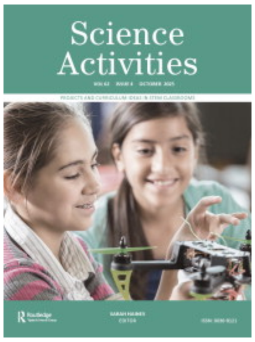

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RESEARCH ARTICLE

Using a systems thinking approach for a climate change education training program in teacher education

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ABSTRACT
One of the biggest problems threatening our present and future is the climate crisis. Since human activities are causing global climate change, it is important to educate citizens about climate change, its causes, consequences and solutions. Science teachers undoubtedly play a key role in teaching environmental issues. However, several studies have shown that there are gaps in science teachers' understanding of climate change and that more research is needed in this area. Therefore, in this study, we designed and implemented a climate change training program using a systems thinking approach to provide a structured framework for climate change education for pre-service science teachers with 123 participants. The introduction of climate change case studies and systems thinking tools used in the training helped participants recognize unintended consequences in complex climate systems and improved their ability to identify underlying patterns and systemic structures. The most significant impact of this iteratively refined environmental education program is that it encourages the use of systems thinking tools with practical applications in future environmental education professional development programs.

KEYWORDS
Climate change; climate change education; systems thinking; pedagogical content knowledge; teacher education

Introduction

You and I are living in a pivotal moment of history, what some have called a "carbon crisis"—a crucial and decisive turning point in which our thoughts and actions are of unusually great importance for the long-term future of the world.

Stager 2011, 12

Global climate change is one of the most critical threats to ecosystems, human well-being, infrastructure, and vulnerability to extreme events (Abumhadi et al. 2012). Climate change seriously affects citizens, communities, countries' economies, and ecosystems (Rojas 2016). Climate change has had dangerous impacts on many socio-ecological systems, such as higher average temperatures and sea level rise, which are expected to continue in the future (Oliver-Smith 2009). The climate crisis also leads to unsustainable behavior in countries and problems that profoundly affect societies, such as poverty and unemployment (Rojas 2016). The implications of climate change extend beyond these immediate costs, significantly impacting the global economy. Furthermore, the financial burden of climate crises considerably influences climate change mitigation and adaptation strategies (Van der Mensbrugghe and Roson 2010).

The Next Generation Science Standards (NGSS 2013) emphasize Earth and Human Activity. One of the NGSS (2013) outcomes is that "students who demonstrate understanding can ask questions to clarify evidence of the factors that have caused the rise in global temperatures over the past century" (190). Global climate change is highlighted in one of the Disciplinary Core Ideas. Human activities such as the use of fossil fuels can cause global warming. It is important to have knowledge to understand and mitigate climate change and to use it wisely (NGSS 2013). In the

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Crosscutting concepts of Earth and Human Activity, under the heading of Stability and Change, attention is drawn to the fact that stability can be disrupted by behavior over time. However, science teachers exhibited deficiencies in their understanding of climate change, as well as a lack of learning experiences (Rajeev Gowda, Fox, and Magelky 1997; Wise 2010).

The study conducted by Boon and James Cook University (2016) as part of the Service Learning for Sustainable Futures course taken by pre-service teachers as a required course revealed that although positive changes were observed in participants' attitudes toward environmental education, there was no change in their understanding of climate change. Herman, Feldman, and Vernaza-Hernandez (2017) found that science teachers have naive views about climate change and frequently overlook the social, political, and economic dimensions. Therefore, they need to understand how to teach these topics in authentic contexts to prepare future citizens for engagement with social science issues such as climate change (Herman, Feldman, and Vernaza-Hernandez 2017).

Climate change is a systems problem due to its inherent complexity and individuals' difficulty comprehending it (Sterman and Sweeney 2002). Climate change can be defined as the result of changes in the components of the climate system over time within the climate system (Roychoudhury, Shepardson, and Hirsch 2017). In climate change education, it has become increasingly important to shift from problem-focused approaches to solution-oriented, action-based strategies for addressing these complex issues (Karaarslan Semiz and Teksöz 2019; Monroe et al. 2019). Recent studies show that programs aimed at developing pre-service teachers' systems thinking skills allow them to understand sustainable development goals and think in a more solution-oriented manner (Peretz, Dori, and Dori 2023; Roos and van der Sluijs 2025). Similarly, although studies in which pre-service teachers analyze sustainable development goals using system dynamics tools show promise, there are limited studies on solution-oriented approaches (e.g. Ceyhan and Budak 2025). Current literature suggests that prominent solution-focused approaches should be more integrated into future practices. In this context, integrating systems thinking with solution-focused educational approaches is considered an effective strategy for climate and sustainability education (Green, Molloy, and Duggan 2021; Hofman-Bergholm 2018). In addition to raising awareness of climate change, it is important to encourage people to develop practical solutions that build social momentum (Rahimi 2020). Therefore, integrating solution-oriented education models that are supported by a systems thinking approach is an effective strategy for climate change education (Hofman-Bergholm 2018).

Systems thinking is a recommended approach to provide individuals with a holistic perspective on socio-scientific issues such as environmental problems and to show them the interconnectedness of environmental system problems without isolating them (Delaney, Ferguson, and Schultz 2021). Systems thinking is defined as the ability of individuals to envision the world as a multitude of intricate, interrelated, and ever-evolving systems, as opposed to perceiving static expressions within these intricate systems (Sterman 2000). Systems thinking is recognized as a prerequisite for successfully managing complex problems, such as climate change, which require urgent and significant action (Sweeney and Sterman 2007). Systems thinking has the potential to help people understand the reality of climate change in various contexts, including local, national, and global levels, as well as across different domains, such as the environment, society, and economics (Bianchi, Pisiotis, and Cabrera 2022). Therefore, systems thinking is an important tool for achieving a sustainable future (Molderez and Fonseca 2018).

The application of systems thinking is becoming increasingly prevalent in managing complex and dynamic problems related to sustainability (Eaton, Delaney, and Schultz 2019). While some governments tend to adopt a wait-and-see policy (i.e., the policy of inaction), many are intent on actively developing policies to mitigate climate change. These policies vary across countries and regions. However, wait-and-see policies ignore multiple feedbacks, time lags, nonlinearities, and accumulations inherent to complex systems (Sterman 1994; Sterman and Sweeney 2002). These policies lead to more significant issues within the broader climate system. Without a comprehensive understanding of the interconnections within the climate system, it becomes challenging to fully comprehend the multifaceted implications of climate change at both local and global scales (Sterman and Sweeney 2002).

Given the pivotal role of educators in disseminating scientific knowledge, they have a significant role and responsibility for fostering awareness about climate change and empowering individuals to take action to address it (Rajeev Gowda, Fox, and Magelky 1997). The literature suggests that when climate change education is approached from a didactic perspective, it does not lead to major changes in attitudes and behavior. For this reason, the importance of a creative, holistic and interdisciplinary approach to climate change education has been emphasized (Rousell and Cutter-Mackenzie-Knowles 2020). Thus, systems thinking is proposed, which provides a holistic perspective by considering climate change as a system (Shepardson et al. 2014; Sterman and Sweeney 2002) In a study, following the completion of the three-course programme designed to develop systems thinking in pre-service biology and geography teachers, it was found that the pre-service teachers' systems thinking ability had improved (Fanta et al. 2020). Thus, the importance of integrating systems thinking into the teacher education curriculum at universities was emphasized in order to increase awareness and critical thinking about a sustainable and livable future (Fanta et al. 2020).

This study aims to design and implement a climate change education training program that employs a systems thinking approach to provide a structured framework for climate education for pre-service teachers who will educate future citizens. This climate change education training program is a product of an effort to develop a program that emphasizes different aspects of climate change for junior and senior pre-service science teachers. This climate education program was implemented in two universities in Turkey by the two authors of this study, who gained various insights into the implementation of this program. Our aim and effort in this study is to iteratively improve the climate change education training program designed with a systems thinking approach in Turkey, based on the feedback received, and to implement it throughout the country.

Design of the climate education program using a systems thinking approach

System dynamics tools

Systems dynamics tools consist of a behavior over time graph, a causal loop diagram, the iceberg model, and a stock flow diagram. A behavior over time graph with time on the horizontal axis and a range of the variable values indicated on the vertical axis captures the dynamics of a significant systems variable (Fisher and Systems Thinking Association 2023). Causal loop diagram identifies the components of the system that generate dynamic behavior. It links variables without differentiating between rates (flows) and levels (stocks) (Forrester 1994). By looking at a problem or event from several angles, the iceberg model helps address its root causes. The mental model, systems structure, pattern and event are among the levels (Senge 1994). A stock flow diagram illustrates how the amount within a stock varies over time based on the rates of inflows and outflows (Sweeney and Sterman 2000). It is crucial for system dynamics modeling and is frequently created with a causal loop diagram (Monat and Gannon 2015).

Implementation of the climate education program using a systems thinking approach

Table 1 shows the theme of each session of the climate education program using the systems thinking pedagogy and the topics covered in the sessions. As seen in Table 1, the first session introduced systems thinking and systems thinking tools; the second session focused on interpreting various graphs and models to understand the SDGs, population, and climate; the third session focused on interpreting and modeling consumption, wealth, and emissions graphs; and the final session focused on climate change impacts using systems thinking tools. Our goal in this program is to equip participants to effectively use systems thinking tools to examine population, economy, wealth, and emissions in the context of the environment. Each session lasts 2 h.

The program was developed collaboratively by the study's authors, who specialize in systems thinking and systems dynamics. This program has been designed with the recently introduced Turkish middle school science curriculum introduced by the Turkish Ministry of National Education (MoNE 2024) in consideration. The reason for this is the need for pre-service science teachers to demonstrate a comprehensive understanding of environmental issues across all grade levels, considering their potential to teach at all middle school levels in their future professional roles. Table 2 shows the science learning outcomes related to environmental education at each grade level in the Turkish middle school science curriculum, which serves as the basis of this study. As shown in Table 2, the Turkish middle school science curriculum significantly emphasizes environmental issues at each grade level.

The following section lists the learning outcomes for each session in this climate change education training program.

Table 1. Session themes and topics introduced in each session.

Sessions	Topics
Session 1: Introduction to Systems Thinking Approach	Introductions and warm-up activity Introduction to systems thinking approach Habits of a system thinker and climate change Systems thinking tools
Session 2: Sustainable Development Goals (SDGs), Population and Climate	SDGs and climate change Population game Interpreting the population simulation model Small group sharing and whole class discussion
Session 3: Economy, Wealth and Climate	Interpreting consumption model Interpreting wealth model Interpreting the emission model Group work: Comparing consumption, wealth, and emissions of various countries Small group sharing and whole class discussion
Session 4: Carbon Cycle and Climate	Triangles game Interpreting key carbon stocks and flows model Bathtub and climate model Case study: Analyzing climate change impacts with systems thinking tools Small group sharing and whole class discussion

Detailed structure of the training program across sessions

This climate change education program is planned to be implemented in one province from each of the seven regions of Turkey (Mediterranean Region, Aegean Region, Eastern Anatolia Region, Southeastern Anatolia Region, Central Anatolia Region, Black Sea Region, Marmara Region). After the pilot implementation in each province, the education program will be implemented in one university in each country region. So far, this climate change education training program has been implemented in the Southeastern Anatolia Region and the Black Sea Region with 123 junior and senior pre-service science teachers. These regions have different geographical, socioeconomic, and educational contexts. The Southeastern Anatolia Region has a

Table 2. Science learning objectives related to environmental education at each grade level in the Turkish middle school science curriculum (MoNE 2024).

Middle school grade level	Unit title	Learning objectives
5	Sustainable Living and Recycling	FB.5.7.1.1. Classify recyclable and non-recyclable materials in household waste. FB.5.7.1.2. Make scientific conclusions about the importance of recycling in the efficient use of resources. FB.5.7.1.3. Reflect on one's experience of the applicability of waste management to one's immediate environment.
6	Sustainable Living and Interaction	FB.6.7.1.1. Question the importance of biodiversity for natural life. FB.6.7.1.2. Predict factors that threaten biodiversity based on research data. FB.6.7.2.1. Discuss the impact of fuel use for heating on humans and the environment. FB.6.7.2.2. Propose a solution to an environmental problem in his/her immediate environment or in our country.
7	Sustainable Living and Energy	FB.7.7.1.1. Structure the relationships between living things in the food chain. FB.7.7.2.1. Question the importance of conserving resources.
8	Seasons and Climate	FB.8.1.1.1. Make scientific inferences about the motion of the Earth around the Sun and the results of axis tilt. FB.8.1.2.1. Compare climate and weather events
8	Sustainable Living and Material Cycles	FB.8.7.2.1. Make scientific deductions from the diagram of cycles of matter. FB.8.7.2.2. Construct the meaning of the cycles of matter in relation to life. FB.8.7.2.3. Discuss the causes and possible consequences of global climate change. FB.8.7.2.4. Propose a solution to a problem caused by global climate change in our country.

predominantly rural population, and the Black Sea Region has environmental characteristics related to climate-related debates. The training program was implemented in two classes of approximately 60 people each in both regions. Throughout the program, participants worked in small groups of four to five people in collaborative activities based on systems thinking. This group structure enabled participants to analyze complex problems together and develop a systemic perspective. The next section provides details on the implementation.

The education program was conducted by two authors experienced in systems thinking in science education and environmental education. They carry out studies on climate and sustainability education and provide teacher training.

Session 1: Introduction to systems thinking approach (2 h)

The first session aimed to introduce participants to the systems thinking approach, analyze and interpret the habits of a systems thinker, and articulate the relationship between systems thinkers' habits and climate change. The session starts with an introduction to the program and a warm-up activity. After all the students introduced themselves, a BINGO game, adapted by the authors of this study to the environmental context, was played as a warm-up activity, as shown in Figure 1.

Instructions for playing BINGO:

- Move around the classroom to find people who fit into the categories.
- You should find a new person for each category.
- The first player to answer the questions shouts BINGO!

After the warm-up activity, the session began with a presentation introducing the systems thinking approach. It discussed what a system can be and the differences between simple and complex and static, and dynamic systems. The interactive presentation also highlighted systems thinking as one of the 21st-century skills. Then, the participants gained insight into how systems literacy is positioned in the international educational policy documents and Turkey's science education curriculum. The interrelationship between systems literacy and science education was also discussed. Thus, the participants gained an insight into the importance of systems thinking in science education.

Since the systems thinking approach was new to the participants, the real story of the Great Sparrow Massacre led by Chairman Mao Zedong (Steinfeld 2018) was presented to illustrate the importance of systems thinking. This story tells of a tragic event that took place in China. Mao had launched a massive sparrow slaughter campaign, encouraging the killing of sparrows throughout the country to increase agricultural production. As a result of the campaign, the drastic reduction in the sparrow population led to a significant increase in the locust population. This had many unintended consequences, including the death of many people from starvation. The message of this story is that when politicians implement a systems problem without thinking holistically, it can lead to unintended consequences that are worse than the intended consequences (Steinfeld 2018). The participants discussed this narrative and underscored

Do not use plastic bags.	Uses a reusable water bottle.	Disposes of waste separately.	Follows climate news.
Can name three different climate risks for the province they live in.	Second-hand shopping.	Follows a climate-related social media account.	Name one of the effects of the climate crisis.

Figure 1. Playing cards for BINGO.

the importance of contemplating a system's myriad subsystems and their intricate interrelationships.

Based on this story, the session emphasized that individuals should develop systems thinking habits to analyze and make informed decisions about complex systems. The habits of a systems thinker are habits that help to develop solutions to solve systems problems in complex and dynamic situations and to question the potential consequences and impacts of these solutions over time. The Habits of Systems Thinker cards were taken from the Water Center for Systems Thinking (https://thinkingtoolsstudio.waterscenterst.org/cards) and given to the participants. Participants were asked to examine the Habits of a Systems Thinker cards and identify two systems thinking habits they would like to develop. A YouTube video titled "How wolves changed rivers" (https://www.youtube.com/watch?v=7GwdCtSGInc) (The European Nature Trust 2014) was shown to help participants see natural systems and think about them in the context of ecosystems. Participants were then given the iceberg worksheet in Figure 2. This worksheet is designed to help individuals see the events on the visible side of the iceberg and the patterns and system structures on the invisible side of the iceberg in the context of the ecosystem.

In the last phase of this session, participants were informed about how to use the systems thinking tools, namely behavior over time, stock-flow diagram, and causal loop diagram, and then presented each of them to the participants with examples from the climate context.

Session 2: SDGs, population, and climate (2 h)

The second session has two goals. The first is to explain and link the Sustainable Development Goals (SDGs) to climate. The second is to analyze and interpret the population graph and simulation model. The session started with the tragedy of the commons. The tragedy of the commons is when individuals try to maximize their benefits and interests in resources that all stakeholders have limited rights to use (Ostrom 2008). The story about the tragedy of the commons was shared with participants (Figure 3). Participants were then asked: "*What kind of problem can occur here?*"

After this engagement activity, the social, environmental, and economic dimensions of

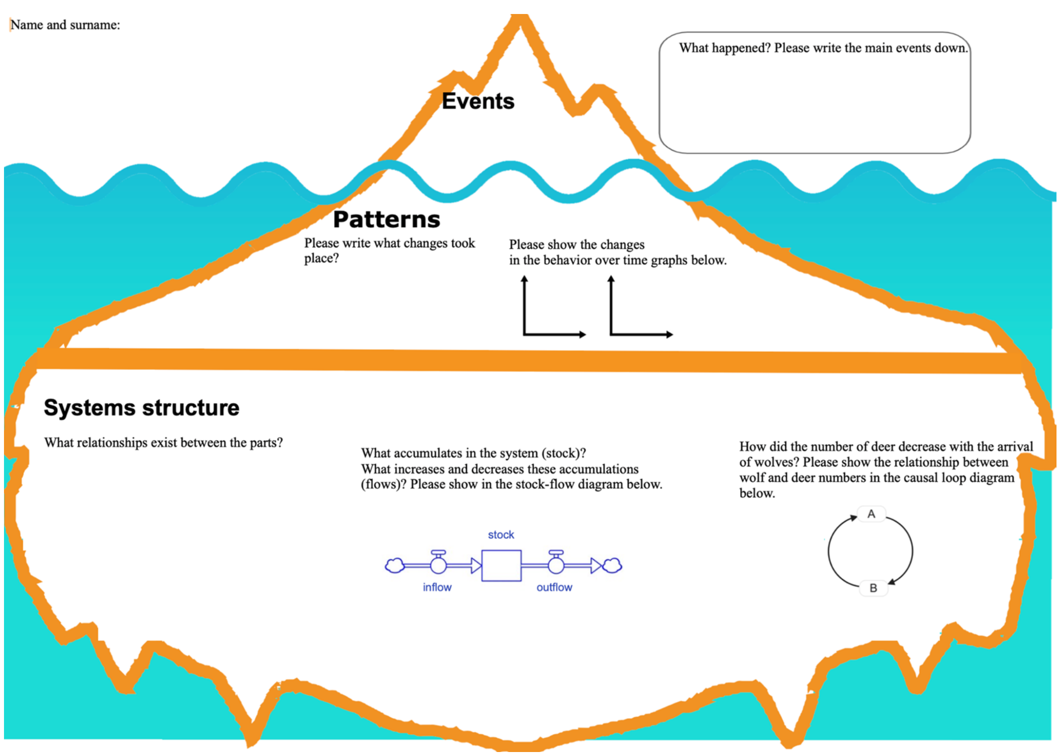

Figure 2. The iceberg worksheet used for "how wolves changed river".

The tragedy of the commons

Imagine a village where the only source of livelihood is animal husbandry, and a common pasture belongs to the village. All the shepherds living in the village aim to sell their sheep(s) when the time comes and to use the money they earn to meet their needs. The only way to sell the sheep easily and for the desired price is to have well-fed animals. For this, the animals need to graze a lot. The pasture is one and belongs to everyone. Everyone must respect each other's rights and graze their animals as much as necessary. Even if all but one shepherd obeys the rule, all their good intentions will be in vain.

Figure 3. The story of the tragedy of the commons presented to participants.

Parachuting Cats in Borneo

In the early 1950s, there was an outbreak of a very serious disease called malaria among the Dayak people of Borneo. The World Health Organization tried to solve the problem. They sprayed large amounts of a chemical called DDT to kill the mosquitoes that carry the malaria germ. The mosquitoes died, and malaria declined. That was good.

However, there were some unexpected effects. One of the first effects was that roofs collapsed on people's heads. It turned out that DDT was killing the wasps that were killing the caterpillars that were eating the thatch that the roofs were made of. Without the wasps to kill them, the reed-eating caterpillars proliferated.

Worse, the insects that died from DDT poisoning were eaten by small lizards (geckos), and cats ate the small lizards. Cats began to die. Mice multiplied. And humans faced two new rat-borne epidemic threats: plague and typhus. To deal with these homegrown problems, the World Health Organization parachuted live cats into Borneo.

Figure 4. The story of the parachuting cats in Borneo presented to participants.

sustainability and the 17 SDGs were introduced. To introduce the connection circle, one of the systems thinking tools that shows the relationships between the elements of a story, Cats Parachuting to Borneo (Klimek and AtKisson 2016), was presented to the participants. The story is shown in Figure 4. The purpose of presenting this story was to enable individuals to identify the variables in a system problem, to relate them to each other, to recognize the hidden dimension between different systems, and to see that one system problem can lead to other large and complicated system problems as a result of policies that did not examine systems only limited cause and effect. In hindsight, these policies led to larger, more complex, system-level problems. Participants were then asked: "*What are the elements in the story that change over time? Are these elements related to each other? If so, how are they related? How would you evaluate the policies implemented in the story?*". The participants then discussed this real story.

The SDGs and Climate Connection Circle worksheet in Figure 5 was distributed to participants, and they were asked to complete the worksheet collaboratively as a group.

The purpose of the first part of this worksheet is to help participants think critically and in detail about the impact of their chosen SDG on climate change and the impact of climate change on their chosen SDG. The purpose of the second part of the worksheet is to have participants show the explanations they wrote in the first part on the connection circle, since the participants had not seen the connection circle before, an expected connection circle was shown as an example on the right side of the page.

For the activity in Figure 5, a group of students chose SDG 14: Life below water. For the first question, they listed the effects of climate change on SDG 14 as dying animals, melting glaciers, and death of some creatures due to global warming, changing water temperatures, and changes in water pH due to acid rain. For the

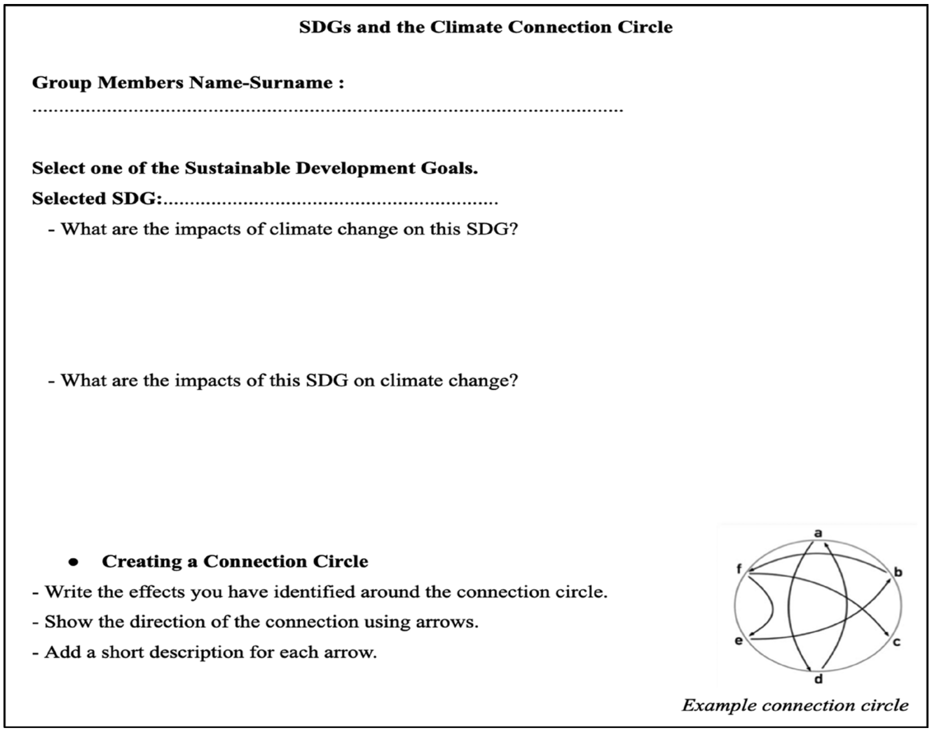

Figure 5. SDGs and the climate connection circle worksheet.

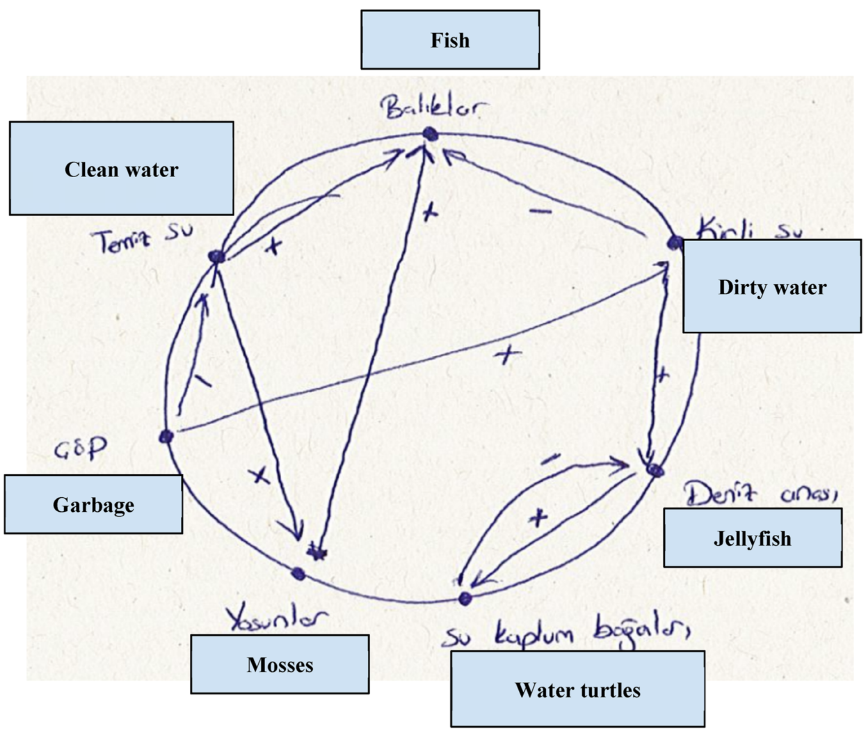

Figure 6. Connection circle drawn by a group showing the impact of SDG 14: Life below water and climate change on each other.

second question, they listed the effects of SDG 14 on climate change as an improvement of animal diversity through the increase of clean water resources and new habitats. Figure 6 shows an example of a group's connection circles.

After the small group activity, models of the Earth system on material cycles, energy flows, webs of life, and climate system components were presented. Before moving on to the population topic in this session, a population game was played to engage the participants and make a smooth transition. This game requires only dice. The game's goal is to develop strategies to keep an animal alive. Participants adopt different axioms, considering different elements (e.g. resource management and balance in the system) and the long-term effects of their decisions. Participants were shown population modeling in stock-flow diagrams, and the discussion was based on the following question: "What are the variables that cause the population in a region to increase/decrease?" The session had two activities for the whole class discussion. First, participants were asked to analyze the populations of different countries by year and actual population using the STELLA (Systems Thinking Experimental Learning Laboratory with Animation) program and share their findings with the whole class. The STELLA program is a computer simulation that allows modeling in the field of system dynamics. The models created in STELLA visualize the elements of the system and their interrelationships (Dyson and Chang 2005).

Link for the activity: https://exchange.iseesystems.com/public/sdd/population-gdp-and-emission-by-country/index.html#page1 (Systems Thinking Association in Turkey 2024).

Participants were asked to use the STELLA program to select Turkey, the US, and China, change the variables, analyze these countries' population and migration graphs, and share their findings with the whole class.

Link for the activity: https://exchange.iseesystems.com/public/sdd/population-gdp-and-emission-by-country/index.html#page2 (Systems Thinking Association in Turkey 2024).

Session 3: Economy, wealth and climate (2 h)

This session aims to analyze and interpret the consumption, wealth, and emissions graphs and develop and use system models. First, the researchers defined consumption through presentations and explained the logic of the transition from a linear to a circular economy. As a whole-class activity, the participants presented the population, consumption, and wealth of some countries by providing empirical data through tables and were asked the following questions:

1. Is the average wealth of individuals living in countries with similar consumption levels the same for both countries?
2. Comparing two countries of the same economic size, which country has more wealth for the average individual?
3. Does the country with the larger population or the country with the smaller population have more wealth?
4. If the average wealth of an individual is the same for both countries, do they have the same economic size?

In another stage of the session, an activity was conducted in which the participants in groups were asked to interpret the consumption, wealth, and emissions graphs of the countries they had selected. First, the groups were given the consumption models of the countries prepared using the STELLA program.

Link for the activity: https://exchange.iseesystems.com/public/sdd/population-gdp-and-emission-by-country/index.html#page3 (Systems Thinking Association in Turkey 2024).

The groups were given the following instruction: "Compare the economic size (consumption) of the two countries you chose in the model and write a conclusion sentence." As a second activity, the groups were given the wealth models of the countries prepared on the STELLA program.

Link for the activity: https://exchange.iseesystems.com/public/sdd/population-gdp-and-emission-by-country/index.html#page4 (Systems Thinking Association in Turkey 2024).

The groups were then given the following instruction: "Choose a country with increasing wealth and decreasing emissions in the model. Research and list the reasons for this difference." The groups carried out these activities in a collaborative way by discussing. They then shared their findings with the whole class and had a whole-class discussion.

Session 4: Carbon cycle and climate (2 h)

The second session has two goals. The first is to explain key carbon stocks and flows and the relationship between the bathtub model and climate.

The second is to analyze climate change impacts with systems thinking tools. The session started with the triangles game (Sweeney and Meadows 2010, 205). The purpose of playing this game is to allow participants to experience feedback loops, bounded rationality, and interdependencies in a system. This session consists of three phases: basic carbon stocks and flows, bathtub and climate, and analyzing a case study. First, for the basic carbon stocks and flows, a carbon cycle activity was conducted with the whole class.

Link for the activity: https://exchange.iseesystems.com/public/sdd/carbon-cycle-for-middle-school/index.html#page1 (Systems Thinking Association in Turkey 2024).

The carbon stocks activity was presented on the STELLA website on the smart board. There are five buttons on the website to describe the activity. First, the class collectively interpreted the behavior of the amount of carbon in the atmosphere over time in the problem button and then interpreted the variables that make up the carbon stocks in the carbon stocks button. The participants were then given time to examine the stocks and flows in the system and find the numerical values that should appear in the question marks in the stock and flow variables, and they discussed their findings. Finally, participants could analyze the amount of carbon in the atmosphere and the stocks and flows before and after the Industrial Revolution.

Second, carbon bathtub activity was conducted with the whole class for the bathtub and climate. In this activity, the relationships between stocks and flows were emphasized and then the given variables were placed in the context of global warming.

Link for the activity: https://exchange.iseesystems.com/public/sdd/bathtub-and-climate/index.html#page1 (Systems Thinking Association in Turkey 2024).

The activity was projected on the STELLA website on the smart board. The following information was explained through the model:

- A factor that increases flow increases stock.
- A factor that decreases flow decreases stock.
- The factor that increases the flow decreases the stock.
- The factor that decreases the flow decreases the stock reduction, i.e. it increases the stock.

Then, the questions tab was opened, and the participants were presented with the global warming stock-flow model. In the model, there are question marks next to various variables, and the participants responded to the following question: "*Which of these variables do you think can be stock and flow, and where should they be placed in the model?*" Participants discussed this question with their friends and then shared their thoughts with their classmates. In the last stage of this activity, the participants were asked to predict the emissions graph, the carbon dioxide in the atmosphere graph, the warming graph, the heat in the world graph, and the heat flow graphs according to the global warming stock flow chart. After predicting these graphs individually, the participants shared their answers with the whole class, and discussions were held. The Intergovernmental Panel on Climate Change (IPCC) and the Conference of the Parties (COP) were mentioned to emphasize the international effort to address the climate crisis.

In the last phase of this session, the Lake Urmia Vignette, developed by Davis et al. (2020) and inspired by a real case study, was used. The purpose of giving this vignette to participants was to measure the extent to which they understand the complexity of a socio-environmental system at the end of a climate change program using a systems thinking pedagogical approach.

The authors of this study, who are experts in systems thinking in science education, adapted the Lake Urmia vignette (Davis et al. 2020) into Turkish, the native language of the participants. In addition, an expert in Turkish language and literature also made various changes to the vignette to ensure its validity. Then, the vignette and the original questions in the vignette were presented. The following questions were asked:

1. *What do you think 'went wrong' in Lake Urmia? Based on the provided text, and your own thoughts, provides a short explanation on why Urmia is suffering from its problems.*

2. *Given the problem, what should be done to protect the environment and ecosystem of Lake Urmia? (Davis et al., 2020, 200).*

Results and discussion

Our implementation of the climate change education training program across two regions in Turkey with 123 pre-service science teachers has yielded several significant insights and outcomes. Introducing systems thinking tools through purposefully selected case studies proved effective in developing participants' holistic understanding of environmental systems. The Great Sparrow Massacre case study resonated with participants, helping them recognize unintended consequences in complex systems. The iceberg model activity through the wolves and river video revealed that while participants initially focused on visible events, they progressively developed the ability to identify underlying patterns and systems structures. This was particularly evident in their analysis of climate change patterns, where they moved beyond surface-level observations to explore deeper structural causes and relationships.

The STELLA program activities enabled participants to visualize and analyze complex relationships between population, economy, and climate. Pre-service teachers showed marked improvement in identifying relationships between population growth and emissions, analyzing connections between economic development and environmental impact, and understanding patterns in wealth-emissions relationships across countries.

The SDGs and Climate Connection Circle activity revealed initial challenges in identifying bidirectional relationships between climate change and sustainable development goals. However, most groups demonstrated a sophisticated understanding of these interconnections, particularly in analyzing consumption patterns and emissions across different countries. We found that incorporating more local climate change examples could enhance participant engagement and understanding of these relationships.

The Lake Urmia vignette provided evidence of participants' ability to apply systems thinking to real-world environmental challenges. Pre-service teachers identified multiple causal factors and recognized time delays in socio-environmental systems. However, some participants continued to propose linear solutions to complex problems, suggesting the need for additional emphasis on feedback thinking in future iterations.

The program demonstrates significant potential for enhancing climate change education through systems thinking approaches, particularly in developing pre-service teachers' ability to understand and communicate complex environmental relationships. Future implementations will strengthen the connection between systems thinking tools and practical classroom applications through increased use of locally relevant examples.

While the program presented in this study is solid, the study has a significant limitation. The main purpose of this study is to present the activity developed for pre-service teachers in detail and demonstrate its feasibility. Therefore, we provide an overview of the activity and share our observations as authors. Therefore, the quantitative and qualitative analyses in this study were limited. We acknowledge this limitation and suggest that future research provide more comprehensive qualitative and quantitative data analyses to gain a deeper understanding of the program's impact on pre-service teachers' practice. Overall, this study demonstrates the program's feasibility, and examining its detailed impacts will provide a solid foundation for future work.

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