Master Thesis

Pilot Study: Effectiveness of System Dynamics based Interactive Learning Environment SD/ILE as an interdisciplinary educational tool in K-12 classrooms

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Abstract

Systems thinking is a methodology used to explore and understand the interrelationships within complex systems. One of the key concepts in systems thinking are the feedback loops. This research aims to assess the effectiveness of an SD/ILE (System Dynamics-based Interactive Learning Environment) as an interdisciplinary educational tool for K-12 students, to help them develop systems thinking skills and build lateral understanding on feedback loop processes. While the concept of feedback loops is far-reaching and present in many disciplines as well as day-to-day life, this ILE references the carbon cycle as a complex system. In this study we chose to develop a lesson about "Carbon Cycle" for two reasons: first, it is part of the US high-school biology curriculum, and second, due to the current environmental crisis, it is important to learn about climate feedbacks and to provide a real-world context.

This is an empirical research project based on observation of students' learning outcomes in a pilot session. During this session, students were provided with guidelines, the online links to the ILEs and challenges to complete both individually and in teams under their teacher's supervision. The session took place in a US high-school biology class. The obtained results through the pilot test and analyzed data, show promising increase in students' learning curve after playing the Carbon Cycle games in comparison with the pre-test results. Evaluation of students' understanding, and page time tracking data reveals that learning curve has a high correlation with the average time that each student spent playing the game. Moreover, the data supports the positive impact of animation-based design in the students' learning curve along the game.

Also, this pilot session provides a useful overview of challenges for real-world experiment setup and limitations of available systems thinking skills measurement tools in real-world classroom experiments. The challenges are related to different aspects of the experience, such as the teachers' role, interactive and engaging level of the ILE (game) design, appropriate timing for playing the game, easy instruction, and suitable assessment tool for measuring individual knowledge development. Among the strongest lesson learned from the classroom experiment, time management, and students' engagement can be underlined.

Key words: K-12 Education, Systems Thinking, Interactive Learning Environment (ILE), System Dynamics, Gaming, Educational Tool Simulators, Carbon Cycle, Climate Feedback, Biology Curriculum Design, The Carbon Cycle, Real-world Classroom Experiment

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Introduction

Along the history of human society, the ethical values behind meeting the essential human needs have been important. However, in modern societies who are challenged with vanishing natural resources, competition on global markets, climate crisis and the most recent Covid-19 pandemic, sustainable decision making is playing a more important role. Sustainable and ethical decision making in part depends on: (1) providing insight into complex non-linear systems; and (2) to educating and train young people in systems thinking by bringing simple models into the classrooms (Kunsch, P. L., et al, 2007).

Various studies show misperception of the complexity as a main cause for human failures. E.g., According to the U.S. National Academy of Engineering, a lack of complex system understanding has been a major cause of "man-made disasters" (Davis, K., et al, 2020). This issue is not limited to a certain group, [whose] study shows even well-educated people including engineers, various politicians, and scientists have difficulties understanding the basic concepts of systems (Sweeney and Sterman, 2000; Sterman, 2008; Cronin et al., 2009; Kapmeier et al., 2017).

System dynamics is a professional field which deals with the understanding of complex systems. It can build the necessary foundation for systems understanding and effective thinking (Forrester, J. W. 1999). One of the most well-recognized tools by the system dynamics community to help people better understand complexity and the decision-making process are interactive learning environments (ILE). ILEs can effectively communicate model insights to non-system dynamics audience and stakeholders (Alessi, S. 2000).

System Dynamics based Interactive Learning Environments (SD/ILEs) became a well-used tool in the management field to help the understanding of complexity and decision-making. Even though, Michael. P Bean in one of his studies mention, the problem is when systems thinking seems successfully understood by an organization the decision makers may still not feel quite comfortable to use it in the real-world problems (Myrtveit, M., & Bean, M. 2000).

The use of SD/ILEs in classrooms and empirical studies has also grown in the last recent years. Research has shown the resulting benefits of using online simulations in the classrooms including providing more realistic interactive learning environments compare to other standards training methods (Yang, M. et al., 2016). One of the earliest uses of SD/ILEs in K-12 education was in 1988 when system dynamics professors from Massachusetts Institution of Technology (MIT) reached out to a middle school science teacher in Tucson New Mexico (US) and shared a system dynamics based educational tool to use in the classroom for the express purpose of increasing the students understanding of ecology. K-12 education refers to the educational system from kindergarten to 12 grades. This exchange helped the middle school students to explore the interconnections and dynamic relations among different concepts in ecology (Forrester JW. 1992). Yet ILEs are still not efficiently consumable material for K-12 educators. There are organizations such as CLE (Creative Learning Exchange), that encourage interactive learning methods to engage students in a real-world problem solving through introducing system thinking and SD/ILEs in the classroom. There are several research studies about the importance of systems thinking and interactive learning tools for educational purposes. (Acaroglu. 2019) talks about the need to create learning environments which are more interactive to increase students' curiosity, creativity, and engagement, which we called out as essential steps for systems learning. In further support of the utility of SD/ILEs in the classroom (LaVigne. 2009) who is a curriculum designer and facilitator for the CLE, notes that students who are using systems concepts and SD/ILEs show more engagement and learning motivations. (Plate. 2006) reported in an assessment of an SD-based educational tool, that students use systems concept tools to clarify and visually represent their understanding of complex systems. This visual approach allows the students and others to interact with and explore thoughts, perceptions, and mental models with more precision and clarity. (Arndt, H. 2006) also talks about the necessity of system thinking skills for acting successfully in a complex world and proposed integrated SD/ILEs have additional positive learning effects.

Building upon the above referenced literature, this work aims to develop an animation based interactive learning environment about the carbon cycle. This ILE is developed for a pilot study to measure the effectiveness of ILEs as an interdisciplinary educational tool in classrooms. The pilot session is a collaboration between the system dynamics group in the University of Bergen and science teacher, Jon Darkow of the Seneca Local Schools in Ohio (USA). The primary goal of the ILE is helping students to understand the Carbon Cycle as a system, with a focus on understanding the relationships between different variables namely how changing one impacts the others. Through this SD/ILE based material students are introduced to the climate feedback concept, and they will experience how changes in the outputs can be directed back at the inputs. The second objective is, to determine if this learning tool helps the students to build a general understanding of system-oriented structures and feedback loop processes. The "handbook" for the interface is attached to this report as extra support material. There is possible to find more detail about the lesson's summaries and objectives.

The experiment investigates the effect of the ILE on system understanding and measures students mental model development through their performance which refers to tracking their interaction with the ILE. To achieve an accountable evaluation, experiment is playing an important role. Empirical studies have been widely used for unpacking the mental models and measuring complexity understanding. To trace general misperceptions of complexity and find out the reasons by tracking people's mental model. For example (Moxnes, E., & Saysel, A. K. 2009) found out majority of participants have lack of correct perception of the accumulation concept over time. The study tries to understand why people don't understand the accumulation concept and how it can be avoided. (Gary, M. S., & Wood, R. E. 2016)., also highlights the power of experimental laboratories for investigating "relationship between mental models and performance on microworld simulations".

Problem Formulation and Research Objectives

As discussed above, the lack of systems thinking skills is an important issue looking back over human history. One way to close this knowledge gap is to introduce systems thinking topics and practical skills in the educational system, which is a fundamental structure in society. There are many ways which we could bring systems-oriented instruction to the classrooms. One of the approached with the most promise is SD/ILEs. While there is much empirical evidence to demonstrate ILEs effectiveness on supplementing and supporting students learning on complexity concepts and recognizing dynamics elements over time , SD based ILEs and material are not standardized in the educational system leaving their general practice and employment as piecemeal (e.g., LaVigne, A. 2009; Plate, R. R. 2006; Hopper, M., & Stave, K. A. 2008; and Roberts, N. 1974).

This research works towards the development of a standard form by studying the effectiveness of the Carbon Cycle SD/ILE as an interdisciplinary educational tool for high-school students. The research aims to provide empirical evidence, on if the ILE provides a platform for students to learn about the principles of the carbon cycle as well as helping them to gain a more generic system concept and understanding of feedback processes.

The research addresses the same challenges as an educator who develops an SD/ILE to teach a particular systems-based concept. Most of the previous empirical evidence from SD/ILE evaluation has been generated from the pilot sessions which were performed and facilitated by the ILE designers. While in this project, data is collected from a real-world session led by a high school biology teacher who did not develop the SD/ILE. This research project answers the following questions about the Carbon Cycle SD/ILE specifically and aims to draw general conclusions which can be used by other ILE authors to develop learning tools which can be useful in the classroom.

Q1: Can this interactive learning environments (ILE) help students to learn about carbon cycle system?

1. To explain what carbon cycle is.
2. What are the steps of carbon cycle?
3. Identifying a group of key variables with least and most impact on the system?
4. Why the carbon cycle is important?

Q2: Can this ILE help students to understand the human impact on the carbon cycle?

1. How human interaction is affecting the carbon cycle?
2. What variables seemed most strongly connected? why?
3. Can student make responsible decision making to reduce human impact?

Q3: Can this ILE build lateral knowledge about systems and feedback process?

1. Can they present other similar systems and causal linking between them to support their generic understanding?

Literature review

What is systems thinking?

Systems theory is a knowledge of identifying and analyzing relations among different elements within a system. One of the main factors of systems theory is the field of system thinking, which is the methodology for understanding the complex systems. Where people can learn about feedback concept and by this knowledge improve their decision making in political and social systems. Feedback concept refers to causal feedback structure of a system meaning how change in one part affects other parts. System thinking is derived from the simulation models in system dynamics field, and it can facilitate understanding of system complexity by visualizing the history of the system behavior over time (Forrester, 1961; Sterman, 2000).

Why systems thinking is important?

Dynamic systems such as the economy, business, renewable energies, natural resources, and climate change/global warming are not easy to understand and make successful decisions for their management. There are many studies which prove the misperception of feedback concept as well as many other features of complex systems such as understanding the problem within the system structure. See following literatures (Diehl & Sterman, 1995; Jensen & Brehmer, 2003; Moxnes, 1998; Moxnes, 2004; Paich & Sterman, 1993; Sterman, 1989; Sterman, 2002 & 2007). One of the primary goals of system dynamics is to improve decision making and problem solving in the complex dynamic systems.

Educational system is a good target to teach and develop system thinking. It is a safe investment on improving next generations' system thinking skills and eventually their critical thinking where students are more prepared for real-world challenge and problem solving. As it's been mentioned previously in the introduction, there are many institutions and independent research groups actively developing system thinking based curriculums for K-12 educators. Among them, we can refer to Creative Learning Exchange. They collaborate across educational and non-profit setting to increase understanding of dynamic, interdependent systems in ways to empower, engage, and motivate to develop who they call, Systems Citizens. System Citizens refers to "K-12 education who are able to use systems thinking, system dynamics and an active learner-centered approach to meet the interconnected challenges that face them at personal, community and global levels". Jay W. Forester mentioned about the promise of systems thinking in K-12 education is best granted by sharing the experience from teachers who observed the impact of it on their students.

SD/ILEs impact on systems thinking development

Build on mentioned literatures, ILEs also known as interface simulations are well known and been widely used in economy and political studies as a training material to improve decision making processes. ILEs are widely used also in high school classrooms in different countries. For example, Jon Darkow, biology science teacher has developed many SD simulations as curriculum to teach biology in Ohio (US). Kerry Tunner is testing different SD based systems thinking approaches with different school ages in Hull (England). Chang-Kwon created "Biodiversity game for sustainability" for 10 years old and higher in Korea. Turkey is also doing a great job on incorporating SD/ILEs for primary school curriculum among other countries. The claim is not, students only be able to identify a problem in the system, but also the casual relations are very important to be understood. To know the ILEs helped improving students understanding on a specific topic under systems thinking umbrella, we need to have a valid and well-grounded method to assess the effectiveness of the methodology. Normally assessments should focus on two different measures of participants (Rouwette, Größler, & Vennix, 2004): their performance, e.g., the data collection from the interaction with the ILEs, and their understanding, for example verbal protocols to measure the mental operations and developing process. Combined understanding and performance measure is very important due to know if the performance is improved based on person's systems understanding and mental model development or if it happens because of various reasons such as trial and error (Kopainsky, B., & Sawicka, A., 2011).

A mental model is a definition of someone's thought processes about how something works in real-world. It's a representation of person's perception of the surroundings and how their different parts are related to each other. (Carruthers, 2000; Fodor, 2003; Margolis & Laurence, 1999; Pinker, 1994; Strasser, in press). As its expected from the definition, it is very challenging to perform an accurate evaluation on mental model change. Ossimitz (2000) summarizes their four empirical studies on teaching systems thinking to high school students in Austria and Germany. They report that systems thinking learning was a very joyful process for students however teachers found it very challenging to measure students' developments of the skill.

There are different methodologies for experiment assessments, among them, verbal protocols play an important role for unpacking the mental model and analyzing people's reasoning development processes (Sterman, 2009). They are especially suitable for characterizing mental model and the way people representing their knowledge (Doyle, Radzicki, & Trees, 2008). However, the challenge of coding and rating such protocols remain. Furthermore, coding and rating the verbal protocols are highly dependent on interpretations of the rates and it's a very gradual process (e.g., Sterman & Booth Sweeney, 2007). Which makes it very hard for large databases.

Luna-Reyes, L. F., & Andersen, D. L. (2003)., cover different methodology on collocating qualitative data and different coding and rating procedures. One way to collect qualitative data is through questioners, there are different format for formulating the questions for the participants, this study has adopted a combination of leading and closed questionary method for the understanding measures during the pilot sessions. There are also handful available data analyzing and coding methods procedures proposed by empirical and social studies literatures, e.g., content analysis, grounded theory, discourse analysis, conversation analysis and narrative analysis. (Denscombe, M. 2010; Boeije H.R. 2009; Muller M.J. & Kogan S. 2010).

Methodology

Research Strategy & Methodology Choice

The study follows a mixed method approach with three key development phases:

1. Development of the Carbon Cycle system dynamics simulation model.
2. Creation of the ILE based on the Carbon Cycle system dynamics model.
3. The pilot phase where the ILE is played in the classroom.

Brief introduction about the project phases

The Carbon Cycle model as the base of the SD/ILE was developed by the GLOBE program. Summary of the model and applied changed is describe further down in model description section of this report. Details about model structure are presented in *Appendix A*.

The ILE design and pilot session are the main body of this study. The SD/ILE developed focuses on interdisciplinary learning objectives and to achieve those objectives, the SD/ILE was developed as two separates by linked ILEs: Carbon Cycle game 1 & 2. The Carbon Cycle 1 game is a single player interface and aims to help students understand the system structure, variables over time and various sources of carbon within the ecosystem. In this SD/ILE, students are introduced to the feedback loop concept via the relative impacts of changing different variables on the system. The Carbon Cycle game 1 demonstrates natural carbon emission and removal processes in pre-human and industrialization times. However, during this first game, students are challenged and prepared for exploring the human impacts in the second game. The first game learning objectives are aiming to elaborate on research question Q1. Learning objectives for the carbon cycle game 1 are listed together with the relevant research question that they are referring to:

1. Introducing the main elements of the system. (Refers to *Q1.1*)
2. Familiarizing students with graphs and reading graphical data. (Refers to *Q1.2*)
3. Learning about how increasing and/or decreasing different carbon source/sinks affects the system's behavior. (Refers to *Q1.3*)
4. Assisting students to predict the general direction and magnitude of changes in the system due to specific changes to the system. (Refers to *Q1.3*)
5. Learning about climate feedback and balancing feedback loop definition. (Refers to *Q1.4*)

The Carbon Cycle 2 is a pair played single player game, where two students are working together using one interface to input their decisions and evaluate outputs. The game guides students through different information and challenges to help them develop their understanding of human impacts on the carbon cycle. Students are introduced to basic human activities which affect the carbon cycle, and the game allow them to play different decision-making roles, discuss in their pairs, and eventually the class about how their decisions impact the carbon cycle. The second game tries to address Q2 and Q3 from the research question list. The learning objectives are listed as follow:

1. Introducing human-interaction to the carbon cycle. (Refers to *Q2.1*)
2. Learning about climate feedbacks and comparing climate feedbacks with and without human impact (Refers to *Q2.1*)
3. Practice decision-making and group discussion to reason the impact of the decision. (Refers to *Q2.3*)
4. Expanding system-oriented learning concept to their day-to- day life. (Refsers to *Q3.1*)

After game development, a pilot session was conducted to assess the functionality of the SD/ILE. The assessment is organized as physical classroom full learning session including a briefing of the purpose, use of the two SD/ILEs and a debriefing.

The pilot session is designed using a task and response format. During the session, students are asked to log their responses to various tasks and challenges in their journal. The journal is available as a google document via google classroom and is concurrently open with the simulation. Normally in group tasks, individual decision making is influenced by the group, and to avoid ending up with only groupthink data, I use a combination of individual and group tasks. Even though individuals might show agreements with their paired teammate during the group tasks, this might be a temporary state of their mental model and doesn't alone demonstrate the learning and requisite mental model change in their learning and experimentation process (Doyle, J. et al., 2008). Individual tasks allow for the measurement of the change in individuals mental models, while the group tasks help to measure the students reasoning ability to back up their learning outcomes.

Phase 1: Model Description

The basis for the SD model which underlies both SD/ILEs is the Carbon Cycle model developed by GLOBE Program and Charles University in 2017. The first step in the development process was to translate that model to the Stella software. It's a rudimentary global carbon cycle model including climate feedbacks as well as global and water temperature. The model aims to explore how the carbon molecules move among the carbon stocks, interaction between carbon stocks and flows. The model also introduces a couple of human impacts such as fossil fuel combustion and deforestation. Since the carbon cycle is the basis of global carbon circulation and an important natural cycle related to climate regulation, a plethora of models were available to choose as a basis for these ILEs. The GLOBE program model was chosen, first due to its simplicity which serves very well the purpose of the curriculum for high school students. Secondly, it includes climate feedbacks which can help students to understand the relationships between atmospheric carbon accumulation and climate concerns. Essentially the model was appropriately dynamically complex while having the least necessary amount of detail complexity. The main stocks and flows are listed in table 1.

Stocks (Giga Tone GT)	Flows (GT/Year)
Atmosphere	Photosynthesis
Plnats	Atmosphere Ocean Exchange
Animals	Animal Respiration
Surface ocean	Plant Respiration
Deep ocean	Siol Respiration
Carbonate Rocks	Volcano

Table 1. List of main stocks and flows

The following are the list of changes applied to the original model for the purpose of adding couple of tangible variables to the model that can help students' learning process. (Seel, N. M. 2006), talks about model centered learning where a person constructs understanding to a "map". The map can be developed more realistic and logical both in cognitive and philosophical education as the case study is more real-world and tangible for the person.

1. Animal respiration, the impact of animal respiration is not significant and is not making significant changes in the carbon cycle behavior, however, is important for educational purposes. Respiration is a key life processes that students normally learn from early ages in biology and chemistry classes. It's a good example to illustrate the non-linear relation between importance and impact on the systems behavior.
2. Farming impact on carbon sequestration, parallel to deforestation that means cutting down forests permanently, farmlands handling has an impact on photosynthesis rate. It will be helpful that students learn about contemporary food industry impact on carbon cycle dynamic behavior.

The model is initialized with carbon budget value from 2019. More detail information about the base and deterministic model can be found under *Appendix A*.

Phase 2: ILE Development

The Carbon Cycle game is a SD/ILE. For this study the Carbon Cycle game was split in two parts, game 1 and 2. Throughout this thesis the word game is used to refer to the SD/ILEs but since that term is so encompassing here the definition is narrowed to the scope of pedagogical tools so that there is no confusion between a 3D immersive virtual reality game, or a board game etc. The Carbon Cycle games are 2D web based educational experiences. They are dynamic, namely allowing for instantaneous simulation of results, and are highly interactive and graphical. The two Carbon Cycle game make user of two different design strategies. The first game walks students step by step through the different elements and concepts of carbon cycle and prepares them to learn about carbon's journies through different flows. Students are going to learn about the interaction among stocks and flows, and feedback loop concept through climate feedbacks. In addition, the Carbon cycle game 1 is a platform where students are prepared for the second game to explore the human impact.
The games are published and can be access through following links:

Game 1 https://exchange.iseesystems.com/public/vir011/carbon-cycle-game
Game 2 https://exchange.iseesystems.com/public/vir011/carbon-cycle-and-human-interaction

The ILEs are designed as animated interactive games. Stella Architect was used to develop the interface and SVGator software for the animation design. SVGator (https://www.svgator.com/) is an online software and easy method to animate SVGs, independent of the simulation model within Stella Architect.

Carbon Cycle Game 1- Without Human Interaction

The Carbon Cycle Game 1 is an interactive tool which allows students to simulate the movement of carbon molecules within the carbon cycle. The students experience the carbon cycle as carbon molecules or as stored carbon which travel the pathways between the various carbon sources and sinks over time (atmosphere, plants, animals, soil, ocean, and fossil fuels). The game aims to help students understand the different carbon transfer processes and their relational impacts within the carbon cycle as well as to explore the concept of feedback processes in the cycle through further discussion and teamwork. The game 1 contains following sections:

- Carbon reservoirs, introducing the carbon pools. (Stocks)
- Carbon cards, carbon flux. (Flows)
- Main simulator, interactive animation to explore interaction between carbon reservoirs and cards.
- Experiment, challenge students to predict graphical behavior based on the learning outcome from the simulator section.
- Feedback process, introduction of feedback concept through a climate feedback in the carbon cycle.
- Homework, the last section of the game is a fun and creative challenge where students can complete at home and the task include all the learning points from other sections.

The students learn step by step in a linear process through the process flow as pictured in Figures 1-6. Each section has its own objective, and challenges students to complete specific tasks before advancing to the next stage, although these stage gates do not prevent the student from advancing if the task is not completed successfully. The tasks prepare students to understand the given content. For example, the students are asked to predict some graphical behaviors over the time after specific changes which can be easier after learning about how interactions among carbon stocks and flows are. Yet they might face some unfamiliar behavior patterns over the time and experience the knowledge gap which means they are ready to be introduced to feedback loop concept that explains the gap between their prediction and the actual simulation result.

Design details and learning outcomes 1

Carbon Reservoirs (Stock)

In this page, the short animation introducing the main carbon reservoirs (stocks). Students can also review the baseline graphs for all the reservoirs by clicking on the “Graphical Data” button.

Figure 1. Carbon Reservoirs

Learning outcome of the page:

- Recognition of different stocks in the carbon cycle.
- Learning the baseline graphs for the stocks and capacity of carbon storage in each stock.

Carbon Cards (Flow)

As they already got introduced to the carbon stocks, the next page is illustrating all the carbon fluxes. We call them carbon cards due to their function in the system, each flux is represented as a card that needs to be played in order to create change in the cycle. The carbon cards are categorized and assigned to different colors. The colors are based on the direction and destination of carbon particle movement. Such as, direct carbon removal from the atmosphere, direct carbon emission to the atmosphere, land sink and ocean uptake.

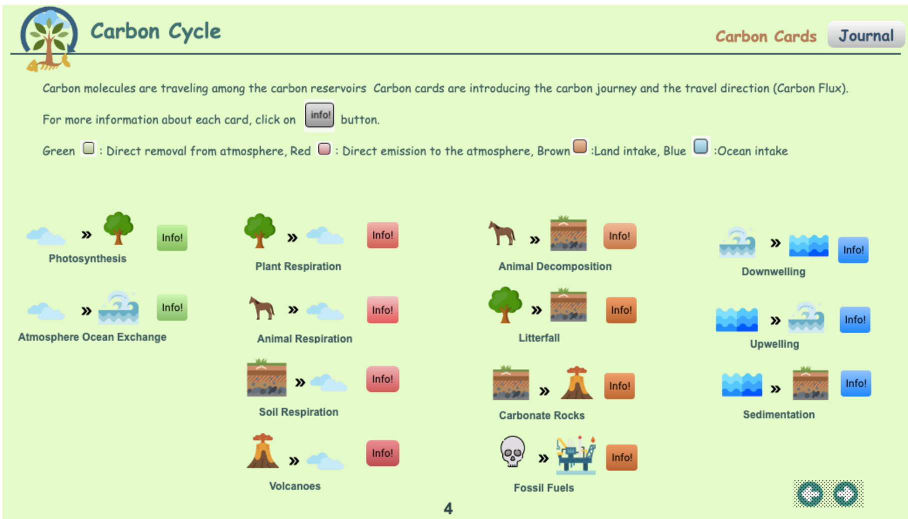


Figure 2. Carbon Cards

Learning outcome of the page:

- Recognition of the carbon cards and their functions.
- Learning about the concept of emission, removal, land sink and ocean sink.

Main Simulator

This page is the interactive animated simulator, which allows student to explore the cycle by controlling different cards and observe the impact of the changes; primarily on the atmospheric carbon and followed by few given challenges in their journal. The journal is a document with certain guidelines and instructions that guide the student's interaction with the game (ILE) to improve their understanding of the learning objectives. It is expected that they learn about the relations between different parts of the carbon cycle. Also, the expand graph button is opening the window of the graphical data of different carbon stocks and flows where they can see the dynamic of impacts over time. *Figure 1B, Appendix B.*

Access link to journal 1
https://drive.google.com/file/d/17gWbvGFsK8i21c-FAmJiac5999CoSWye/view

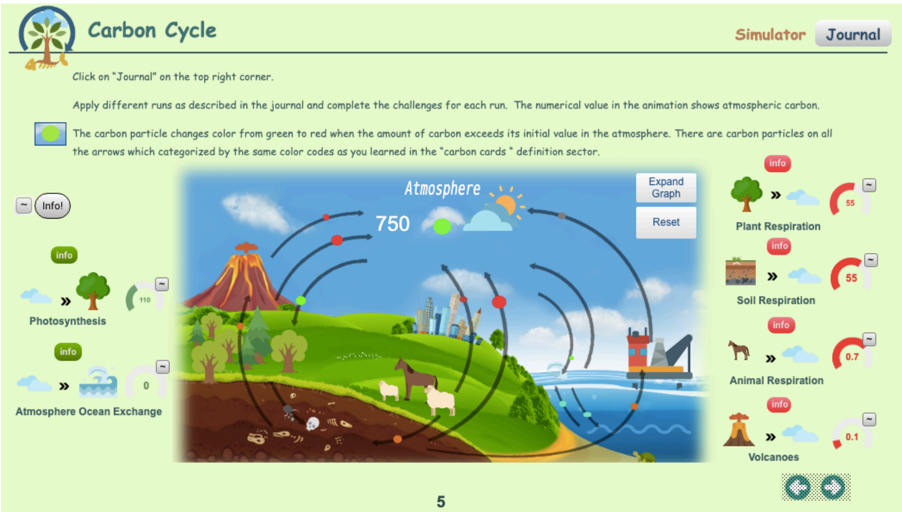


Figure 3. Main Simulator

Learning outcome of the page:

- Learning the systematic relations between different variables.
- Reading graphical data over time.
- Ability to describe why different changes impact the system the way they do.
- Determine the most and least dominant carbon cards (Flows).

Experiments

In this section students are challenged to make changes in certain variables and to predict graphically the impact of the change on atmospheric carbon; after, they are going to apply the change and simulate. They will have access to the comparison data from their prediction and the simulation result. They can evaluate their prediction and describe why it was easy or difficult to predict. After second experiment students are introduced to climate feedback concept before they move on to the 3rd experiment.

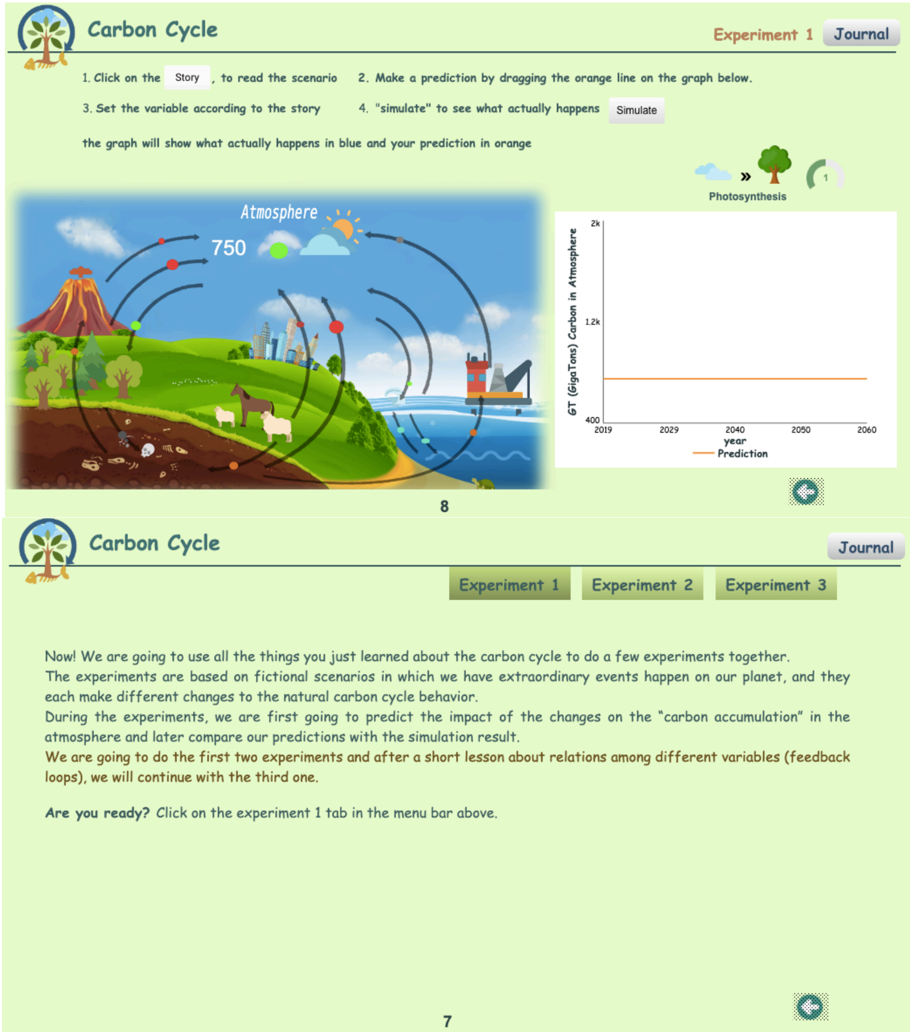


Figure 4. Experiment

Learning outcome of the page:

- To prepare students for learning feedback loop concept in the next step by graphical prediction challenge.
- To emphasize diverse impact of different carbon cards (flows) in the cycle.

Feedback Process

This section is trying to build up on the previous challenge and teach students about feedback loop concept through a step change in the photosynthesis process and reviewing the graphical data after the change.

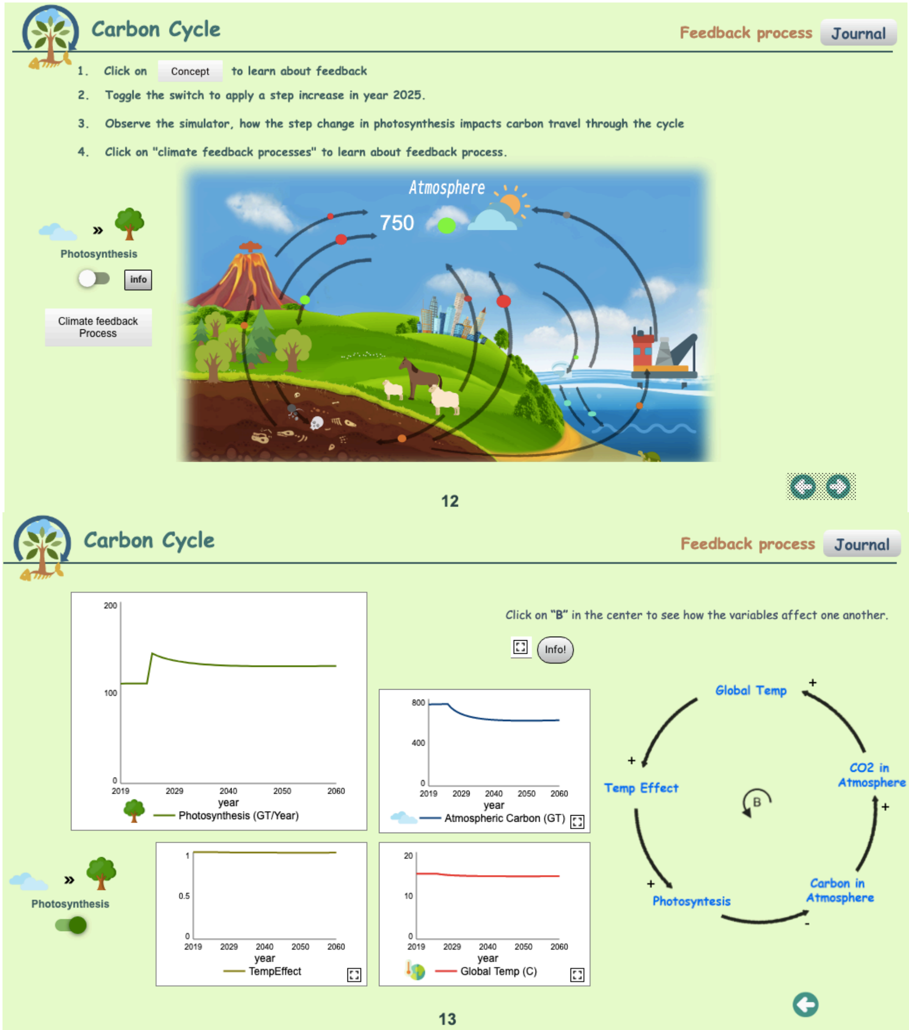


Figure 5. Feedback Process

Learning outcome of the page:

- Feedback concept.
- Climate feedback.
- Behavior over longer period (*Figure 2B, Appendix B*).

Homework

The last experiment is a final challenge for the first carbon cycle game! Students are asked to create their own story where impact carbon cycle. They are asked to identify the relation between happening in their story and available carbon cards in the game. Then, they need to propose solutions to stabilized atmospheric carbon around its initial value (750 GT).

This task allows students to apply all the lessons learned from the game. Depends on time limit and the teacher preferences, the experiment can be, do in class and homework. *Figure 3B, Appendix B*

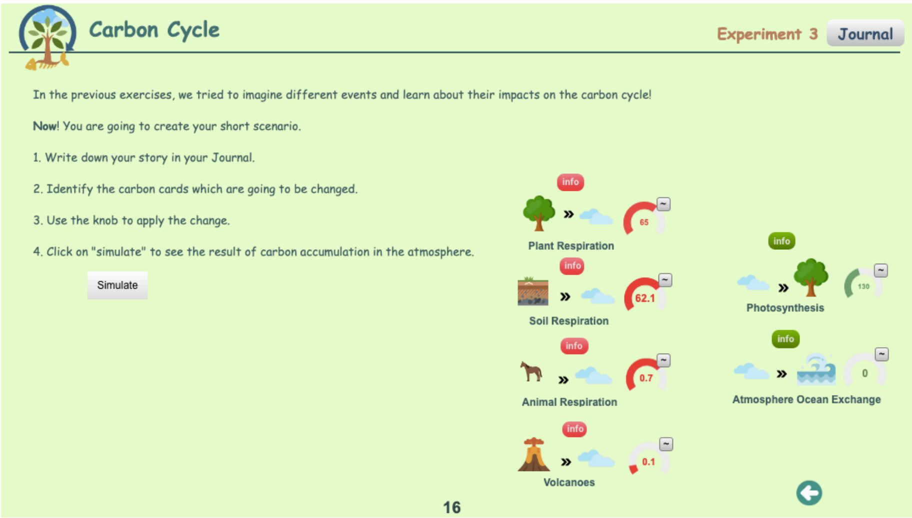


Figure 6. Experiment 3

This experiment is considered as homework due to the following reasons:

- Time limitation during the pilot session.
- Give students time to process all the learning out come from the session.
- To have more time and to do at home could increase the creativity both in terms of story itself and proposed solutions.

Carbon Cycle Game 2- With Human Interaction

The carbon cycle involves the movement of carbon between the atmosphere, biosphere, oceans, and geosphere. Since the Industrial Revolution approximately 150 years ago, human activities such as the burning of fossil fuels and deforestation have begun to influence the carbon cycle and the rise of carbon dioxide in the atmosphere. Human activities affect the carbon cycle through emissions of carbon dioxide (sources) and removal of carbon dioxide (sinks). The carbon cycle can be affected when carbon dioxide is either released into the atmosphere or removed from the atmosphere.

The game aims to help students understand, how human actions impact the carbon cycle. They are introduced to some basic human activities which are concerning the carbon cycle, and the game allows them to take different decision-making roles and discuss in groups, how their decisions have effect upon the carbon cycle.

The design strategy for the second game is quite different in comparison to the first one. The game is designed based on the assumption that students already have a basic common knowledge about the carbon cycle system. They are given a navigation menu which includes Briefing, Experiment, Debriefing and Similar Systems. They can navigate through the game and explore the human interactions within the carbon cycle.

This game is combination of paired and single player. The hybrid design aims to give students chance to explore and express their understanding of human impact on carbon cycle and climate feedbacks individually, though the given platform for teamwork and discussion in the decision-making experiments, as well as write their individual responds in their journals. As

Doyle, J. et al., (2008) mentioned in the procedure for the mental model change measurements, group assignments are very good learning techniques, however if the cognitive learning process is missing individual learning development in isolation the group data would not be very reliable.

Competitive vs. Cooperative Group Activity

Competitive or cooperative was another topic yet to be considered for the paired single player part. There are cons and pros to each design approach.

Paired Game	Cons.	Pros.
Competitive	• The wining dynamics might take over the concept of system understanding and climate feedback consideration. • Win-lose situations.	Can create more fun and real computer game environment which can lead to more fun and learning motivations.
Cooperative	• Teamwork and group dynamics. • To increase focus on the task goal and learning objectives. • Win-win situations.	Deviate from the game expectation for kids and lead to a lesson base activity.

Table 2. Competitive Vs. Cooperative education tools (Kwon, J. E.,2018)

Following Jon's experience on how to increase the students' engagement and learning curve as well as addressing to the table2, we decide to design a cooperative multiplayer section in this game. As it is mentioned before in this report, Jon Drakow is the science teacher Seneca Local Schools in Ohio (USA), where the pilot session took place.

Design details and learning outcomes 2

Briefing

Describe the objectives of the game and introduce the list of human impact within the boundary of this carbon cycle simulation such as: fossil fuel combustion, deforestation, and farming impact. In this section students also get access to the interactive simulator page where they can observe the relationships between different human interaction and the carbon cycle. If it is possible, the briefing is recommended to be done together with the teacher as a class.

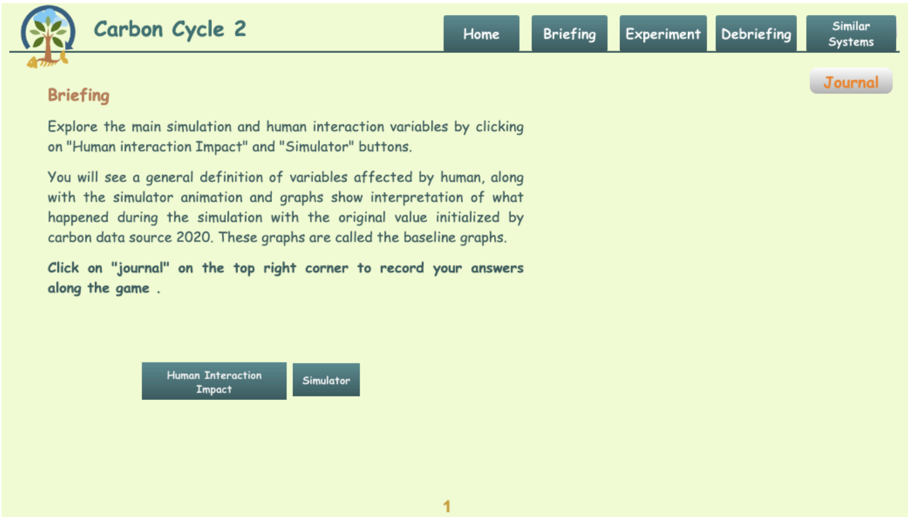


Figure 7. Briefing

Learning outcomes of the page:

- Familiarizing with human interaction variables.
- Learning about the definition and the impact.
- Human interaction impact on atmospheric carbon and global temperature.

Main Simulator

This page is the interactive animated simulator, which allows student to explore the impact of different human interaction on the cycle by controlling different variables and observing the impact through the animation and well as graphical data over time. The graphs are accessible by clicking on "Graph Expand" button.

Access link to the journal 2
https://drive.google.com/file/d/1RbhoSr_ctoEYfv8ypfriBEkX52BKOitY/view?usp=sharing

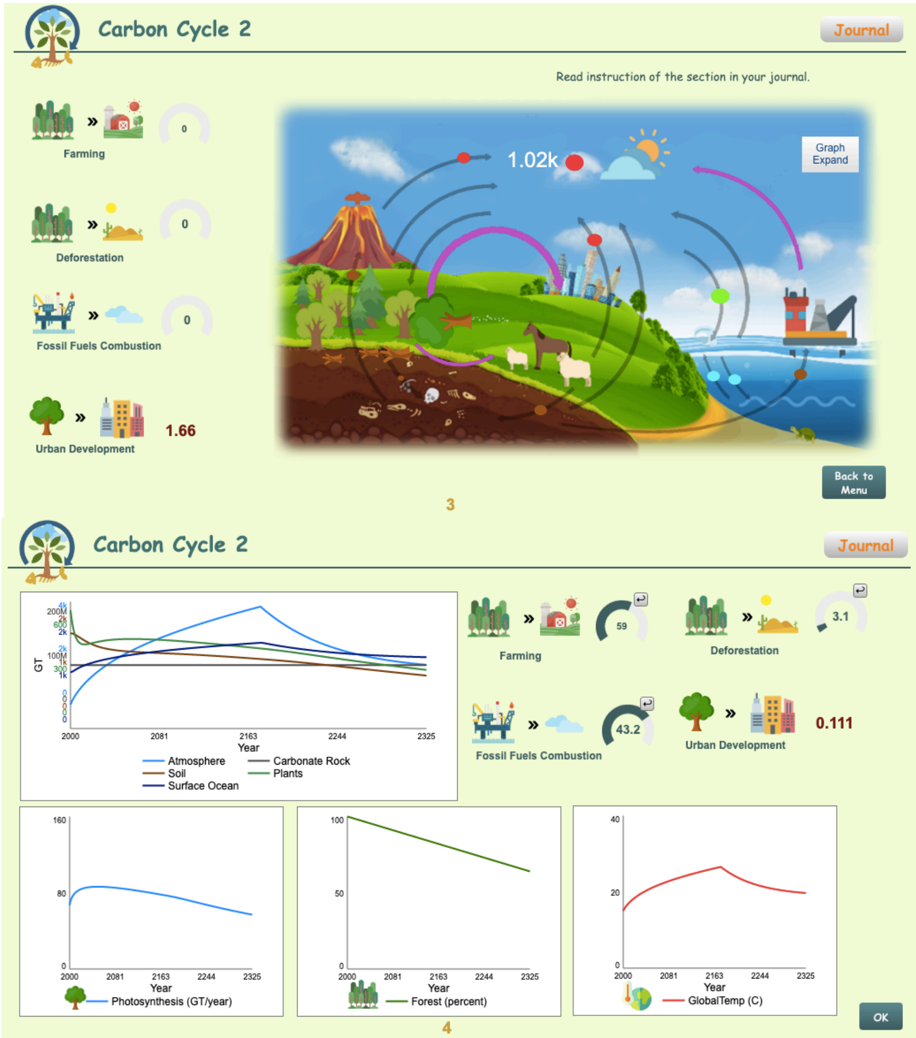


Figure 8. "Main Simulator" and graph reading page

Learning outcome of the page:

- Learning the systematic relations between different variables.
- Reading graphical data over time.
- Ability to describe why different changes impact the system the way they do.
- Determine the most and least dominant human practice on the cycle.

Experiment

In this section students are given different scenarios about human interaction, and they are challenged to make decisions every 50 years. Since all-natural processes' time scale and magnitude vary a lot. Some occur very quick others might take hundreds of years, for that reason the decision-making interval is 50 years where students can see the impact of their decisions.

The goal is, to avoid dramatic atmospheric carbon increasing. The students are playing the role of the minister of energy and human right representative. The detail of their roles is given in the journal. They should finalize their decision in a dialog before they apply it to the system, based on the system outcome they will make decision for the next 50 years.

They should be encouraged for realistic decisions based on given scenario, for example: if they decide to stop oil and gas combustion, they should propose the alternative energy source in their journal. *Figure 4B, Appendix B*

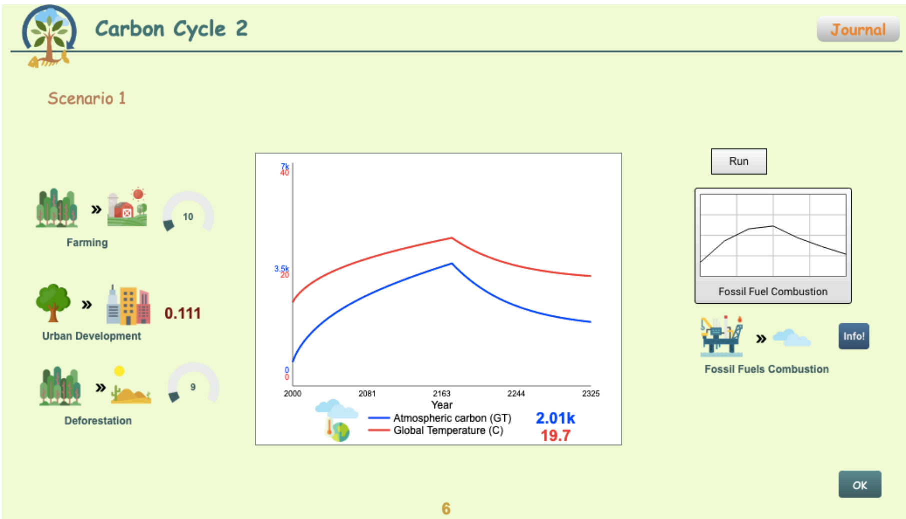


Figure 9. Experiment

Learning outcomes of the page:

- Responsible decision-making and follow-up discussion.
- Climate feedback and human impact.

Debriefing

This section is dedicated to more general definition of system and summarized the concept in relation with carbon cycle system. Debriefing also includes an example of photosynthesis feedback loop with and without fossil fuel combustion.

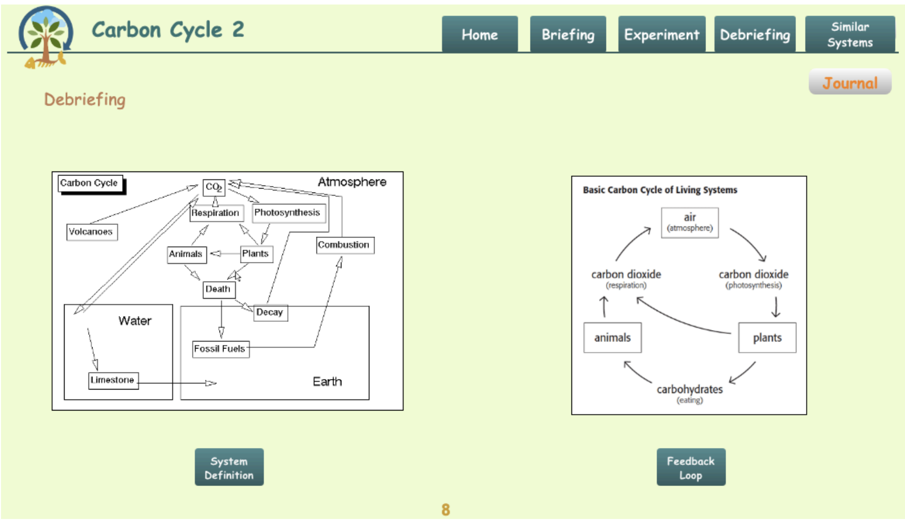


Figure 10. Debriefing

Learning outcomes of the page:

- Impact of human interaction on the feedback loops.
- General definition of system, understanding feedback loops as a system principle.

Similar Systems

Students are asked to relate their learning outcomes about system thinking and feedback loop processes to the day-to-day life. They are given couple of examples of feedback loops which made based on personal experience, and they are challenged to modify them to their own real-world experience. The purpose is to let the student connect their system understanding to their daily life and practice system thinking. *Figure 5B, Appendix B*

It's also important for us to be able to evaluate if the game serve to the purpose of teaching a generic concept through a narrative subject.

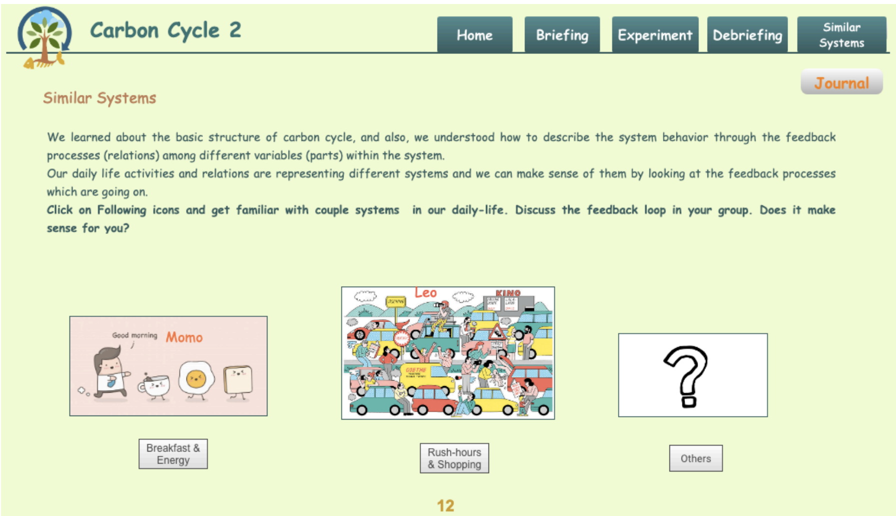


Figure 11. Similar Systems

Learning outcomes of the page:

- Practicing systems thinking.
- Develop system understanding.
- To be able to zoom out from the subject and scale their understanding of feedback loops.

Due to time limitation during the experiment session and pedagogical reasons like the first game, this section designed as homework where students can have time to process the learning outcomes from the game and come up with more fun and creative examples of the day-to-day life surrounding systems. Full description of the game about page -by- page educational intention and learning objectives are listed in the "handbook" attached as support material to this thesis.

Summary of all the listed activities in the Carbon Cycle games, the relation to the RQ (Research Questions), and the given tasks under the journals are generated in the following table. The students' responses for the tasks that are listed under "How is it measured?" are coded and scored for further evaluations. The evaluation procedure explained under the coding procedure chapter in this report.

Activity in the game!	Which RQ it refers to?	How is it measured?
Game 1		Journal 1
Carbon Reservoirs and Cards	Q1.1 & Q1.2	The first three Runs
Main Simulator	Q1.3	The first three Runs
Experiments	Q1.2 & Q1.3	Behavior prediction over time
Feedback Process (Climate Feedback)	Q1.4 & Q3	Feedback Loop Processes example
Game 2		Journal 2
Briefing	Q2.1	First section tasks 5 & 6
Main Simulator	Q2.2	First section tasks 5 & 6
Decision-Making	Q2.3	Senario 1 & 2
Climate Feedback Comparison	Q2.1 & Q3	Feedback loop task
Similar Systems	Q3.1	Similar systems tasks

Table 3. Summary of activities in the game and their relations to listed RQ

Phase 3: Pilot Session

Up to now, the focus was on the design and ILE development, learning curve evaluation the during the pilot session needs a prior system thinking (systems understanding) assessment tool, yet is very challenging and the tools are limited to capture individuals' understanding of complex systems. Some of the limitation is due to different definition and understanding of complex systems (Hopper, 2007; Mitchell, 2009; Jackson, 2019; Mahmoudi et al., 2019). In this study, we assume students have some common background knowledge about the carbon cycle system as part of their biology curriculum in high school. Students are required to read couple of scenarios and provide answers to the questions in their own word based on their background knowledge about the carbon cycle system prior to the games. Scenarios are short and expected to take not more than 10 minutes to complete. The pre-test includes several points such as feedback concept, climate, and the main carbon cycle elements. There will be also data collection from the online interaction to evaluate students' interaction with the games as well as individual journals to complete along the game to assess their understanding. The coding process for the verbal protocols is adopted from "understanding of complexity in socio-environmental systems" by (Davis, K., et al 2020.), that is based on (Kim & Andersen's 2012.) paper in System Dynamics Review. It is providing a method to transform textual data into word and arrow diagrams. Of course, there are limitations with all experimental and analytical method which I elaborate more on those terms in the result and conclusion sections later in this report.

Research Ethics

This empirical research includes primary data collection and analyzing the data through the interaction with the game and answer to the questions which are available as individual journal for each student. Following the (Denscombe, 2012) codes of research ethics I formulate the considered in this research as:

> No harm to participants, the data regards students' performance and interaction with the game is collected automatically by "isee Exchange" server. The answer to the questioners along the game are recoded by students in their journal. Student are registered both on the game and journals anonymously with an individual number (game ID) to protect the players' identity. While the game ID allows matching the result from game out come and questioners for further data analyzing. All the data was treated carefully and will be used only for academic research development purposes.
>
> Scientific integrity**,** this research aims to evaluate and answer research questions regards effectiveness of ILE as an interdisciplinary educational tool for high students. All data analysis and manipulation were done aligned with research ethical principles and the research integrity requirements of University of Bergen for this master thesis.

The Pilot Study

Pilot Session Material

To best support the SD/ILE facilitator a handbook was developed, that offered useful information about the: case, learning objectives, preparation steps, and an answer key for all simulation questions and tasks. For the actual study conducted this handbook was used by Jon Darkow the biology teacher at Seneca Local Schools in Ohio (USA).

The facilitator's handbook provides information about the expected learning outcome for each page in the ILE. In addition to the facilitator's handbook, there are few other documents which are a key part of the SD/ILE. Those documents include the: pre-test scenario questionnaire, and the aforementioned journals for both ILEs. Students are required to read the pre-test questionnaire text and answer the questions in their own words before starting the first Carbon Cycle game. This carbon cycle SD/ILE experience assumes that students have some familiarity with the carbon cycle topic. The pre-test is used to establish a baseline level of knowledge for each of the students so that it possible to compare their understanding after their experience interacting with the two carbon cycle games. A list of all material for the pilot study is summarized and made accessible by following the links in table 4.

Document	Access
Handbook	Support Material
Pre-test	https://drive.google.com/file/d/1AlCMb7tGeHQUPpV9dfH7_xvFHdoWUqXS/view?usp=sharing
Journal 1	https://drive.google.com/file/d/17gWbvGFsK8i21c-FAmJiac5999CoSWye/view?usp=sharing
Journal 2	https://drive.google.com/file/d/1RbhoSr_ctoEYfv8ypfriBEkX52BKOitY/view?usp=sharing
Carbon Cycle Game 1	https://exchange.iseesystems.com/public/vir011/carbon-cycle-game
Carbon Cycle Game 2	https://exchange.iseesystems.com/public/vir011/carbon-cycle-and-human-interaction

Table 4. List of available materials for the pilot study and their access links

Procedure

In this chapter the pilot test procedure is described in detail for both Carbon Cycle game sessions.

Session 1

Two biology high school science classes participated in the pilot study. There were 17 students in the first class and 13 students in the second. The participants were between 16 and 18 years old, with an equal mix between genders, and had been classified by the school system as having normal learning abilities. Based on information from the teacher, there were 2 students with unspecified learning disabilities and 2 who were particularly gifted. Due to school confidential information policies, there is no more detail available on how to identify these 4 students and the assumptions made for the data analysis portion of this thesis were that all students were of normal learning abilities.

The dedicated time for the pilot session was one class period for each game, which means around 50 minutes per session and therefore 100 minutes total. The experience was planned by dividing time proportionally for each section of each game, and a detailed action plan for each section was established and documented in the teachers' handbook. This timing was not enforced within the experience and during the game sessions individuals moved at their own speed.

Action	Explanation	Time (min)
Assign students with the ID numbers	Ask students to register their ID number on their journals and first page of the simulations.	5
Pre-test	Individual class activities	10
Game 1	Individual activity in the class, exploring the interactive online simulation and writing their answers for each challenge in their personal journal 1.	35
Game 1, page 1-6	Exploring the carbon pools, fluxes and animation simulator and answer the relevant challenges in the journal 1.	15
Game 1, page 7-11	Exploring the carbon pools, fluxes and animation simulator and answer the relevant challenges in the journal 1.	10
Game 1, page 12-15	Feedback concept through an example from carbon cycle system and answer the relevant challenges in the journal 1.	10
Game 1, page 16-17	Individual activity, student can complete this section as fun and creative homework. If they have extra time, it can be also done in the class.	-

	Homework: https://drive.google.com/file/d/1V1NSsHgW4XnHQo7JwIjAaFh8le5XMeTW/view?usp=sharing	
Game 2	This game has some parts for individual activity and a section for teamwork	40
Game 2, page 1-4	Team activities Exploring different human actions and their impacts on the carbon cycle and answering the relevant challenges in the journal.	15
Game 2, page 5-7	Team activities The experiment contains two decision-making scenarios. Students in each team have different roles and making decision according to the role (Page 3-4 in Journal 2).	15
Game 2, page 8-11	Team activities Exploring climate feedback under human interaction and answering the relevant challenges in the journal.	10
Game 2, page 12-14	Individual activities Individual activity, student can complete this section as fun and creative homework. If they have extra time, it can be also done in the class. Homework: https://drive.google.com/file/d/1N-wJ5b8_JD8WXJ18hvoNC1-vCSOwS2Lz/view?usp=sharing	-

Table 5. Pilot session timetable and action plan summary

Participants gained unrestricted access to the support material and the journals via a link through the ILEs. The journal materials were hosted on the “google class” platform because that ensured each student directly received their own copy of each of the documents in their classroom folder under their name and all registered answers showed up in the teacher folder labeled by student. The teacher shared their teacher folder with me so that participants' responses were able to be monitored as they were filled in.

Randomized ID numbers were assigned to all students for use as user identification within the game. This was done to keep participants anonymous while their performance remained traceable. During the first session, participants received the pre-test form and had an enforced maximum of 10 minutes to read through and register their answers. The pre-test questionnaire included tasks such as: naming carbon storages, their fluxes and describing the carbon journey in the case of an old forest fire scenario. The questions and answer boxes were on the same page so that students could refer to the questions while they were writing the answers. The size of answer boxes guided students about the length of expected answers for each question. The prior carbon cycle system knowledge analysis is based on the students’ answers to these questions. The questions are listed in table 6.

	Pre-test
1.	Systems consist of groups of interacting components which together form a unified system. In the environment, systems tend to be large with many interrelated components and it is those interactions among the components which leads to complexity. To deal with the complexity, we need to learn about and study the system by understanding the interactions between components. The carbon cycle system is a story of carbon atom travelling among different carbon storage through different process (Flux). Can you name some carbon storage and its fluxes?
2.	Forest Fire Imagine there is a big forest fire burning many big old trees and threatening wildlife in the forest. Can you draw a simple diagram of the carbon atom journey due to the fire in forest? (You can use text and arrow to demonstrate the diagram).
3.	Build on your carbon journey diagram from the previous section, do you think the carbon released from the burning forest will increase the soil carbon storage? Explain why?

Table 6. The pre-test questionnaires

After the pre-test was completed, the link to the first Carbon Cycle game was provided. Parallel to the game, we shared a journal through "google class" with participants, where they can register their answers to the questions along with the game. The journal is a document with certain guidelines and instructions that guide the student's interaction with the game (ILE) to improve their understanding of the learning objectives. like the pre-test form, the scenarios, questions, and answer boxes are listed on the same pages. The students filled in the tasks through the process flow as pictured in Figures 12-14. Participants had 40 minutes to complete the session and write their answers. The first three sections of the journal include tasks such as describing the relationship between the carbon cycle variables based on the observed behavior from the ILE, naming variables with the most and the least impact on the atmospheric carbon, and graph reading.

After these tasks students are asked to predict graphical behavior over time under different scenarios and compare the prediction with actual result from the simulation. The prediction tasks are given for a couple of reasons (1) for students to reflect on their own understanding about relations between the carbon cycle variables (2) to generate a feedback about the level of students' engagement and understanding from the game.

By the end of the session, students have received a homework document so that they can summarize their learning achievements from the session in form of storytelling. The homework is for improving cognitive learning process after the session that aims to reflect on the understanding and retention of what they learn (Conti, R., et al. 1995), and was not part of the evaluation. This ended carbon cycle game one, and the first of the two classroom sessions.

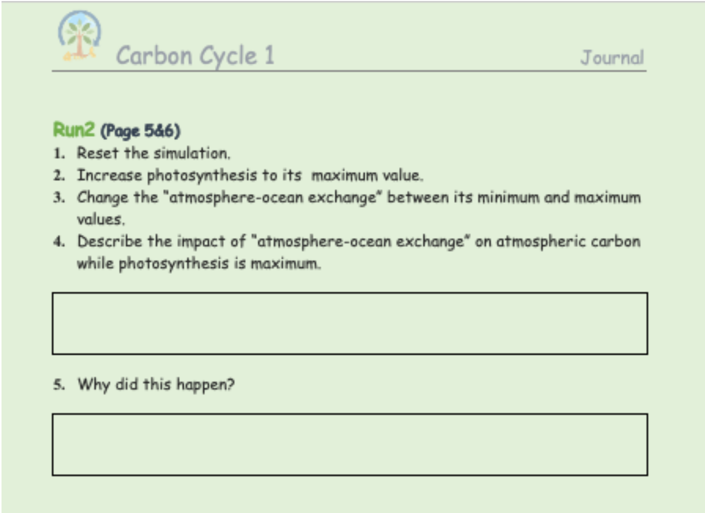


Figure 12. Example of tasks to describe the relations between the carbon cycle variables

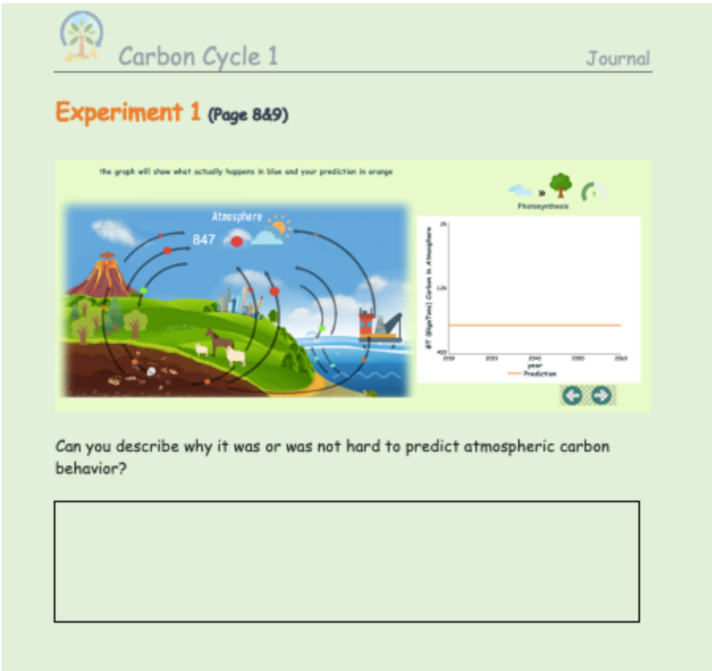


Figure 13. Behavior predictions over time

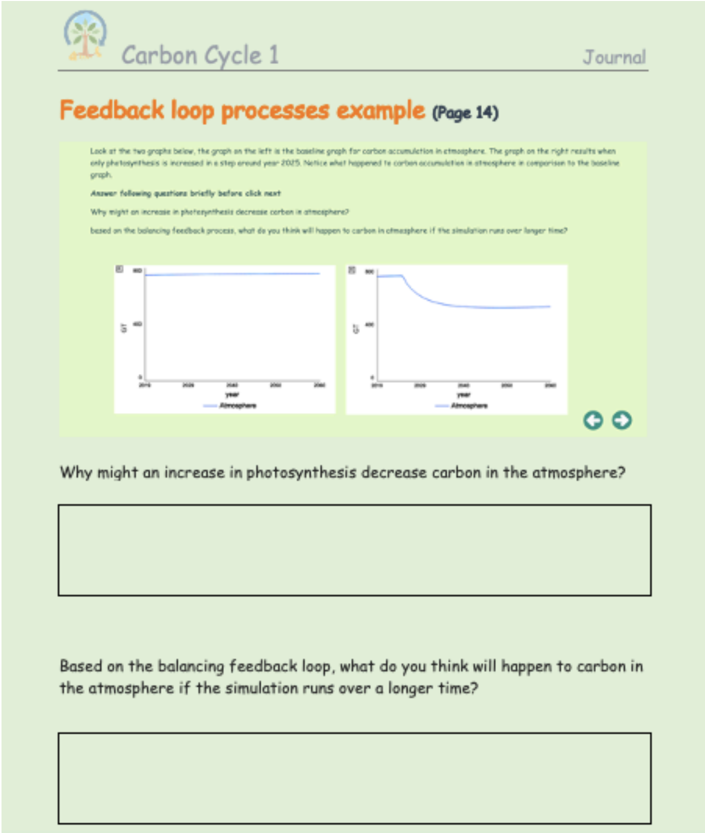
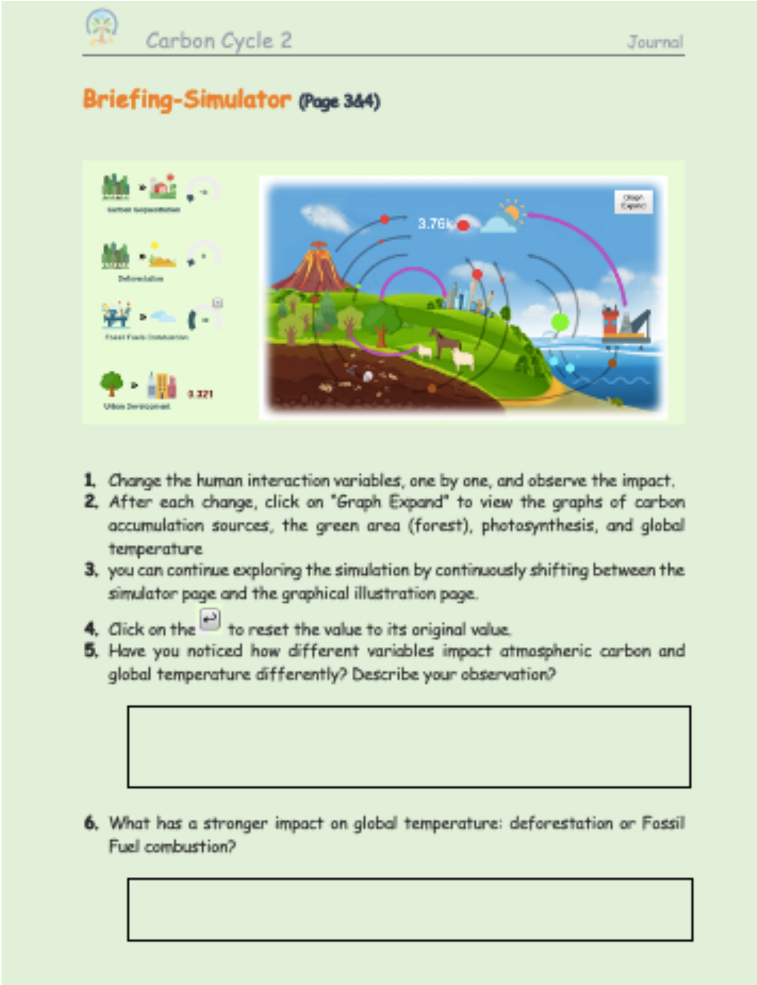


Figure 14. Feedback loop process related questions

Session 2

On the second day, in the second 50 minutes long session the students worked through for the Carbon Cycle game 2. Just as in the first game, "google class" was used to share the journal with students via an in-game link. The journal design followed the same strategy as the first game. Scenarios, questions, and answer boxes are listed on the same pages. Students were paired in groups for this session, to be able to discuss, challenge each other, and make collective decisions towards more environmentally friendly actions during the game. By pairing the students, the experiment measured their engagement and interaction through the “Stella page tracking data” as well as the data from their journals in comparison with the individual understanding during the first session.

During the second session, students first being asked to change different human interaction variables in the game and describe the relationship between them as well as their impact on global temperature and atmospheric carbon. This task aims to help them to understand the human impact on the carbon cycle and global warming, which measures Q2.1 and Q2.2.



Carbon Cycle 2 Journal

Briefing-Simulator (Page 3&4)

1. Change the human interaction variables, one by one, and observe the impact.
2. After each change, click on "Graph Expand" to view the graphs of carbon accumulation sources, the green area (forest), photosynthesis, and global temperature
3. you can continue exploring the simulation by continuously shifting between the simulator page and the graphical illustration page.
4. Click on the to reset the value to its original value.
5. Have you noticed how different variables impact atmospheric carbon and global temperature differently? Describe your observation?
6. What has a stronger impact on global temperature: deforestation or Fossil Fuel combustion?

Figure 15. Task refers to the relations between the variables and the human impact on global temperature

The next section in the game two and its journal invite students to a group decision-making session, where assigned to different roles and should make-decision every 50 years. This section measures Q2.3, to make responsible decision-making and reduce human impact on the carbon cycle. The scenario and instruction for task are given as can be seen in figure 16.

The students were asked to describe two atmospheric carbon graphs with and without fossil fuel combustion according to their understanding of the illustrated climate feedback loop during the game so that they can review the climate feedback and visualize the human impact over time. Another task at the end of the session has been hands out to the students which they are asked to complete and submit during the next biology class. The homework stablished based on the last chapter (Similar Systems) in the second game, where students are given a creative space to come up with at least one feedback loop within their day-to-day life. It measures Q3, if the ILEs help students to gain lateral knowledge about complex systems and feedback concept. This ended Carbon Cycle game 2, and the pilot session for this study.

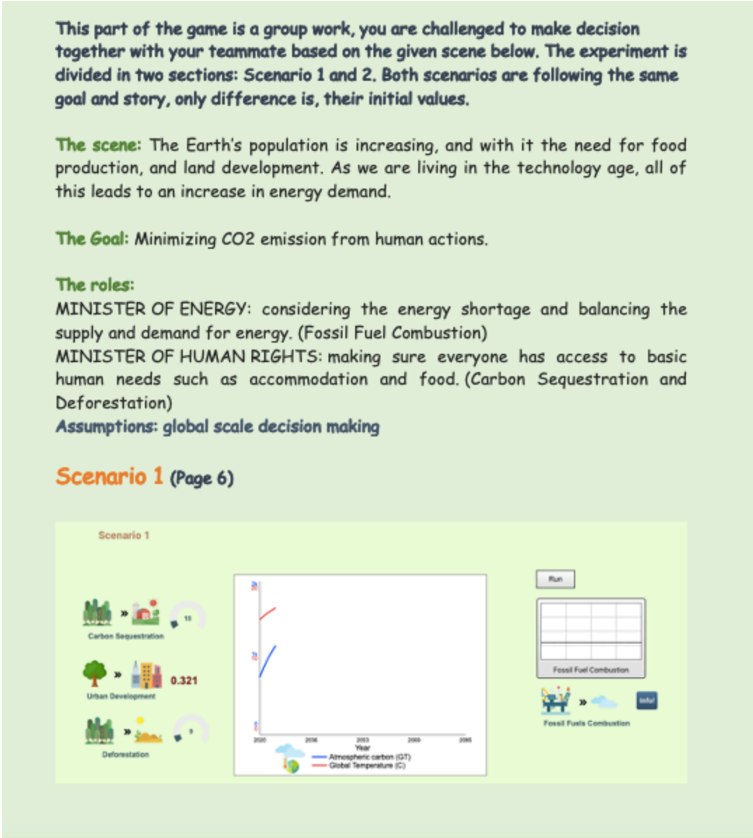


Figure 16. Decision- making task scenario

Coding and Scoring Procedure

The coding procedure is adopted from "Kirsten Davis et al.: Understanding of Complexity in Socio-Environmental Systems" based on Kim & Andersen (2012), which provides a methodology to convert textual data into word and arrow diagrams making it possible to score participants' responses. In this study, students are scored according to predefined suggested answers for their given tasks, table 7 shows an example of the scoring process. It has been also considered that, there is no unique answer and individuals might have a different way to explain similar concepts. For this reason, the scores are awarded based on words that indicate participants' understanding of required themes.

The Pre-test responses were scored based on the following items (total 10 points): (1) identifying stocks and flows in the carbon cycle system (min 4 items), 1 point for each item; (2) naming variables includes direct emission/removal, land sink, and ocean sink (1 point each); answers to prove the knowledge about feedback concepts and reason for increasing soil carbon after forest fire (max 3 point).

The same coding procedure policy from the pre-test was used for the Journals, excepting for some small changes in the scoring strategy because the journals followed a bit of a different structure than the pre-test. The students complete their journals while they are playing the game, therefore the questions are more detailed and the keywords in the answers for scoring are a bit different. 10 points is the maximum earned on journal 1 and were allocated as follows:

- The first three sections (challenges about variables and the causal relationships among them) have a total of 6-points, where 1 point is awarded for each correct relation.
- Naming variables with most and least impact (1 point for each).
- Describing behavior over time based on feedback concepts, 1 point for correct behavior like increasing or decreasing, and 1 point for the balancing or reinforcing impact.

The total earned score on journal 2 is 15 points and were allocated as follows:

- The first two sections (challenges about three human interactions and their impacts on the carbon cycle) have a total of 3-points, where 1 point is awarded for each correct relation.
- Identify a human interaction with most impact on global temperature (1 point).
- Considering all introduced human interaction while completing the decision-making tasks. Total of 6-points, where 1 point awarded for each human impact per task.
- Comparing behavior over time based on feedback concepts, (climate feedback with and without fossil fuel combustion) have a total of 3 points, where 1 point is awarded for similarity and 2 points for the differences.
- Naming two similar systems based on general system definition from the debriefing section (1 point each).

After finalizing the coding procedure, general scoring process is done based on following steps:

- Create list of suggested answers and validation process according to coding procedure.
- Highlight the key words (key concept) in the answers.
- Dedicate points to the highlighted answers.
- Data sampling from students' responses after the pilot session.
- Highlight the points according to the prepare suggested answer sheets.
- Assign points to the highlight texts.
- Calculate the total score for each participant.

Table 6 illustrates an example of coding procedure steps.

Student response	Suggested answer
Describe your observation about how different variables impact atmospheric carbon? Photosynthesis and ocean atmosphere changes cause the atmosphere graph to decrease. Plant and soil respiration cause the graph to first decrease the curve up to increase. Animal respiration and volcanoes do not change the atmosphere as much. Student's response refers to the concept of two categories for the variables. The student has pointed out the removal and emission concept. Score: 2 Points	Photosynthesis, lower value strong impact on increasing atmospheric carbon and higher value leads to very fast and noticeable carbon reduction. Atmosphere ocean exchange, lower value of exchange means carbon in the ocean and the atmosphere are in balance and this state illustrates the baseline atmospheric carbon, and in higher values shows carbon reduction over time. Plant respiration since it's in direct emission category has a direct relation with atmospheric carbon. Soil respiration has similar impact as plant respiration and has direct relation to atmospheric carbon. Animal respiration, direct relation but very little impact. Volcanoes, direct relation, and very small impact. Generally, if students can categorize the fluxes and their impact based on removal and emission direction is good enough. (1) point removal (1) point emission
Name variables with the most and the least impact? Most: Photosynthesis Least: Animal's respiration	Most impact: Photosynthesis and Atmosphere Ocean exchange (1) Least impact: Volcanoes and Animal respiration (1)

Score: 2 Points	
Describe the impact of "atmosphere-ocean exchange" on atmospheric carbon while photosynthesis is maximum. The atmosphere-ocean change did not impact it at all. Why did this happen? Photosynthesis does not affect the ocean. Score: 1 Point	Very little impact, almost nothing (1) Maximum photosynthesis decreases the atmospheric carbon to very low levels, and in that case, there will be no extra carbon in the atmosphere to be absorbed by the ocean. (1)
Total score for the section: 5 out of 6	

Table 7. Example of coding procedure

Results

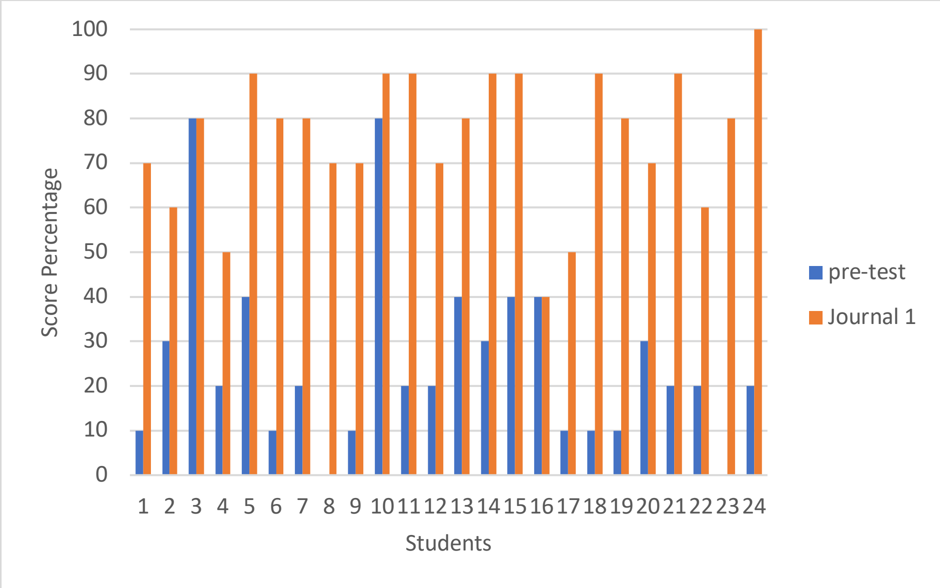
Pilot session 1: The Carbon Cycle game 1

Table 8 reports the summary statistic. Out of 30 students, 24 (80%) of them completed and delivered the pre-test and journal 1, the rest of students (20%) delivered one or none of the questionaries and were therefore removed from the results because of their incomplete data.

By reviewing the collected data from questionnaires, and the page time tacking data for individuals, students were categorized into three main groups. The first (Students type 1) are students who didn't engage with the game (6.66%). This type contains students who have shown zero interaction time with the game. The second (Students type 2) are students who showed motivation and tried to interact with the game, but page time tracking data showed that they stopped in the middle or in a very beginning (13.33%). The third (Students type 3) are students who participated in the game and delivered both questionaries (80%). The statistics and data analysis are mainly focused on the 24 students of Student type 3 where it's possible to compare their understanding about the carbon cycle system. Graph 1 illustrates the overview of students' scores about the carbon cycle knowledge before and after interacting with the Carbon Cycle game 1.

Variable	Observation	Min	Max	Mean	Std. deviation
Students type 1	2	-	-	-	-
Students type 2	4	-	-	-	-
Students type 3					
Pre-test score	24	0	80%	26.1%	20.83
Journal 1 score	24	40%	100%	76.1%	15.59

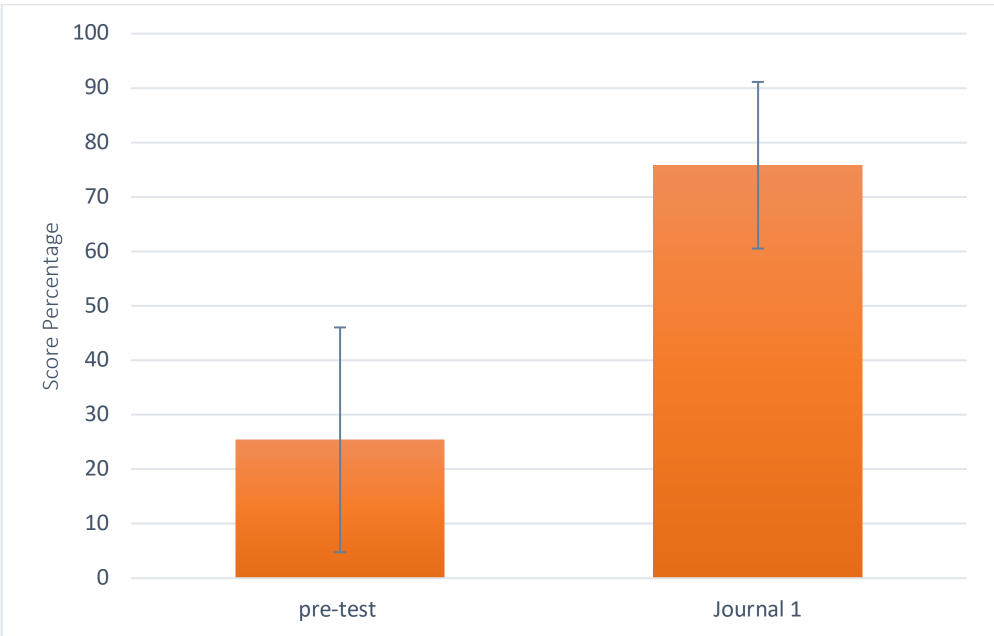
Table 8. Summary of the game 1 results from the pilot session



Graph 1. Pre-test, and journal 1 scores for individual students

Average scores for the pre-test and Journal 1 tasks are reported in percentage as 26.1% and 76.1%. A Wilcoxon signed-rank test was preformed to measure the probability that the improvement in students' scores was caused by the ILE (Research Question 1). The p-value calculated was less 0.0001 and the null hypothesis was rejected at an alpha of 0.05.

> H_0: The two samples follow the same distribution, means there was no evidence of the game impact on student understanding according to the Journal 1 scores.
> H_a: The distribution of the two samples is different, means the statistics result show the impact of the game on students' understanding about the carbon cycle.



Graph 2. Mean value for pre-test and journal 1 scores (+/- S.D.)

Summary of the statistic is reported as follow, more detail calculation and results are available under *Appendix D.*

Variable	Observation	Min	Max	Mean	Std. deviation
Pre-test	23	0	80%	26.1%	20.83
Journal 1	23	40%	100%	76.1%	15.59

P-values:

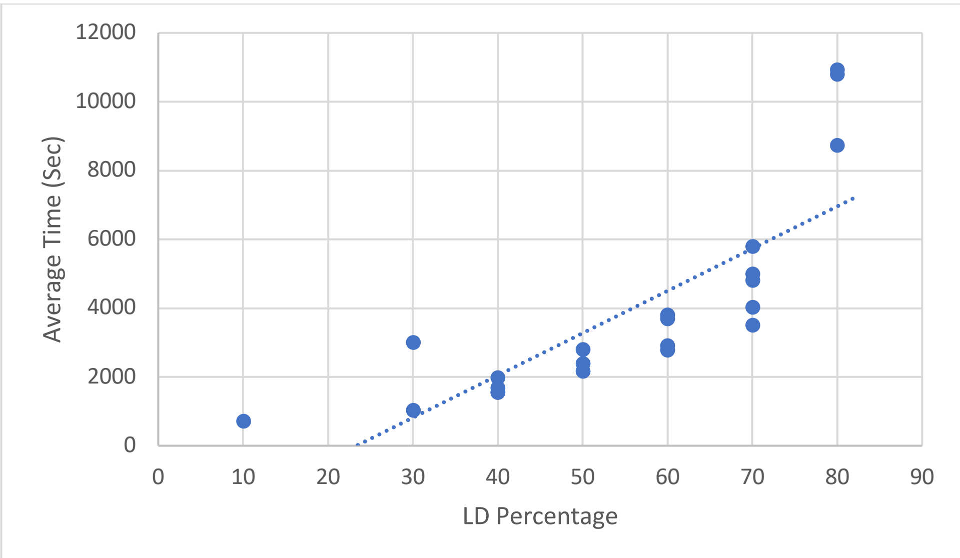
Variable\Subsamples	Sign test	Wilcoxon signed-rank test
Pre-test-Journal 1	**<0.0001**	**<0.0001**

Table 9. Summary of the Wilcoxon signed-rank statistic results

Applying a correlation test and spearman's correlation coefficient showed a linear correlation between learning scores and average time spent by students on the main interactive animation pages in the Carbon Cycle game 1. The average time data collected from the page time tracking data on "isee Exchange" server. The spearman method was used because of its higher accuracy for non-parametric values. The Learning Difference (LD) was calculated for each student equal as the difference between their journal 1 and pre-test sources (LD = journal 1 – pre-test). The correlation illustrates the finding that the more time students spend on the main animation simulator the higher their LDs are. Graph 3 shows the linear correlation between LD and average time spent by students. More detail calculation and data for correlation test can be found under *Appendix C.*

Variables	Average time	Learning
Average time	1	**0.913**
LD	**0.913**	1

Table 10. Correlation matrix between LD and average time (Spearman)



Graph 3. Correlation line between LD and average time

Moreover, tracking the page data students who have the largest net LD show a unique pattern of behavior when using game 1. These students frequently switch between the main animation and its graphical data illustration page. The average number of switches is 8.75 per student. Although with only 8 samples the sample size is too small to conclude the generic effect of interactive animation design combined with graphical data on students learning curve.

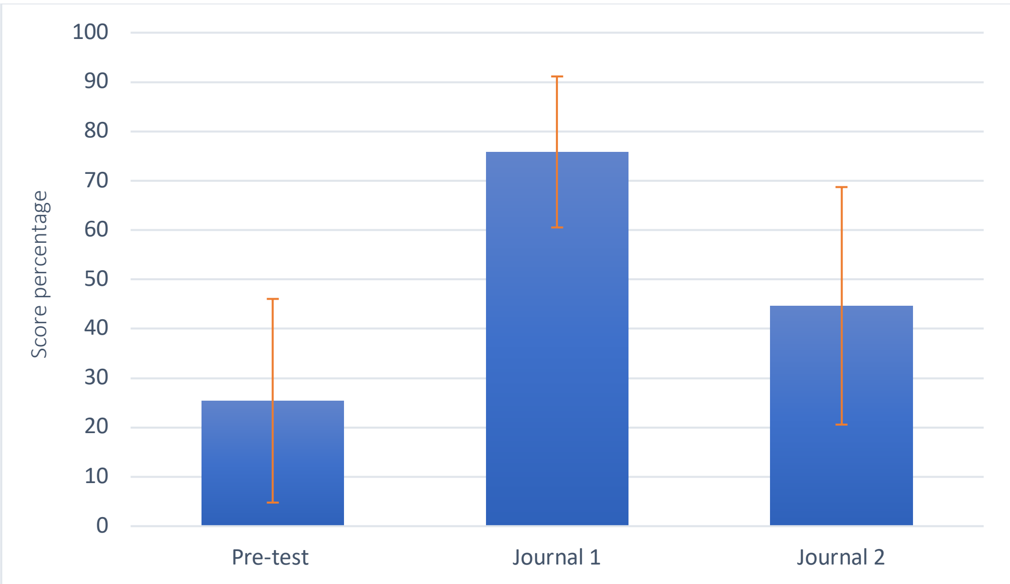
Variable	Observations	Minimum	Maximum	Mean	Std. deviation
LD	8	70	80	73.75	5.17
Number of switches	8	6	12	8.75	1.90

Table 11. Summary data observation between LD and number of switches between animation and graph pages

Another interesting observation is, the proportional relation between average spent time on the game 1 and journal 1 scores for students who have LD equal to 0. In other words, students with the same pre-test and journal 1 score, have a proportional score to the time they spend to play the game.

Pilot session 2: The Carbon Cycle game 2

The second session followed by one day after the first session with the same participants. Despite the fact that game 2 was designed to build upon game 1 students performed worse on average in game 2. The average score for journal 2 is plotting on graph 4 compared to the pre-test and game 1. As it can be seen, the mean score for the journal 2 tasks scores is lower than journal 1. A Wilcoxon signed-rank test was performed to measure the probability that the samples follow the same distribution and improvement in students' scores was caused by the ILE (Research Question 2). The p-value calculated was less 0.0001 and the null hypothesis was rejected at an alpha of 0.05.



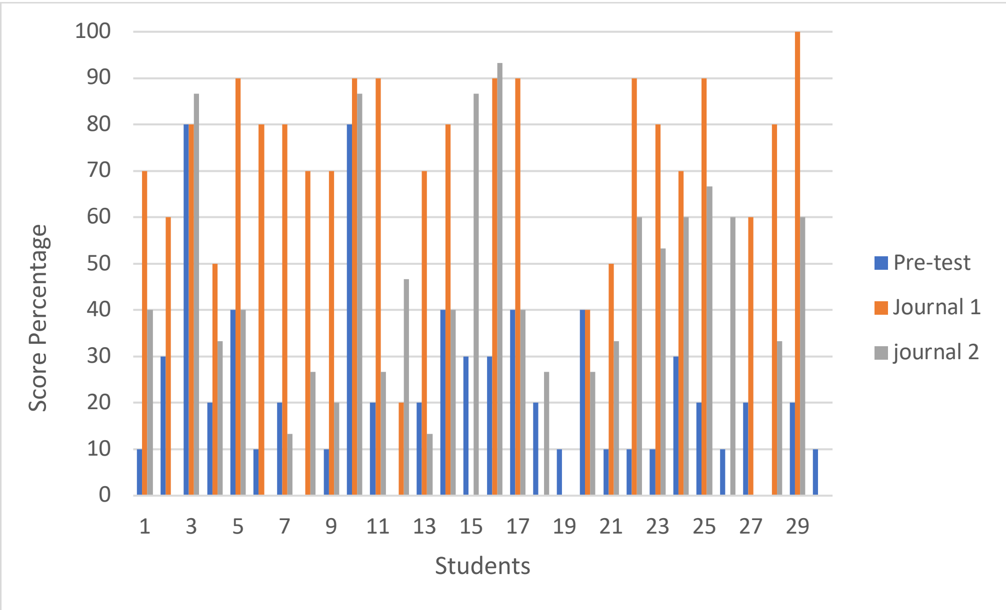
Graph 4. Mean value for scores (+/- S.D)

Wilcoxon signed-rank summary result, more detailed calculation under *Appendix C.*

Variable	Observations	Minimum	Maximum	Mean	Std. deviation
Journal 1	24	40%	100%	75.83%	15.299
journal 2	24	0	93%	39.70%	26.893

Table 12. Summary table for game 2 statistic test

The result from conducted statistic demonstrates a significant difference between two samples in journal 1 and 2 scores. Addressing the probability value and comparison graph, they claim to reject the assumption of if students did well in journal 1, they would do as well in journal 2.



Graph 5. Comparison of pre-test, Journal 1, and 2 scores for individuals

A correlation test was conducted to investigate if there is any correlation between the two set of samples from game 1 and 2. Table 13 shows correlation coefficient equal to 0.573 that indicates low correlation between the two samples.

Variables	journal 2	Journal 1
journal 2	**1**	**0.573**
Journal 1	**0.573**	**1**

Table 13. Correlation matrix between journal 1 and 2 sample results (Spearman)

Reviewing the data in graph 5 shows most of students with high scores in journal 1 have shown a dramatic drop in their journal 2 scores, and very few students kept their scores the same for both journals. All of this while the students with lower score in journal 1 showed increase in their journal 2 scores. Another interesting observation is that the few students who didn't deliver journal 1 received high score in journal 2 (e.g., student number 15 and 26). In addition, by looking at the pairing in game 2 shown in table 14, students who scored between 0 to 30%

for journal 1 are teamed up with high score students from the game 1. However, it was not intentionally planned and happened randomly.

Team Members ID	ID (journal 1 score %)	ID (journal 2 score %)
1 - 9	1 (70%) – 9 (70%)	1 (40%) – 9 (20%)
3 - 15 - 10	3 (80%)- 15 (0)-10 (90%)	3 (87%)-15(87%)- 10 (87%)
4 - 7 - 17	4 (50%)-7 (80%)- 17 (90%)	4 (33%)- 7 (13%)- 17(40%)
5 - 14	5 (90%)- 14 (80%)	5 (40%)- 14 (40%)
8 - 11	8 (70%)- 11 (90%)	8 (27%)-11(27%)
12 – 16 - 13	12 (20%)- 16 (90%)	12 (47%)-16 (93%)
18 - 20	18 (0)- 20 (40%)	18 (27%)- 20 (27%)
28 - 21	28 (80%)- 21(50%)	28 (33%)-21 (33%)
22 – 30 - 24	22 (90%)- 30 (0)- 24 (70%)	22 (60%)- 30 (0)- 24 (60%)
23 - 26	23 (80%)- 26(0)	23 (53%)-26 (60%)
25 - 29	25 (90%)- 29 (100%)	25 (67%)-29 (60%)

Table 14. summary of team members and their scores

These are interesting findings during the pilot session and result of pairing, but the sample size and evidence are not big enough to draw a conclusion on the impact.

This study also addressed the concern of interdisciplinary effect of ILE in (Q3: This ILE can laterally build knowledge about systems and feedback processes?) in the "similar systems" section of the second game. Data from the section which was handed out to students as homework were collected and analyzed to address this research question. The obtained data shows that 14 (46.66 percent) students out of 30 delivered their homework, and 7 students out of 14 came up with a day-to-day life system and a feedback concept example within the system. The rest of students demonstrated examples of a daily tasks cycle without including any feedback concept in the system. 9 out of 14 people who submit the homework were students with journal 2 scores around the mean value (39.70 %), and 5 out of 7 students with correct examples of feedback loop concept were among these 9 students.

Data samples for this section is too small to draw conclusions. However, 50 % correct submitted answers is good enough to keep the research question valid for future studies, and further experiment developments.

Results on the design of the experience

Journal 1 includes couple of questions to help the designer receiving feedback from students about the game design and the basic communication level. To check if it is easy to follow the game and understand the basic logics in the game or not. The questions are given halfway in the game 1, pages 9 and 11 after the prediction tasks. Figure 12 shows a picture of the graphical behaviour prediction over time.

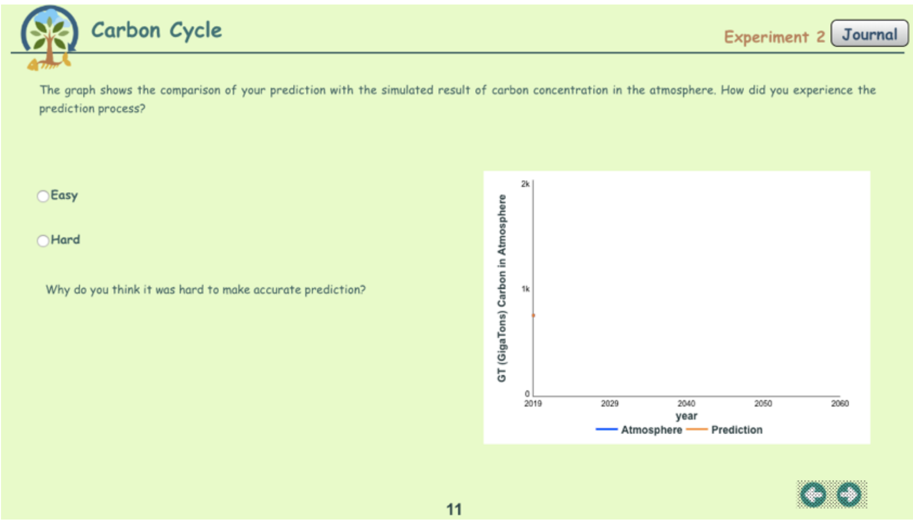


Figure 12. Evaluation of how difficult was to predict graphical behaviors

This is a multipurpose question, and the answers have been detected in following categories: (1) easy, because students learned and understood the relationship and impact from pervious sections during the game; (2) hard, because students found a knowledge gap about feedback concept; (3) hard, because students could not understand the logic and structure of the game. Total registered responses were 22 (73%) out 30 participants, where 7 students (31.81% of 73%) answered within 3rd category, 13 students (59.09% of 73%) answered within 1st category, and 2 students (9.09% of 73%) answered within 2nd category.

Interpretation of categories: categories 1 and 2 are interpreted as positive feedback and show that students understood the game concept and they are learning in accordance to planned learning objectives, however the students in category 2 are even a step ahead and ready to be introduced to feedback concept in the next chapter of the game. category 3 represents students who have difficulty to understand the game due to lack of common knowledge about the carbon cycle either lack of easy or understandable instructions in the game. Table 15 shows the summary of students' feedback during game 1.

Feedback category	Number of students (%)	Type of comment	Interpretation
1	13 (50.09 %)	**Easy** Relationship and impacts of different variables are learned from previous section of the game	Positive
2	2 (9.09 %)	**Hard** Due to the complexity of the relation and lack of feedback knowledge	Positive
3	7 (31.81 %)	**Hard** - Lost track between the game and journal - The instruction was hard to follow - Scale from zero on the graphs and difficulty to read small changes	Negative

Table 15. Summary of students' feedback on the graphical behavior prediction during the pilot session

Discussion

First I discuss the main research hypothesis about SD/ILE effectiveness as an interdisciplinary educational tool in classrooms and speculate about results in response to the research questions, and then briefly elaborate on result validation.

SD/ILE impact on students' learning in classroom

Carbon Cycle Game 1

Results from the first pilot session and the comparison graph between the pre-test and journal 1 scores demonstrates a probability that distribution of the two samples is different, means the results show the impact of the game on students' interaction and understanding about the carbon cycle.

The mean value of journal 1 scores shows a big improvement in comparison with the pre-test. The individuals' compared scores also support the learning impact of SD/ILE after playing game 1. Traced page time tracking data on "isee Exchange" server for individual players shows a high correlation between the average time spent on the main animation interactive page (page 5 in the game 1) and the gained knowledge from the ILE. This page is highly graphical and interactive which helped students to visualized better the relationship between the variables in the carbon cycle system and their impact on atmospheric carbon (Q1 research question).

Further investigation on time tracking data illustrates a pattern of performance which is not only the time they spend on the animation page but also the number of times they switch between the page and graph expansion button (page 5 and 6 in the game 1). The available data shows the switch between these pages can help students to learn more about the relationship between different variables at certain time both through the animation and the history of change development over time. Note that same pattern is shown for the rest of students as higher spent time and more frequent switching between animation and graph data pages, they show more learning improvements and higher LD (table 11). This addresses to the impact of the ILE design on students' learning enhancement.

Carbon Cycle Game 2

Looking at the summary results from the second game pilot session, it is important to note several interesting observations. First of all, despite the fact that the second game was built based on the learning attainment from the first game, yet majority of the participants with high performance during game one show a dramatic decrease in their scores. This was while the students were paired for the second session to have a discussion and decision-making platform. Secondly, pairing cause the lack of ID registration on majority of students game page. This might has happened due to students played the second game on shared computers without registering both players' ID number on the main page. This made the data tracking from "isee Exchange" server difficult and to some extend impossible. Another important observation was majority of students spend very long time on the discussion and decision-making tasks and didn't manage to finish the game. This can be discussed as an important factor for dropping their scores during the second session, but also as a time management challenge for group tasks in the real-world experiments. On the other hand, the impact of paired session is obvious on the results from students who didn't participate or complete their first game.

To perform an accurate evolution for the second game was generally more difficult. Some of the causes are listed as follows:

- Lack of data traceability from players' performance.
- Lack of enough sample and data to measure the pairing impact.
- Lack of time for majority of students to finish the second game.
- Impact of groupthink data vs. individual mental model change.

Results from game 2, address the Q2 (second research question) and shows a positive impact of SD/ILE on gaining knowledge about human interaction and its impact on the carbon cycle, however, it rejects the assumption of game 1 is a fundamental base to achieve the learning objectives for the second game.

The result from "similar systems" homework were too small to draw a conclusion whether playing the ILEs helped students to improve their generic knowledge about feedback concept (Q3 research question) or not. However, 50 % of submitted answers were supporting the hypothesis.

There might be different reasons for why all students didn't submit the homework, e.g., as could be that the pilot session was organized after the final exam for biology students, who were already in vacation mood and there was not enough motivation to do homework. It could be also due to the complexity of feedback loop and lack of enough basic knowledge about the concept. In my opinion, preparing students for real-world problem-solving skills by building lateral knowledge about complex systems and feedback concept is an important learning objective, and it should be part of every SD/ILE curriculum design study.

Validation of the pilot results

All the evaluation and scores measure which has been used for the statistic and measurement of the pilot session is adopted from Kirsten Davis et. al., (2020). A Couple of validation guidelines have been used by answering following question:

Does the pilot session provide enough variation in data?

The pilot experiment was divided into two sessions and designed to answer the three main questions to elaborate on the research hypothesis. It has been implemented as the real-world experiment in the classroom and referenced to graph 5, it provides very diverse types of data. Looking at the maximum and minimum scores and the standard deviations for small number of samples (n=24) illustrates the data variation. The samples are not normally distributed, and the mean values are varied for each set of samples. Moreover, the standard deviations are not sufficiently small in comparison to the mean values that demonstrate data is not clustered around the mean value, and the variation is large enough to be analyzed.

Are the scores reliable?

The scores' reliability is dependent on the coding purpose and procedure. In this study the scores are awarded based on individuals' understanding according to the coding procedure. The maximum score has been awarded in view of participants' age group and their knowledge backgrounds. The biggest challenge for such scoring method is coder interpretation of the students' understanding might vary from one person to another. For this master thesis the author was the only coder and there was not a possibility to hire more people for the scoring process. In general, the score reliability is increasing by comparing scores from different coders which is recommended for future experimental sessions.

Lesson learned from the real-world pilot session

There is a handful of valuable lessons learned and challenges to share about real-world curriculum design and pilot session facilitation. In real-world studies normally, ILE is going to be used by a group of people or in a classroom where the facilitator is different than the ILE designer. To make sure that the facilitator has complete overview about the learning objectives, briefing, debriefing, and session set up preparation necessary steps, providing a handbook is essential. The handbook should be easy to access and searchable. Keep in mind to write the handbook in easy vocabulary and avoid using system dynamics (SD) language and abbreviations as much as possible that people with different backgrounds can understand the content. Moreover, the handbook should be brief yet includes key information. Based on experience from this study the exception and adoption points during the session should be listed in separate chapter to make sure they are seen and understood. For example, in the handbook, I included few points that could have been adopted and changed by the teacher depends on the class dynamics and time limitation, but since there was not a dedicated chapter only for those points they were missed. I used this example to emphasis the importance of the handbook preparation and its impact on the pilot results.

It is very important to be in contact with the facilitators and make sure the game and handbook materials are clear and easy to follow, however, the handbook and the game should be designed as independent as possible from the designer. Sometimes facilitators (teachers) don't have enough time to read all the pages and details included in the handbook. They need the most critical information in the shortest time to be able to hold the session. Being complete and concise is the best strategy for a practical handbook.

The Carbon Cycle games in this study are developed in detail to evaluate the ILEs as an interdisciplinary educational tool and for this reason, the journals and the game pages contain detailed information and instructions to make the evaluation measurable. At the other hand the games are designed for physical classroom experiment and teachers' roles are very important. It was very challenging to provide a summary of all necessary information for the teacher yet avoid being wordy and overexplaining. How to make an efficient communication with the facilitators and specially teachers in case of curriculum designs is a key factor to have an accurate results and reliable evaluations. Real-world ILEs and classroom empirical studies deserve a narrative focus in research development to offer more efficient and explicit methodologies. Other interesting experience from the pilot session is impact of pairing the students on data traceability. During the second game the students were paired up to have discussion and decision-making sessions. It creates a big chaos on data traceability from Stella software data collection. The pairing itself as a factor as already mentioned before in the result section, provides many useful insights to the experiment. However, needs more instruction, set up rules and organizationto avoid the chaotic data collection and time management.

Overall, real-world experiments with a 3rd person facilitator are more demanding and challenging to be handled in a way to get the maximum learning potential out of the session. Anyway, this will be the reality of the ILEs out of the research world if they become standard and available teaching tools for the educators. Pilot studies such as this master thesis are important to help overcoming the difficulties for the future of SD/ILEs in classrooms.

Limitation and Improvements

While analyzing the empirical data I have noticed possible ways for future improvements.

Pilot session and ILE design

Results from the experience feedback shows that there was some misunderstanding in order to how to simultaneously follow the instructions both for the games and journals. This potentially could lead to making students rather tired and lose their motivation to continue the game. Moreover, working with two screen windows open at the same time might have been one of the reasons that majority of the students faced lack of time.

Also, as some students were interacting with the game but not filling in their journals, I believe it might have been difficult for them to work with both document at the same time. Apart from time that has been reported as the main challenge for the class, there was lack of classroom briefing and debriefing session. The sessions were included in the games and students given unrestricted accesses to the material, and they were encouraged to ask questions in case of any unclarity. However, I noticed some students didn't follow the order of the instructions and reading materials, that could cause confusion and reduce the learning potential. This can also lead to lose the willingness and motivation for students to finish the game.

General feedback from students' performance showed that the games and the pilot session instructions were user-friendly and they had no problem to interact with the games. However, as some students had difficulty to follow the instruction and to understand the principles more emphasize should have been given on the task description and game rules. In addition, to improve time management, a systematic game advanced function might help.

Implications for further Research

As it has been mentioned before, time is an important factor to be addressed in future studies. This research has shown that 50 minutes long session per game is not enough for students to cover all the learning materials and journals attached to the games, in some cases showed neither a complete version of briefing and debriefing sessions. Longer sessions, maybe around

2-3 hours per game would be optimal time scope to reach the potential learning outcomes from the experiment.

It can be useful to have more than one coder for future experiments, to be able to compare different sets of scores from different coders. This will increase the reliability of the coding and scoring procedure. Tailoring different assessment tools to fit the purpose of individuals' understanding of complex systems and feedback concept terms in real world experiments and compare the results to find the optimal methodology for the classroom purpose. Evaluation is an important tool to visualize the impact of SD/ILEs for the educators who according to empirical study by Ossimitz 2000, are facing difficulties to measure students' systems thinking skills.

The Carbon Cycle Game Potential

The games and the experiment materials can be adopted to different age groups and transformed into a weekly course or periodic science workshops for students. The sessions can enrich the research related to improving understanding and learning by SD/ILE for youth and high school students.

This project has been awarded by Bergen Municipality for summer schools' activity during summer 2021. The games and learning objectives will be adopted for age group 12-15 years old students. The experiments will be one-week workshop and includes briefing, debriefing, and group CLD (Casual Loop Diagram) developing sessions. All mentioned limitation and potential challenges from before have been considered as potential improvement for the summer school experiment.

Conclusion

Understanding complex systems is a key skill for all people, unfortunately despite its importance, it is not officially part of the educational curriculum. The practice of systems thinking exists only in special fields of studies and professions, while the history of human failure in different industries, humanity, phycology, and political sciences has proven the universal need for systems thinking skills.

The main contribution of this study is to assess the effectiveness of an SD/ILE (System Dynamics-based Interactive Learning Environment) as an interdisciplinary educational tool for K-12 students, to help students develop systems thinking skills and build a lateral understanding of feedback loop processes. Built on referenced literature the feedback loop and systems concepts are present in many disciplines while in this study, we chose to develop a lesson about the carbon cycle. Mainly for two reasons: first, because it is part of the current US high-school biology curriculum, an ideal context where we get the chance to develop a pilot real experience; and second because due to the actual environmental crisis, it is important to learn about climate feedbacks, providing pedagogical content very useful in a real-world context.

Assessing systems thinking and the feedback loop understanding are very demanding and require special assessment tools. The first step towards this goal was to change the main hypothesis into more detailed and measurable questions (Q1-Q3). Refer to the research questions: *Q1:* Can this interactive learning environment (ILE) help students to learn about the carbon cycle system?; *Q2:* Can this ILE help students to understand the human impact on the carbon cycle?; *Q3:* Can this ILE help students to build a lateral knowledge about systems and feedback processes concept?

Thus, in order to measure mental model change, the participants' understanding, and performance must be investigated. To improve system (the carbon cycle) understanding, one should first start by learning general relations among the variables within the system.

To address the questions, two ILEs have been developed based on a generic existing carbon cycle model. The first one focused on general understanding of the carbon cycle system and climate feedback concept, and the second one aims to expand the students learning from the first one and challenge them about human impact on the system, having a specific interest in bringing the generic feedback topic to the day-to-day life with simple and tangible examples. The games are developed in parallel with certain guidelines and instructions that guide the student's interaction with the game (ILE), and it can help them to improve their understanding of the learning objectives while they are interacting with the games.

The results of students' interaction with the games during the pilot experiment, it was very satisfactory. The samples from the first Carbon Cycle game and the pre-test questioners showed that 73% of the students improved their knowledge. Showing that the learning was in correlation with the average time spent on the game. Moreover, the data illustrated a significant impact of animation-based ILE design on the individual learning curve.

The results from Interacting with the second game were also positive. Despite the fact that the majority of students performed poorly in comparison with the first game, it has identified valuable classroom challenges for paired activity sessions. About 20% of students showed knowledge improvement, which they were mostly students who had very low or zero scores during the first game. Also, the average number of students who didn't deliver their journal 1 or pre-test, they show improvement in the second game. This could suggest that the group-work moderating effect motivates more students to play the game.

It was also noticed that time management in paired activity was more difficult. The students were encouraged to have decision-making and group problem-solving sessions, and it might have caused a lack of time to play the entire game. Something to take into consideration for future real case experiments.

This pilot experiment was a unique opportunity in order to avoid, control, confront, and resolve some theoretical and practical problems that appeared along with the development of the project. When the experiments are considered in the real-world context, there are many factors that come into play. These factors are related to different aspects of the experience, such as the teachers' role, interactive and engaging level of the ILE (game) design, appropriate timing for playing the game, easy instruction, and suitable assessment tool for measuring individual knowledge development. Among the strongest lesson learned from the classroom experiment, time management and students' engagement can be underlined.

System dynamics is a powerful field with a rich history in experiment development research (Arango Arambulo et al., 2012; Sterman, 2018), however, still is missing suitable and sensitive techniques for real-world studies measurement. In this project LUV (Lake Urmia Vignette) assessment tool has been adopted which is different from many conventional tools. This method can provide rich textual data about how students think and respond to different systems thinking tasks. However, this method was useful to some extent but it lacks enough sensitivity for step-by-step learning where students at each stage learn a new concept to complete the previous stage. The coding procedure for this method is working very well by hunting keywords, while this study aims for conceptual learning rather than exact words in the texts and this might make the scoring process less robust.

The obtained results through the pilot test and analyzed data, show promising findings that students after playing the Carbon Cycle games have shown gaining more knowledge about the carbon cycle system in comparison to pre-test results. The good news is that the knowledge improvement has a linear correlation with the average time where each student spent playing the game. Moreover, the data proves animation-based design has shown a significant impact on the individual learning curve.

Even though, the evidence from data collection was not enough to prove the ILEs helped to improve generic feedback knowledge from narrative topic, still more than 50% of the submitted homework successfully managed to come up with a day-to-day life feedback concept, which Is strong enough to keep the research question valid for further investigation.

Overall, results from the study supported the effectiveness of SD/ILEs in the classroom and addressed very important challenges that real-world pilot studies are facing. The pilot experiment also sets the ground for future investigation. Future research can focus on different assessment tools that make easier and more accurate evaluations. This can also help us to improve ILE development aligned with maximizing the effect of ILE on students' learning.

There is no doubt that the Carbon Cycle games (ILES) improve the students' understanding of causal relations, and the climate feedback within the carbon cycle. Nonetheless, it must be considered that learning these concepts require consistence practice and empowerment of systems thinking skills. After the pilot experience, I believe that using SD/ILE as a standard curriculum in the classroom can result in a more and more successful systems thinking skills.

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Appendix A

The Carbon Cycle Model

The Carbon Cycle model translated to stock and flow diagram (SFD) in Stella Architect.

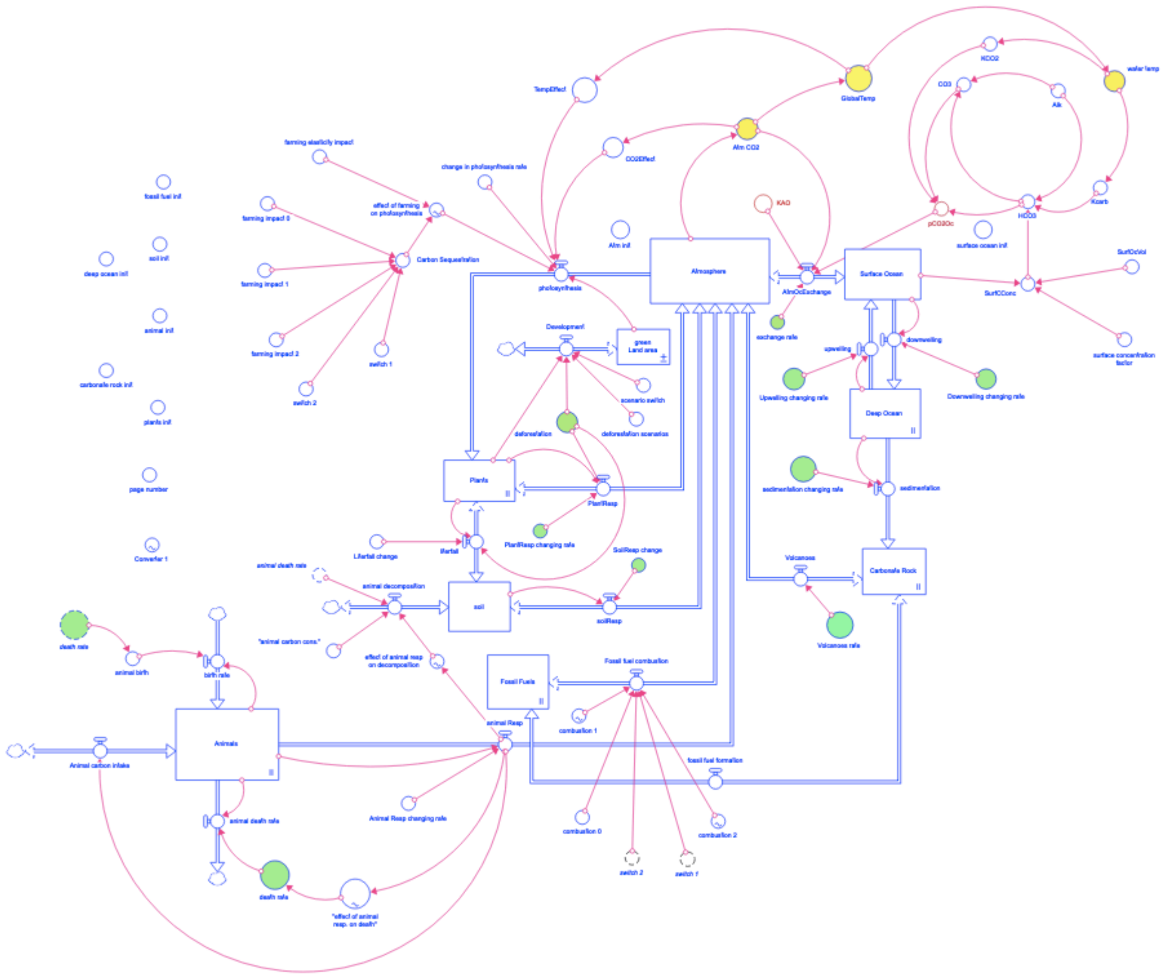


Figure 1A. The Carbon Cycle Stock and Flow Diagram (SFD)

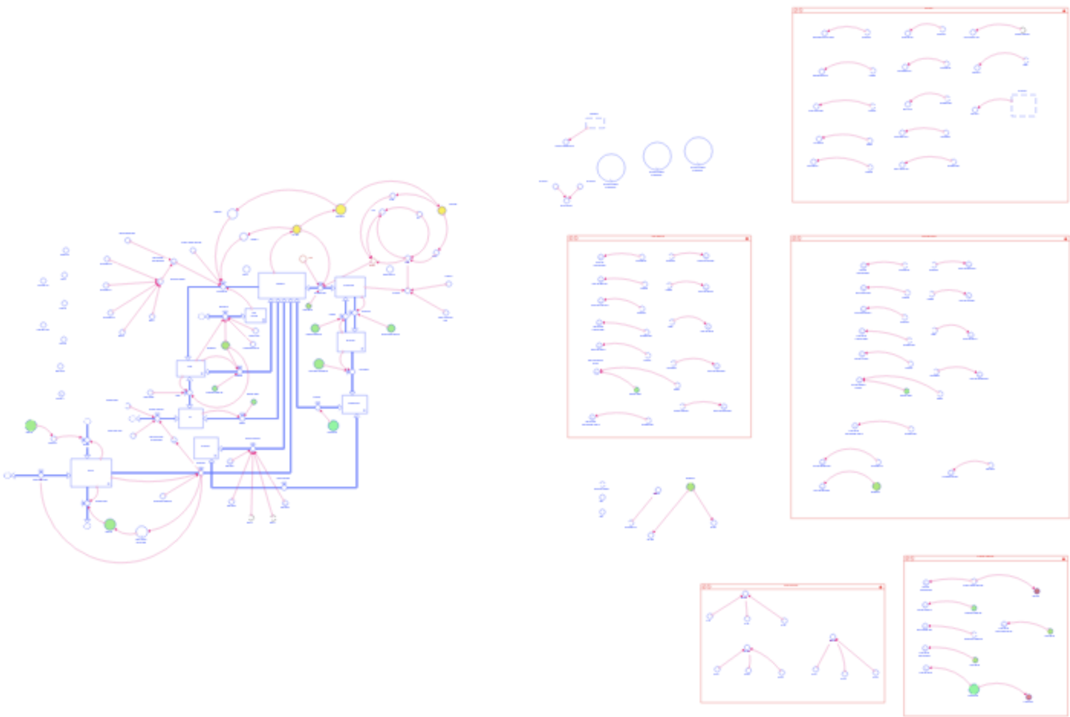


Figure 2A. SFD includes modeling section for animation

Equaitions and model details

	Equation	Properties	Units
Top-Level Model:			
Animals(t)	Animals (t - dt) + (Animal_carbon_intake + birth_rate - animal_Resp - animal_death_rate) * dt	INIT Animals = animal_init	GT
Atmosphere(t)	Atmosphere (t - dt) + (Fossil_fuel_combustion + PlantResp + soilResp + Volcanoes + animal_Resp - photosynthesis - AtmOcExchange) * dt	INIT Atmosphere = Atm_init	GT
Carbonate_Rock(t)	Carbonate_Rock (t - dt) + (sedimentation - Volcanoes - fossil_fuel_formation) * dt	INIT Carbonate_Rock = carbonate_rock_init	GT

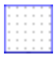
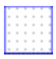
Deep_Ocean(t)	Deep_Ocean (t - dt) + (downwelling - upwelling - sedimentation) * dt	INIT Deep_Ocean = deep_ocean_init	GT
Fossil_Fuels(t)	Fossil_Fuels(t - dt) + (fossil_fuel_formation - Fossil_fuel_combustion) * dt	INIT Fossil_Fuels = fossil_fuel_init	GT
green_Land_area(t)	green_Land_area(t - dt) + (- Development) * dt	INIT green_Land_area = 100	percent
Plants(t)	Plants (t - dt) + (photosynthesis - PlantResp - literfall) * dt	INIT Plants = plants_init	GT
soil(t)	soil(t - dt) + (literfall + animal_decomposition - soilResp) * dt	INIT soil = soil_init	GT
Surface_Ocean(t)	Surface_Ocean(t - dt) + (AtmOcExchange + upwelling - downwelling) * dt	INIT Surface_Ocean = surface_ocean_init	GT
Animal_carbon_intake	animal_Resp		GT/year
animal_death_rate	death_rate*Animals	OUTFLOW PRIORITY: 2	GT/year
animal_decomposition	animal_death_rate*"animal_carbon_cons."*effect_of_animal_resp_on_decomposition		GT/year
animal_Resp	Animals*(0.7/INIT(Animals))*Animal_Resp_changing_rate	OUTFLOW PRIORITY: 1	GT/year
AtmOcExchange	KAO*(Atm_CO2-pCO2Oc)*exchange_rate	OUTFLOW PRIORITY: 6	GT/year
birth_rate	animal_birth*Animals		GT/year
Development	(deforestation/INIT(Plants)*0.2)*100+((deforestation_scenarios*scenario_switch)/INIT(Plants)*0.2)*100		percent/year
downwelling	Surface_Ocean*(90.1/INIT(Surface_Ocean))*Downwelling_changing_rate		GT/year
Fossil_fuel_combustion	combustion_1*switch_1+combustion_2*switch_2+combustion_0		GT/year

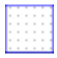
fossil_fuel_formation	0	OUTFLOW PRIORITY: 2	GT/year
literfall	((Plants*(55/INIT(Plants)))+(deforestation/2))*Literfall_change	OUTFLOW PRIORITY: 2	GT/year
photosynthesis	110*CO2Effect*(green_Land_area/100)*TempEffect*change_in_photosynthesis_rate*(effect_of_farming_on_photosynthesis)	OUTFLOW PRIORITY: 2	GT/year
PlantResp	((Plants*(55/INIT(Plants)))+deforestation/2)*PlantResp_changing_rate	OUTFLOW PRIORITY: 1	GT/year
sedimentation	Deep_Ocean*(0.1/INIT(Deep_Ocean))*sedimentation_changing_rate	OUTFLOW PRIORITY: 2	GT/year
soilResp	soil*(55/INIT(soil))*SoilResp_change		GT/year
upwelling	Deep_Ocean*(90/INIT(Deep_Ocean))*Upwelling_changing_rate	OUTFLOW PRIORITY: 1	GT/year
Volcanoes	Volcanoes_rate	OUTFLOW PRIORITY: 1	GT/year
"animal_carbon_cons."	0.004		GT/year
"animal_decomp._color"	IF animal_decomposition=0THEN 0 ELSE 1		Dimentionless
"effect_of_animal_resp._on_death"	GRAPH(animal_Resp) Points: (0.000, 0.000), (0.100, 0.33583091167), (0.200, 0.560945103841), (0.300, 0.7118436595), (0.400, 0.812993986277), (0.500, 0.880797077978), (0.600, 0.926246849528), (0.700, 0.956712742486), (0.800, 0.977134641257), (0.900, 0.99082384938), (1.000, 1.000)		Dimentionless
Alk	2.222446077610055*0 +2.17		Dimentionless
animal_birth	death_rate		Number/year
animal_init	2500		GT
Animal_Resp_changing_rate	1		GT/year

animal_resp_color	IF animal_Resp=0 THEN 0 ELSE 1		Dimentionless
arrow_size_animal_resp	GRAPH(Animal_Resp_changing_rate) Points: (0.000, 0.9000), (0.200, 0.9200), (0.400, 0.9400), (0.600, 0.9600), (0.800, 0.9800), (1.000, 1.0000), (1.200, 1.0200), (1.400, 1.0400), (1.600, 1.0600), (1.800, 1.0800), (2.000, 1.1000)		Dimentionless
arrow_size_animal_resp_2	GRAPH(animal_Resp) Points: (0.000, 0.9000), (0.166666666667, 0.933333333333), (0.333333333333, 0.966666666667), (0.500, 1.0000), (0.666666666667, 1.03333333333), (0.833333333333, 1.06666666667), (1.000, 1.1000)		Dimentionless
arrow_size_change_for_soil_resp_2	GRAPH(SoilResp_change*0+soilResp) Points: (0.0, 0.9000), (10.0, 0.9200), (20.0, 0.9400), (30.0, 0.9600), (40.0, 0.9800), (50.0, 1.0000), (60.0, 1.0200), (70.0, 1.0400), (80.0, 1.0600), (90.0, 1.0800), (100.0, 1.1000)		Dimentionless
arrow_size_deforestation	GRAPH(deforestation) Points: (0.0, 1.00334642546), (10.0, 1.00899310498), (20.0, 1.02371293659), (30.0, 1.05960146101), (40.0, 1.13447071069), (50.0, 1.2500), (60.0, 1.36552928932), (70.0, 1.44039853899), (80.0, 1.47628706341), (90.0, 1.49100689502), (100.0, 1.49665357454)		Dimentionless
arrow_size_farming_impact	GRAPH (farming_impact_0) Points: (0.0, 1.00334642546), (10.0, 1.00899310498), (20.0, 1.02371293659), (30.0, 1.05960146101), (40.0, 1.13447071069), (50.0, 1.2500), (60.0, 1.36552928932), (70.0, 1.44039853899), (80.0, 1.47628706341), (90.0,		Dimentionless

	1.49100689502), (100.0, 1.49665357454)		
arrow_size_of_photosynthesis	GRAPH (change_in_photosynthesis_rate) Points: (0.000, 0.9000), (0.200, 0.9200), (0.400, 0.9400), (0.600, 0.9600), (0.800, 0.9800), (1.000, 1.0000), (1.200, 1.0200), (1.400, 1.0400), (1.600, 1.0600), (1.800, 1.0800), (2.000, 1.1000)		Dimentionless
arrow_size_of_photosynthesis_2	GRAPH (photosynthesis) Points: (0.0, 0.9000), (100.0, 0.966666666667), (200.0, 1.03333333333), (300.0, 1.1000)		Dimentionless
arrow_size_plant_resp	GRAPH(PlantResp_changing_rate) Points: (0.000, 0.9000), (0.200, 0.9200), (0.400, 0.9400), (0.600, 0.9600), (0.800, 0.9800), (1.000, 1.0000), (1.200, 1.0200), (1.400, 1.0400), (1.600, 1.0600), (1.800, 1.0800), (2.000, 1.1000)		Dimentionless
arrow_size_plant_resp_2	GRAPH(PlantResp) Points: (0.0, 0.9), (33.3333333333, 0.933333333333), (66.6666666667, 0.966666666667), (100.0, 1)		Dimentionless
arrow_size_sky_ocean_exchange	GRAPH (exchange_rate) Points: (0.000, 0.9000), (0.666666666667, 0.966666666667), (1.33333333333, 1.03333333333), (2.000, 1.1000)		Dimentionless
arrow_size_sky_ocean_exchange_2	GRAPH(AtmOcExchange) Points: (0.05, 0.9000), (17.00, 1.1000)		Dimentionless
arrow_size_sky_ocean_exchange_reverse	GRAPH (exchange_rate) Points: (0.000, 1.1000), (0.666666666667, 1.03333333333), (1.33333333333, 0.966666666667), (2.000, 0.9000)		Dimentionless

arrow_size_sky_ocean_exchange_reverse_2	GRAPH(AtmOcExchange) Points: (-17.00, 1.1000), (0.90, 0.9000)		Dimentionless
arrow_size_volcano	GRAPH(Volcanoes_rate) Points: (0.000, 0.9000), (0.100, 0.9200), (0.200, 0.9400), (0.300, 0.9600), (0.400, 0.9800), (0.500, 1.0000), (0.600, 1.0200), (0.700, 1.0400), (0.800, 1.0600), (0.900, 1.0800), (1.000, 1.1000)		Dimentionless
arrow_size_volcano_2	GRAPH(Volcanoes) Points: (0.0000, 0.9500), (0.2500, 1.0750), (0.5000, 1.2000)		Dimentionless
Atm_CO2	Atmosphere*(280/INIT(Atmosphere))		GT
Atm_init	750		GT
atmo_ex_color	IF AtmOcExchange=0 THEN 0 ELSE 1		Dimentionless
atmo_ex_reverse_color	IF AtmOcExchange=0 AND AtmOcExchange >1 THEN 0 ELSE 1		Dimentionless
Carbon_in_atmosphere_color	IF Atmosphere>750 THEN 1 ELSE 0		Dimentionless
Carbon_Sequestration	(farming_impact_1/100) *(switch_1)+(farming_impact_2/100)*switch_2+farming_impact_0		Dimentionless
carbon_size_animal_resp_1	GRAPH (animal_Resp) Points: (0.000, 0.000), (0.375, 0.625), (0.750, 1.250), (1.125, 1.875), (1.500, 2.500)		Dimentionless
carbon_size_change_for_soil_resp	GRAPH(SoilResp_change*0+soilResp) Points: (0.00, 0.000), (8.80, 0.300), (17.60, 0.600), (26.40, 0.900), (35.20, 1.200), (44.00, 1.500), (52.80, 1.800), (61.60, 2.100), (70.40, 2.400), (79.20, 2.700), (88.00, 3.000)		Dimentionless
Carbon_size_decomposition	GRAPH (animal_decomposition) Points: (0.000, 1.000), (0.100, 1.100), (0.200, 1.200), (0.300, 1.300), (0.400, 1.400), (0.500, 1.500), (0.600, 1.600), (0.700,		Dimentionless

	1.700), (0.800, 1.800), (0.900, 1.900), (1.000, 2.000)		
carbon_size_downwelling	GRAPH (downwelling) Points: (70.00, 1.2000), (90.00, 1.3500), (110.00, 1.5000)		Dimentionless
carbon_size_downwelling_1	GRAPH (downwelling) Points: (70.00, 1.0000), (90.00, 1.0000), (110.00, 1.0000)		Dimentionless
carbon_size_liter_fall	GRAPH (literfall) Points: (0.00, 0.000), (32.3333333333, 0.666666666667), (64.6666666667, 1.33333333333), (97.00, 2.000)		Dimentionless
carbon_size_liter_fall_1	GRAPH (literfall) Points: (0.00, 0.500), (55.00, 1.000), (64.6666666667, 1.893), (97.00, 2.987)		Dimentionless
carbon_size_of_photosynthesis_1	GRAPH (photosynthesis) Points: (0.00, 0.000), (13.3333333333, 0.460474432696), (26.6666666667, 1.1031182724), (40.00, 2.000)		Dimentionless
carbon_size_plant_resp_1	GRAPH(PlantResp) Points: (0.00, 0.000), (10.00, 0.600), (20.00, 1.200), (30.00, 1.800)		Dimentionless
carbon_size_sedimentation	GRAPH (sedimentation) Points: (0.000, 1.2000), (0.100, 1.2000), (0.200, 1.2000), (0.300, 1.2000), (0.400, 1.2000), (0.500, 1.2000), (0.600, 1.2000), (0.700, 1.2000), (0.800, 1.2000), (0.900, 1.2000), (1.000, 1.2000)		Dimentionless
carbon_size_sedimentation_1	GRAPH (sedimentation) Points: (0.000, 1.0000), (0.100, 1.0000), (0.200, 1.0000), (0.300, 1.0000), (0.400, 1.0000), (0.500, 1.0000), (0.600, 1.0000), (0.700, 1.0000), (0.800, 1.0000), (0.900, 1.0000), (1.000, 1.0000)		Dimentionless
carbon_size_sky_ocean_exchange_1	GRAPH(AtmOcExchange) Points: (0.100, 0.800), (0.733333333333, 1.200),		Dimentionless

	(1.36666666667, 1.600), (2.000, 2.000)		
carbon_size_sky_ocean_exchange_reverse_2	GRAPH(AtmOcExchange) Points: (-17.00, 3.000), (0.90, 0.000)		Dimentionless
carbon_size_upwelling	GRAPH (upwelling) Points: (80.00, 1.2000), (110.00, 1.5000)		Dimentionless
carbon_size_upwelling_1	GRAPH (upwelling) Points: (80.00, 1.0000), (110.00, 1.0000)		Dimentionless
Carbon_size_volcano_1	GRAPH(Volcanoes) Points: (0.000, 0.800), (0.100, 1.020), (0.200, 1.240), (0.300, 1.460), (0.400, 1.680), (0.500, 1.900), (0.600, 2.120), (0.700, 2.340), (0.800, 2.560), (0.900, 2.780), (1.000, 3.000)		Dimentionless
carbonate_rock_init	100000000		GT
change_in_photosynthesis_rate	1		GT/year
CO2Effect	1.5*((Atm_CO2)-40)/((Atm_CO2) +80)		Dimentionless
CO3	(Alk-HCO3)/2		GT/year
combustion_0	0		GT/year
combustion_1	GRAPH(TIME) Points: (2000.0, 8.50), (2033.33333333, 21.57), (2066.66666667, 28.92), (2100.0, 30.64), (2133.33333333, 23.53), (2166.66666667, 18.14), (2200.0, 13.48)		Dimentionless
combustion_2	GRAPH(TIME) Points: (2000.0, 10.30), (2025.0, 23.00), (2050.0, 40.44), (2075.0, 45.34), (2100.0, 47.79), (2125.0, 42.65), (2150.0, 30.39), (2175.0, 12.99), (2200.0, 0.00)		Dimentionless
Combustion_arrow_size	GRAPH (combustion_0) Points: (0.0, 1.000), (10.0, 1.06120702456), (20.0, 1.12885124809), (30.0, 1.2036096767), (40.0, 1.28623051789), (50.0, 1.3775406688), (60.0,		Dimentionless

	1.47845399211), (70.0, 1.58998046227), (80.0, 1.7132362737), (90.0, 1.84945501197), (100.0, 2.000)		
death_rate	0.02*"effect_of_animal_resp._on_death"		Number/year
deep_ocean_init	38000		GT
deforestation	0		Percent/year
deforestation_scenarios	9		Percent/Year
downwelling_arrow_color_change	IF downwelling= 0 THEN 0 ELSE 1		Dimentionless
Downwelling_changing_rate	1		GT/Year
effect_of_animal_resp_on_decomposition	GRAPH (animal_Resp) Points: (0.000, 0.000), (0.100, 0.100), (0.200, 0.200), (0.300, 0.300), (0.400, 0.400), (0.500, 0.500), (0.600, 0.600), (0.700, 0.700), (0.800, 0.800), (0.900, 0.900), (1.000, 1.000)		Dimentionless
effect_of_farming_on_photosynthesis	GRAPH((Carbon_Sequestration/100)^farming_elasticity_impact) Points: (0.000, 1.0000), (0.100, 0.769224032225), (0.200, 0.614530274882), (0.300, 0.510835948339), (0.400, 0.441327562596), (0.500, 0.394734698266), (0.600, 0.363502567303), (0.700, 0.342567043838), (0.800, 0.328533542785), (0.900, 0.319126605713), (1.000, 0.312820947222)		Dimentionless
exchange_rate	1		GT/year
farming_elasticity_impact	3		Dimentionless
farming_impact_0	0		Dimentionless
farming_impact_1	10		Dimentionless
farming_impact_2	40		Dimentionless
fossil_color	IF Fossil_Fuels=0 THEN 0 ELSE 1		Dimentionless
fossil_fuel_init	7500		GT
GlobalTemp	15+((Atm_CO2-280) *0.01)		C

HCO3	(SurfCConc-(SQRT(((SurfCConc^2)-Alk)*(2*SurfCConc-Alk)*(1-4*Kcarb))))/(1-(4*Kcarb))		GT/year
ID_number_1	0		Dimentionless
ID_number_2	0		Dimentionless
KAO	0.278 +0.00046*0		Dimentionless
Kcarb	0.000575+(0.000006*(water_temp-278))		Dimentionless
KCO2	0.35+(0.0019*(water_temp-278))		Dimentionless
Literfall_change	1		GT/year
literfall_color	IF literfall=55 THEN 0 ELSE 1		Dimentionless
page_number	0		Dimentionless
pCO2Oc	280*KCO2*((HCO3^2)/CO3)		GT/Year
Photosynthesis_color	IF photosynthesis=0 THEN 0 ELSE 1		Dimentionless
PLant_resp_color	IF PlantResp= 0 THEN 0 ELSE 1		Dimentionless
PlantResp_changing_rate	1		Dimensionless
plants_init	560		Dimentionless
scenario_switch	0		Dimentionless
Sedimentation_color	IF sedimentation=0THEN 0 ELSE 1		Dimentionless
soil_init	1500		GT
"soil-resp_color"	IF soilResp= 0 THEN 0 ELSE 1		Dimentionless
SoilResp_change	1		Dimensionless
Sum_ID_numbers	ID_number_1+ID_number_2		Dimentionless
surface_concentration_factor	12000		
surface_ocean_init	890		GT
SurfCConc	((Surface_Ocean/surface_concentration_factor)/SurfOcVol)		
SurfOcVol	0.0362*0 +0.0235		
switch_1	0		Dimentionless
switch_2	0		Dimentionless

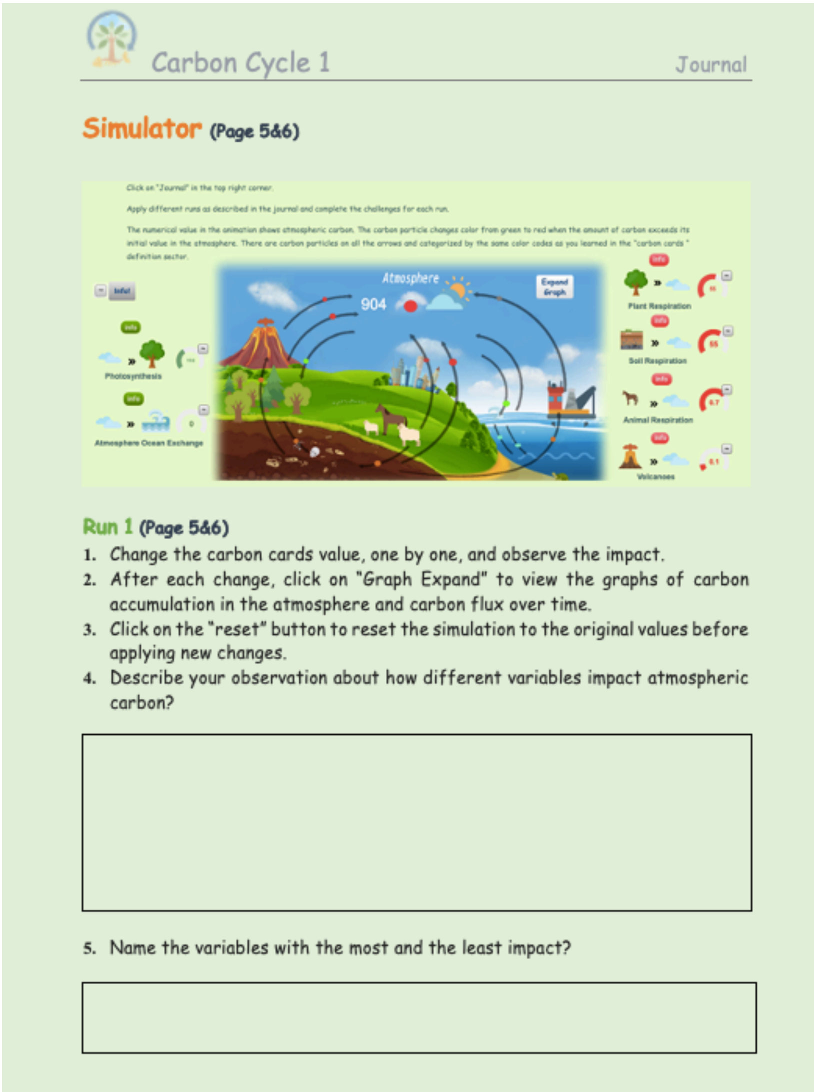
TempEffect	((60-GlobalTemp)*(GlobalTemp+15))/(((60+15)/2)^(2))/0.96		Dimentionless
tree_color	IF farming_impact_0 = 0 THEN 0 ELSE 1		Dimentionless
tree_rotate	IF deforestation < 10 THEN 0 ELSE -90		Dimentionless
tree_size	IF deforestation < 9.5 THEN 1 ELSE 0		Dimentionless
"tree-scale"	GRAPH (change_in_photosynthesis_rate) Points: (0.000, 0.500), (0.200, 0.563), (0.400, 0.672), (0.600, 0.789), (0.800, 0.914), (1.000, 1.008), (1.200, 1.102), (1.400, 1.250), (1.600, 1.406), (1.800, 1.727), (2.000, 2.000)		Dimentionless
upwelling_change_color	IF upwelling=0THEN 0 ELSE 1		Dimentionless
volcano_color_change	IF Volcanoes= 0 THEN 0 ELSE 1		Dimentionless
"volcano-scale"	GRAPH(Volcanoes_rate) Points: (0.000, 0.500), (0.100, 0.59181053684), (0.200, 0.693276872129), (0.300, 0.805414515053), (0.400, 0.929345776835), (0.500, 1.0663110032), (0.600, 1.21768098816), (0.700, 1.38497069341), (0.800, 1.56985441055), (0.900, 1.77418251795), (1.000, 2.000)		Dimentionless
Volcanoes_rate	0.1		GT/Year
water_temp	273+GlobalTemp		C
Your_carbon_prediction_in_atmosphere_1	GRAPH(TIME) Points: (0.00, 750), (16.6666666667, 750), (33.3333333333, 750), (50.00, 750)		GT
Your_carbon_prediction_in_atmosphere_2	GRAPH(TIME) Points: (0.00, 750), (16.6666666667, 750), (33.3333333333, 750), (50.00, 750)		GT
Your_carbon_prediction_in_atmosphere_3	GRAPH(TIME) Points: (0.00, 750), (16.6666666667, 750), (33.3333333333, 750), (50.00, 750)		GT

Table 1A. Model documentation

Appendix B

Journals

Few illustrations of games and journals setup are available under this section.



Carbon Cycle 1 Journal

Simulator (Page 5&6)

Click on "Journal" in the top right corner.

Apply different runs as described in the journal and complete the challenges for each run.

The numerical value in the animation shows atmospheric carbon. The carbon particle changes color from green to red when the amount of carbon exceeds its initial value in the atmosphere. There are carbon particles on all the arrows and categorized by the same color codes as you learned in the "carbon cards" definition sector.

Run 1 (Page 5&6)

1. Change the carbon cards value, one by one, and observe the impact.
2. After each change, click on "Graph Expand" to view the graphs of carbon accumulation in the atmosphere and carbon flux over time.
3. Click on the "reset" button to reset the simulation to the original values before applying new changes.
4. Describe your observation about how different variables impact atmospheric carbon?

5. Name the variables with the most and the least impact?

Figure 1B. Journal 1, page set up illustration

After students being introduced to the climate feedback concept through the step change in photosynthesis carbon flow, they have been asked about the impact of photosynthesis step change on the atmospheric carbon and to predict the level of carbon in atmosphere in case of running the simulation over longer time. The questions are shown in figure 2B.

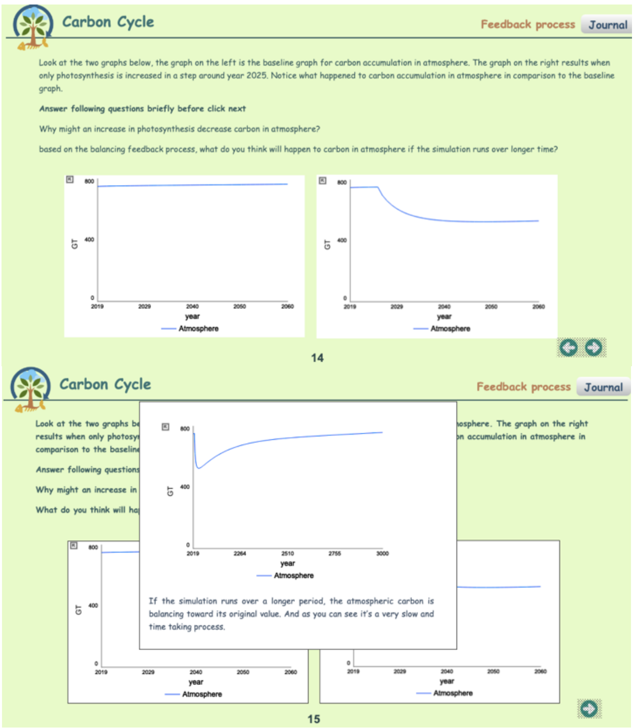


Figure 2B. Feedback loop concept and running over longer time

The homework tasks details and answer boxes are captured in figure 3B. This task is aiming to challenge students to include all their learning achievements during the session by creating a fun fiction scenario.

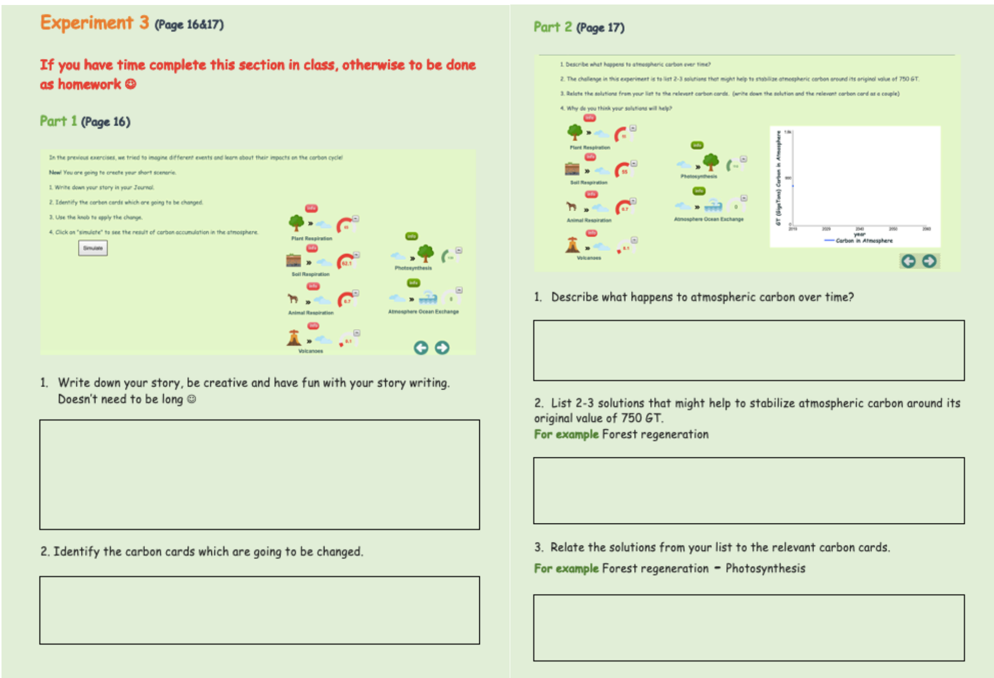


Figure 3B. Task detail under homework section game 1

Figure 4B illustrates the scenario and students' roles for the decision-making experiments.

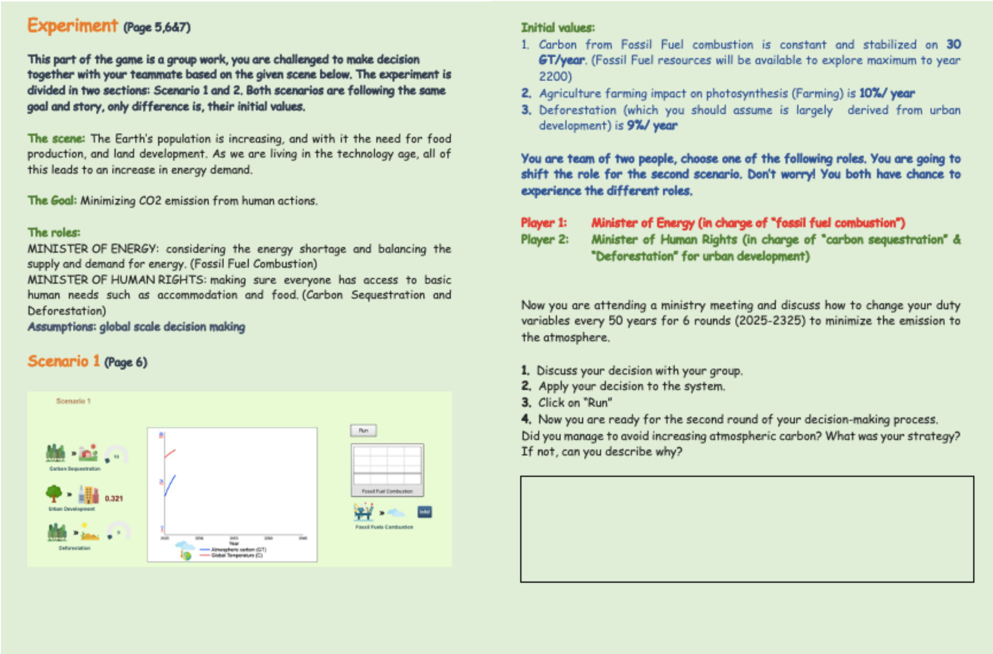


Figure 4B. Journal 2, decision-making tasks

Examples of day-to-day life and generic concept of feedback loop demonstration are shown in figure 5B.

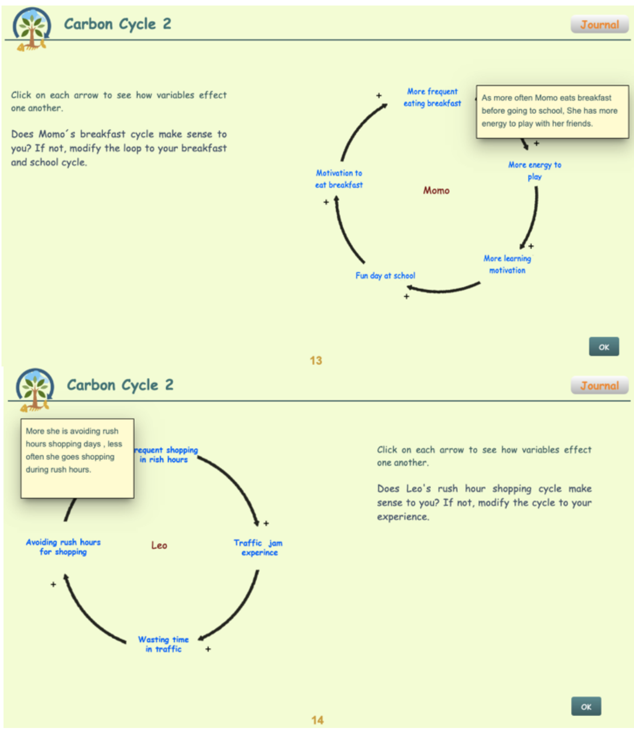


Figure 5B. Game 2, generic concept of feedback loop in the day-to-day life

Appendix C

Data analyzing and statistics results

Nonparametric statistic (Wilcoxon, Mann-Whitney)

Summary of comparison of two sample nonparametric statistic (Wilcoxon, Mann-Whitney):

Variable	Observations	Minimum	Maximum	Mean	Std. deviation
Pre-test	23	0	80%	26.087	20.83
Journal 1	23	40%	100%	76.087	15.59

Table 1C. Summary of comparison of two sample nonparametric statistic (Wilcoxon, Mann-Whitney)

N+	0
Expected value	10.5
Variance (N+)	5.250
p-value (Two-tailed)	<0.0001
alpha	0.050

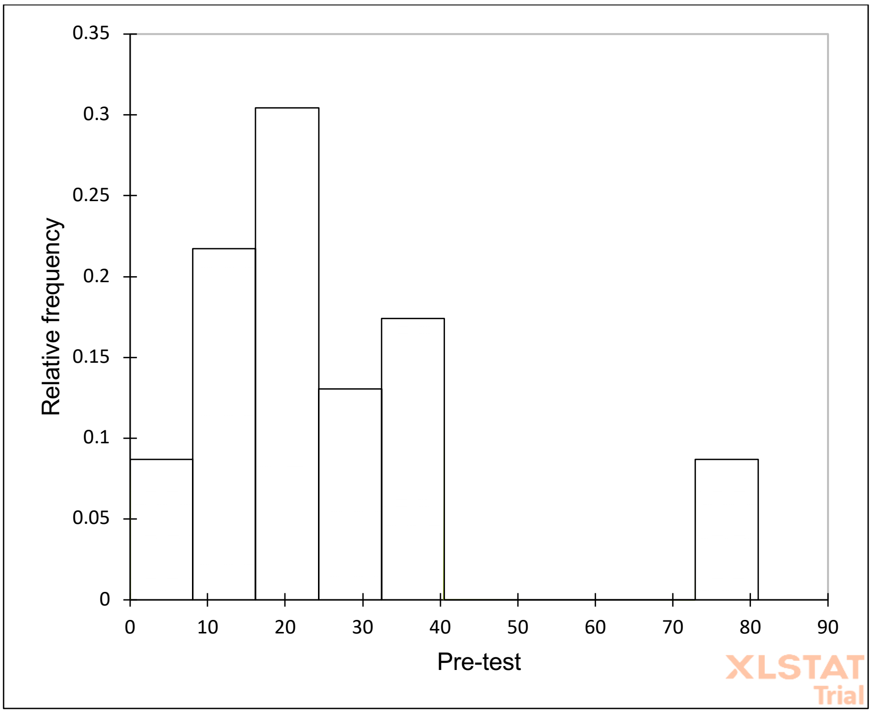
Table 2C. Sign test / Two-tailed test

V	0
V (standardized)	-4.028
Expected value	115.500
Variance (V)	822.375
p-value (Two-tailed)	<0.0001
alpha	0.050

Table 3C. Wilcoxon signed-rank test / Two-tailed test

Test interpretation:
H0: The two samples follow the same distribution.
Ha: The distributions of the two samples are different. As the computed p-value is lower than the significance level alpha=0.05, one should reject the null hypothesis H0, and accept the alternative hypothesis Ha.

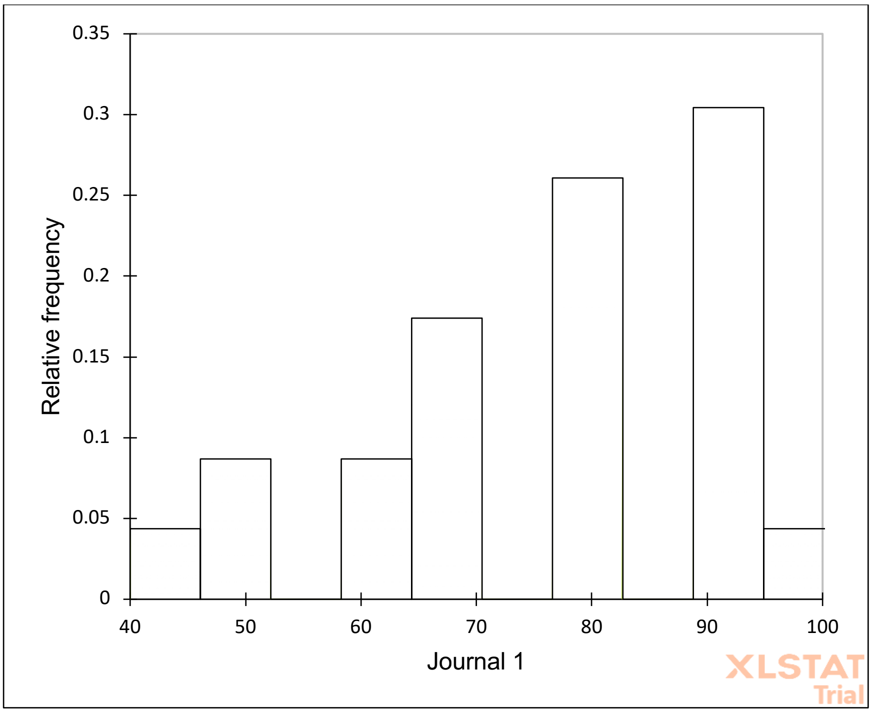
Descriptive statistic for the intervals:



Graph 1C. Pre-test Histogram

Lower bound	Upper bound	Frequency	Relative frequency	Density
0	8.1	2	0.087	0.011
8.1	16.2	5	0.217	0.027
16.2	24.3	7	0.304	0.038
24.3	32.4	3	0.130	0.016
32.4	40.5	4	0.174	0.021
40.5	48.6	0	0.000	0.000
48.6	56.7	0	0.000	0.000
56.7	64.8	0	0.000	0.000
64.8	72.9	0	0.000	0.000
72.9	81	2	0.087	0.011

Table 4C. Descriptive statistic for the pre-test sample intervals



Graph 2C. Journal 1 Histogram

Lower bound	Upper bound	Frequency	Relative frequency	Density
40	46.1	1	0.043	0.007
46.1	52.2	2	0.087	0.014
52.2	58.3	0	0.000	0.000
58.3	64.4	2	0.087	0.014
64.4	70.5	4	0.174	0.029
70.5	76.6	0	0.000	0.000
76.6	82.7	6	0.261	0.043
82.7	88.8	0	0.000	0.000
88.8	94.9	7	0.304	0.050
94.9	100	1	0.043	0.007

Table 5C. Descriptive statistic for the Journal 1 sample intervals

Correlation test detail information (Spearman correlation)

Correlation matrix

Variables	Average time	Learning
Average time	**1**	**0.913**
LD	**0.913**	**1**

Table 6C. Correlation matrix between learning difference (LD) and average time (game 1)

Variables	Average time	Learning
Average time	2.43848E-06	<0.0001
LD	<0.0001	2.43848E-06

Table 7C. P-values, LD, and average time

Variables	Average time	Learning
Average time	1	0.834
Learning	0.834	1

Table 8C. Coefficients of determination