement of reactive nitrogen and phosphorus into atmospheric, terrestrial, aquatic and marine environments. Both carbon and nitrogen flows intersect other Earth system processes, such as freshwater use and biosphere integrity. The interactive learning tool’s representation of these flows and cycles illustrates the complex dynamics of the Earth system, and its timeline animation highlights the fact that the Earth system is being driven out of equilibrium by human activity.

Material flows and process connections can also be used to start a discussion about emergent system behaviour, which arises from interactions and which cannot readily be predicted from the behaviour of the contributing components. One relatively simple example of emergence is the beneficial impact on the health of humans and other living beings as a result of shielding from UV-B light by stratospheric ozone. This effect emerges from a complex set of processes and reactions driven by photochemistry from the natural Chapman cycle. Novel entities such as CFCs and nitrous oxide from the biogeochemical flows Earth System process are transported into the stratosphere, where they perturb the Chapman cycle through a set of interacting catalytic cycles. A more complicated example of emergence can be studied through a life cycle analysis of fixed nitrogen in the context of biogeochemical flows, where reactive nitrogen species exhibit multiple simultaneous unintended consequences, from which emerge planetary challenges that can be mapped onto the UN sustainable Development Goals.12,26

A closer examination of the boundaries and how the "safe operating space" is defined reveals the probabilistic nature of complex systems. As mentioned earlier, the transition of a control variable from "safe" to "high risk" condition is generally quite smooth, due to both uncertainties and the generally continuous nature of the Earth system’s responses to change. The control variable graphs in the interactive learning tool help users to visualize these features and put them in context. This sort of probabilistic complexity is a common and challenging feature of systems with many components, and the "safe boundary" approach is an important tool for making decisions in the face of uncertainty.

Ultimately, all of these processes and their boundaries are defined by human concerns and driven by human activity. This naturally connects the (chemical, physical, biological) Earth system to socio-
economic systems, which are also critical to understanding both the problems and solutions of sustainability. A notable framework for working with these inter-system connections is the "Doughnut of social and planetary boundaries", first published as an OXFAM discussion paper by Kate Raworth in 2012, and since developed further into "Doughnut Economics" and a community-level sustainability action initiative.

**CURRICULUM CONNECTIONS TO THE PLANETARY BOUNDARIES FRAMEWORK**

The nine Earth system processes are closely connected to concepts from across the chemistry curriculum, so as well as promoting systems thinking, the Planetary Boundaries framework can be a useful way to link diverse curriculum topics together in a larger coherent sustainability context. The interactive learning tool's "Curriculum" Web view, described earlier, can help educators find entry points into the Planetary Boundaries framework from the curriculum they already teach.

Our development of this interactive learning tool has been motivated in part by approaches we have taken at the King's University over the past decade to weave sustainability considerations into chemistry topics across the curriculum. In Chemistry 201, our second term general chemistry course at the King's University, we use rich contexts that are based on the Planetary Boundaries framework's ocean acidification and climate change Earth system processes. The ocean acidification process provides a straightforward context for introducing systems thinking, by linking the speciation of carbon following the introduction of carbon dioxide into the ocean to the aragonite saturation state, with implications for the health of the marine ecosystem.

General chemistry students are introduced to a set of topics related to speciation, acid-base chemistry, and solubility and precipitation concepts through the rich context of ocean acidification, in a sequence which begins and ends in links to other Earth system processes. Ocean acidification results from the increased levels of atmospheric carbon dioxide interacting with seawater. Students use Henry's Law to see how the concentration of atmospheric carbon dioxide — a control variable for climate change — affects the amount of carbon dioxide that dissolves in the ocean at a particular temperature. Students then use equilibrium principles to see how carbon dioxide will react with water to create bicarbonate and carbonate ions that dissociate to produce hydronium ions, from which they
can calculate ocean pH. A KCVS interactive learning tool on ocean acidification is used to help students see how a decrease in pH will affect the ratio of carbonate to bicarbonate ions. The saturation state of carbonate ions with respect to the carbonate mineral aragonite is the control variable for this Earth system process in the Planetary Boundaries Framework. Marine organisms need carbonate ions to form shells and other structures, so changes in carbonate availability can disrupt another Earth system process: biosphere integrity.

The interconnected pH dependent speciation of carbon dioxide and derived species in aqueous solution form a thread through several general chemistry topics which are often taught in isolation, including acid-base chemistry, equilibria, and complexation and precipitation reactions. The common context of Earth system change encourages systems thinking, which then helps students to better see the power of interconnected knowledge in addressing the challenges faced by marine organisms as a result of increasing levels of atmospheric carbon dioxide, which also affect the human food chain, with socio-economic-political consequences.

Intimately connected to ocean acidification through the flow of chemical substances from the atmosphere to the oceans is climate change, which is perhaps the defining global challenge of the 21st Century, with strong connections to the entire web of other Earth system processes (Figure 2). Climate change is thus one of the strongest indicators of planetary health (part of why it is termed a “core boundary”) in the Planetary Boundaries framework. This makes it a particularly rich context for introducing systems thinking. In addition, understanding interconnected climate change processes builds on content knowledge from several traditional topics in secondary and post-secondary chemistry curriculum. Students can use stoichiometry to determine the amount of carbon dioxide produced by burning fossil fuels such as gasoline. Molecular structure and bonding considerations determine the vibrational modes and consequent infrared absorption spectra of greenhouse gases. These absorption spectra help to explain the global warming potential of some greenhouse gases, since Earth’s blackbody radiation curve peaks in the infrared. (KCVS has additional tools supporting many of these explorations, particularly through the "Visualizing the Chemistry of Climate Change" suite of resources.)
INTRODUCTION OF THE RESOURCES TO EDUCATORS

To give feedback during development of the resource, early (beta) versions of the Planetary Boundaries interactive learning tool (before the web of Earth system connections (“connections” view) and web of curriculum connections (“curriculum”) views had been developed) were piloted at a small Canadian undergraduate university in (a) introductory general chemistry courses; (b) two senior level environmental chemistry courses that focus on the environmental chemistry of the atmosphere and water and soil matrices; and (c) a chemistry course for students majoring in subjects outside of the natural and physical sciences. General chemistry students in their first term of university study were introduced to the Planetary Boundaries framework after which they completed an activity that evaluated their level of understanding of that framework and then challenged them to explain the connections of chemistry to the different Earth system processes in the framework. After this introduction, students were invited to identify features of the Planetary Boundaries framework that they would like to explore further. Their choices included: how the Earth system processes are chosen and quantified, what actions can be taken to reduce the impacts humans have on the Earth, and how the Earth system processes are interconnected (details in supporting information). Third and fourth year undergraduate students majoring in chemistry and environmental studies, who had already been introduced to the Planetary Boundaries framework in general chemistry and other courses were challenged throughout the environmental chemistry course work to build on that understanding to become deeper systems thinkers. In one of these courses, the upper level students created case studies that connected chemistry principles to different Earth system processes and presented these case studies to their peers.

At a large Midwestern US University, a beta version of the Planetary Boundaries interactive learning tool (before the “connections” and “curriculum” views were developed) was piloted in a general chemistry honours class to provide formative feedback in the development of the tool. The Planetary Boundaries framework was briefly presented and students were then invited to explore the interactive KCVS learning tool and suggest which Earth system process has the most direct connection to general chemistry concepts. Students described several further themes and key messages of interest to them, including: how the Earth system processes have changed over time; the extent to which humans have
impacted the planet; the level of interconnectedness among the Earth system processes; and how humans can measure the impact they are having on the Earth system processes. Students also said the tool introduced them to Earth system processes they were unaware of before (details in supporting information).

A later beta version of the KCVS learning tool, which now included the web of planetary boundaries “connections” view was introduced to a group of students in a third year sustainable chemistry course at a large Eastern Canadian university in a one-hour workshop. After being briefly introduced to the learning tool, students were put in groups of three and given a short assignment to pick an Earth system process in the planetary boundaries framework, review how the control variable(s) are defined and explore the connections in the web of planetary boundaries for that Earth system. They were then asked to pick an important chemistry topic in one of their undergraduate courses and think about how that topic could be connected to sustainability considerations of one or more Earth system processes. In a subsequent session, groups reported and discussed the connections they had explored to three topics: Microplastics (focusing on the novel entities and biosphere integrity Earth system processes); the phosphorous cycle (focusing on biogeochemical flows of phosphorous and freshwater Earth system processes); and climate change (focusing on the alternative control variable of the change in Earth’s radiation balance since 1750, and examining why this is considered a core Earth system process in the planetary boundaries framework).

The learning tool has been introduced to chemistry educators in professional development workshops focused on systems thinking and sustainability in teaching chemistry for both secondary and post-secondary chemistry educators in Australia and Taiwan. In both cases, teachers were asked to identify ways in which the tool could be used to help them build connections between topics they currently teach in chemistry courses and sustainability considerations. Examples of topics selected by educators included endangered elements such as lithium, cobalt, and silver, connected to the climate change Earth system process and acid base chemistry connected to the ocean acidification Earth system process.

Finally, a project based on linking this interactive learning tool to chemistry curriculum has been approved by the International Year of Basic Sciences for Sustainable Development as an IYBSSD
activity. A working group of the IUPAC STCS-2030+ project is developing these curriculum connections over the next 18 months and will make them available as open source materials for educators.

CONCLUSIONS

Since the flow of matter and energy is at the heart of all Earth and societal processes, the profession of chemistry has a unique and powerful role to play as stewards of matter and energy in achieving global sustainability goals. Steps are underway in several global IUPAC projects to reimagine chemistry education to better equip students to understand the role for chemistry in understanding and offering solutions to sustainability challenges. Incorporating new pedagogical approaches such as systems thinking involve many interconnected factors that can hinder adoption of new pedagogical approaches. These factors have been explored using a Teacher-Centred Systemic Reform model, and the willingness and ability of educators to implement systems thinking in chemistry education has been found to be influenced by their knowledge, beliefs, experiences, contextual and personal factors, as well as the availability of resources to support systems thinking approaches. The KCVS Planetary Boundaries interactive learning tool offers an approach and resources to support educators and students in the use of systems thinking to relate chemistry content to Earth and societal systems and sustainability challenges. The new interactive learning tool incorporates essential features of systems thinking including: the identification of components of a system, how system components dynamically interact with each other, how system-level behaviours emerge, and how these behaviours change over time. The interest shown by educators and students when introduced to this interactive tool is encouraging and suggests an agenda for chemistry education research to consider its effectiveness in building student conceptual understanding of chemistry and its application to societal challenges, its effectiveness as a tool to facilitate systems thinking, and its impact on affective learning gains.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available on the ACS Publications website at DOI: TBD
Details about Planetary Boundaries worksheet and key student messages used at a small Canadian Undergraduate University general chemistry class (Canadian University Worksheet)

Details about Planetary Boundaries activity and key student messages piloted at a large US Midwestern University honors general chemistry class (Midwestern US University Activity)

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