International Journal of Science and Mathematics Education
https://doi.org/10.1007/s10763-023-10431-5

Challenging Greek Primary Students' Knowledge of Ocean Acidification Using the Carbon Cycle Context

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Received: 29 April 2023 / Accepted: 26 October 2023

Abstract

The purpose of the present study was to investigate the impact of an intervention on primary school students' construction of knowledge on ocean acidification and the development of their systems thinking. Eighty-five 11 to 12-year-old students from five different classes of two public primary schools in Greece participated in the 8-h intervention. The intervention included inquiry-based and knowledge-integration activities, and students worked in groups during all activities. Rich pictures, made by the groups at the beginning and the end of the intervention, were used to evaluate their progress in their knowledge concerning the carbon cycle, as well as in their systems thinking. Our findings showed that the intervention contributed to primary students' conceptual knowledge of the carbon cycle and the inclusion of ocean acidification in the carbon cycle. It also helped them improve their systems thinking, indicating that students' systems thinking at this age could be developed through formal instruction with interventions which emphasize content knowledge and use an earth systems approach. Moreover, our findings indicate that the systems thinking perspective can serve as an effective approach to help children better understand and critically engage with complex environmental issues, such as ocean acidification.

Keywords Carbon cycle · Ocean acidification · Primary students · Systems thinking · Teaching intervention

Introduction

Ocean acidification, which is caused by increased anthropogenic atmospheric carbon dioxide (CO_2), brings about pH reductions in the ocean and alterations in its fundamental chemical balances and impacts processes so fundamental that it could

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Published online: 21 November 2023

have far-reaching consequences for the ocean and the millions of people that depend on it (Doney et al., 2009). It is a global issue, commonly referred to as "the other CO_2 problem." Therefore, it is not possible to diminish CO_2-driven acidification at a local scale only by reducing regional emissions. The results of research programs on ocean acidification, nongovernmental organizations declarations, laws, and regulations guide stakeholders to take on more pro-environmental behaviors (Doney et al., 2009; Sterner, 2003).

Indeed, according to the global framework for ocean sustainability (United Nations Educational, Scientific and Cultural Organization [UNESCO], 2017), one of the future targets is to minimize and address the impacts of ocean acidification. Considering that citizens through their everyday lives contribute to the increased CO_2 emissions, they have a responsibility to make informed lifestyle choices to minimize this impact. To do so, citizens, as well as students who are regarded as future decision-makers and have a high likelihood of becoming opinion-shapers in terms of the environment, need to have a solid understanding of this complex environmental issue and hold certain attitudes that shape their behavior. However, the dearth of research concerning either the public's or students' knowledge of ocean acidification or the carbon cycle has articulated participants' low awareness (e.g. Danielson & Tanner, 2015; Hartley et al., 2011; Ocean Project, 2012; Spence, 2017; Spence et al., 2018).

Complex environmental issues, such as ocean acidification should be focused on in science curriculum (Wan & Bi, 2020). These issues require the understanding of many elements and their direct and indirect effects, and, therefore, probably demand a systems thinking perspective (Mambrey et al., 2022). Systems thinking is a higher-order way of thinking and a combination of different skills (Ben-Zvi Assaraf & Orion, 2005a, b; Senge, 1990). It concerns thinking in terms of connectedness, understanding relationships, patterns, and contexts (Streiling et al., 2021). Systems thinking has been investigated in various fields, such as ecosystems (Evagorou et al., 2009; Hokayem & Gotwals, 2016; Hokayem et al., 2015; Jin et al., 2019; Mambrey et al., 2022), climate change (Roychoudhury et al., 2017; Shepardson et al., 2014), energy transfer (Lin & Hu, 2003), and groundwater systems (Ben-Zvi Assaraf & Orion, 2005a; Pan & Liu, 2018). Additionally, various systems thinking models, with similarities and differences among them, have been created and used in interventions within the science and sustainability education context (see in Evagorou et al., 2009; Karaarslan Semiz, 2021). Among these, the structural hierarchical model by Ben-Zvi Assaraf and Orion (2005b) determines the characteristics of systems thinking in the field of earth system science, and it is one of the most commonly used systems thinking models in the literature (Karaarslan Semiz, 2021). It views the world as one system with four subsystems, namely, the geosphere, hydrosphere, atmosphere, and biosphere. Moreover, it emphasizes the study of biogeochemical cycles, including the rock cycle, the water cycle, the carbon cycle, and energy cycles, as well as the interrelations among the different subsystems in terms of transitions of matter and energy from one subsystem to another. Engaging students in systemic reasoning about environmental issues will help them develop a deeper understanding of the relationships within and between the subsystems, and how the whole system works (Meadows, 2008). Systemic reasoning will also help them understand the fundamental reasons behind the problems and how to find solutions (Meadows, 2008).

Systems thinking has been investigated mostly at the secondary school level (e.g. Ben-Zvi Assaraf & Orion, 2005a, b; Cox et al., 2018; Düsing et al., 2019; Gilissen et al., 2020; Hmelo-Silver & Pfeffer, 2004; Hmelo-Silver et al., 2007; Hmelo-Silver et al., 2014; Hmelo-Silver et al., 2015; Hogan, 2000; Jordan et al., 2013; Kali et al., 2003; Lin & Hu, 2003; Liu & Hmelo-Silver, 2009; Pan & Liu, 2018; Puttick & Raymond, 2018; Riess & Mischo, 2010; Shepardson et al., 2014; Stephens et al., 2023; Sweeney & Sterman, 2007). As for the primary school level, studies concerning systems thinking are limited and elementary school students' systems thinking is still largely unexplored, while only a few examples of interventions that target elementary school students can be found in the literature (Ben-Zvi Assaraf & Orion, 2010; Brandstädter et al., 2012; Evagorou et al., 2009; Gillmeister, 2017; Haas et al., 2020; Hogan, 2000; Hokayem & Gotwals, 2016; Hokayem et al., 2015; Mambrey et al., 2022; Peppler et al., 2018; Sommer & Lücken, 2010). These very few studies reveal that primary school students engage in systems thinking, using monocausal reasoning (e.g. Evagorou et al., 2009; Hokayem & Gotwals, 2016; Hokayem et al., 2015) and are able to identify essential components of complex systems, as well as interdependency between two components of a system (e.g. Ben-Zvi Assaraf & Orion, 2010; Sommer & Lücken, 2010). Additionally, research reveals that students show a major improvement in abilities through formal instruction at this early science education level, therefore indicating that there is great potential for learning systems thinking at the primary school level and underlining the importance of introducing activities about complex systems in the early school years (e.g. Ben-Zvi Assaraf & Orion, 2010; Evagorou et al., 2009; Mambrey et al., 2022; Peppler et al., 2018; Sommer & Lücken, 2010).

However, in elementary education, complex environmental issues usually are not taught in ways to highlight systemic reasoning (Sweeny & Sterman, 2007), and, in this context, recent studies highlight the importance to trace and evaluate the system thinking skills in science curricula (Karaarslan Semiz & Teksöz, 2023). Most science textbooks provide learning science as a set of facts to be learned rather than developing a systemic and integrated understanding of complex phenomena (Liu & Hmelo-Silver, 2009). As for ocean acidification, students should first understand the carbon cycle system and causal mechanisms for the transfer and transformation of carbon, to make connections between carbon cycling and to understand the impact of carbon dioxide accumulation in the atmosphere (Puttick & Raymond, 2018; Zangori et al., 2017), as well as in the hydrosphere. However, the extremely limited peer-reviewed research publications concerning ocean acidification teaching do not incorporate ocean acidification in the carbon cycle context (e.g. Anderson et al., 2022; Bielik et al., 2019; Fauville et al., 2011, 2021; Gorospe et al., 2013). In addition, information and teaching methods relevant to ocean acidification are offered by well-established institutions and research centers providing documentation (e.g. fact sheets, lesson plans) mainly for secondary education. However, there is no evaluation or quantitative information available on how this information was used by teachers or students and what the impact of this education initiative was (Fauville et al., 2013). Furthermore, these teaching approaches present this phenomenon disconnected from the carbon cycle. Additionally, to the best of our knowledge, there are no relevant studies concerning teaching ocean acidification to primary students, despite ocean acidification could be taught to 11–12-year-old primary students, according to Ocean Literacy Guide (National Oceanic and Atmospheric Administration [NOAA], 2013) and Scope and Sequence for Ocean Literacy (National Marine Educators Association [NMEA], 2010).

According to the Ocean Literacy Guide (NOAA, 2013), there are seven essential principles as well as 45 fundamental concepts, which all students should understand by the end of high school. The Ocean Literacy Scope and Sequence (NMEA, 2010) provides information and guidance as to what students need to comprehend in grade bands K-2, 3–5, 6–8, and 9–12, to achieve a full understanding of these concepts. These progressions show how students' thinking about the ocean may develop in more complex ways across many years of thoughtful and coherent science instruction. The Scope and Sequence (NMEA, 2010), represented in a series of conceptual flow diagrams that include cross-references, also shows how concepts about the ocean are interconnected (NMEA, 2010). Concerning carbon cycle and ocean acidification, the Ocean Literacy Framework includes these concepts and processes and gives in detail how they are incorporated into ocean literacy, as well as the progressive way they should be taught throughout the grades.

Taking into account that (a) ocean acidification is a complex environmental issue and part of the carbon cycle, (b) systems thinking could probably be used as a teaching approach to help students understand complex environmental issues, and (c) systems thinking research is very limited and an ongoing issue at the primary school level, the purpose of the present study is to investigate the impact of a teaching intervention, based on the carbon cycle, on elementary school students' construction of knowledge on ocean acidification and development of their systems thinking. The following research questions were developed:

1. Are there signs of students' systems thinking in relation to the carbon cycle before and after the intervention?
2. What are the gains in primary students' knowledge on ocean acidification in the context of the carbon cycle?

Overall, this research will add important information to the limited existing literature on whether the introduction of earth systems in the early school years can help students enhance their systems thinking and understand crucial environmental problems, such as ocean acidification, as well as human impact on them. This is the first crucial step to help them realize how important everyday individual action is for the mitigation of such environmental problems.

Methodology

Sample

The study was conducted during the school year 2018 with a convenient sample of 85 students at the age of 11 to 12 years (6th grade) from five classes in two public primary schools located in a coastal provincial town, in Greece. The 6th grade is the last grade of Greek primary education. Both schools have a population of approximately 300 students and are considered regular ones representing the vast majority of Greek primary schools in relation to both students and teachers. Each class consisted of about 18–20 students from various socioeconomic backgrounds, 90% of them with Greek citizenship, while the cognitive characteristic of the sample was typical, with no special cognitive or behavioral difficulties. If a pupil is diagnosed with a special need or learning difficulty, then a special education teacher supports the young learner in the class (Karampelas, 2019). Female students constituted 52.9% of the sample.

Description of the Intervention

The authors developed a teaching intervention for the age group of the present study taking into account (a) the Ocean Literacy Guide (NOAA, 2013), especially the fundamental concepts which concern the domination of the ocean on the carbon cycle and the balance of pH (principle 1, concept e; principle 2, concept d; principle 3, concepts a, e, f); (b) the Ocean Literacy Scope and Sequence for the corresponding age (grade band 6–8) (NMEA, 2010), according to which sixth graders should accomplish to understand the role of the ocean in the carbon cycle, as well as the effects of the increased CO_2 on the pH of the seawater; (c) the educational resources from universities and institutions around the world related to ocean acidification (see Fauville et al., 2013); and (d) other sources concerning both the carbon cycle and the ocean acidification (e.g. Castro & Huber, 2012; Matracia & Zillmer, 2012).

The intervention was implemented by one of the authors, who worked as a primary mainstream teacher for 15 years. In Greece, the elementary school is inclusive of children between the ages of 6 and 12 years old. It is completed in six different grades, 1–6. Mainstream elementary school teachers teach the majority of subjects, i.e. Greek Language, Mathematics, History, Science, Geography, Environmental Study, Politics-Social Studies, and Religion, while specialized teachers teach subjects such as English, French, German, Arts, Music, Drama, Physical Education, and Information and Communication Technologies (Karampelas, 2019). The teachers of the classes of the present study were not involved during the intervention sessions and were asked not to support or answer questions and clarify misunderstandings between the sessions.

The intervention included 8 h of inquiry-based and knowledge-integration activities. The 85 students worked during all activities in groups of four to five persons. There were 20 groups overall. According to the literature, children are more likely to be supported by experience-based learning approaches in systems thinking (Streiling et al., 2021). Moreover, inquiry-based teaching and computer simulation programs, as well as problem-based activities and group work, are the most commonly used strategies to foster systems thinking skills (e.g. Ben-Zvi Assaraf & Orion, 2010; Evagorou et al., 2009; Fanta et al., 2020; Jeronen et al., 2016). These approaches help learners to actively construct new understanding, to adopt the prospect of inquiry as a way of learning by making assumptions, for instance in interactive simulation environments, and testing them, encouraging collaboration, discussion, and reflection in the group, thus facilitating deep understanding (e.g. Bergan-Roller et al., 2018; Evagorou et al., 2009; Fung & Liang, 2023; Hmelo-Silver & Azevedo, 2006). Therefore, our research tool was a group product and our approach focused on the progress students make in systems thinking as a group, not individually. Throughout the 8-h learning environment, the groups were introduced to an inquiry at the beginning of each session; the educator helped the groups go through the tasks and encouraged them to discuss their findings with the other groups in a reflective process.

Ocean acidification and generally the carbon cycle are not included in the Greek science education curricula, although components and processes of the carbon cycle, such as photosynthesis, respiration, and decomposition, are taught as fragmented parts. Greek primary students are taught only about the water cycle. Therefore, during the first unit (2 h) of the intervention, the educator had a discussion, as a reminder, with the students about the water cycle and then asked them to work in groups and draw the water cycle. This was the first step to the earth system approach they would use in the following procedure. Students were then informed that the next activity aimed to compose the carbon cycle. Each group was encouraged first to discuss and write down the subsystems (i.e. geosphere, hydrosphere, atmosphere, biosphere), the elements and processes they thought that should be included in the carbon cycle and then draw them. They were urged to have the water cycle as a model in their attempt to draw the carbon cycle and try to show connections between the subsystems and the elements using arrows, so as to present how the carbon moves. They were, also, encouraged to use words and comments where they thought this would help them give details and describe processes which were difficult to accomplish only by drawing. Each group had 1 h to discuss and draw the carbon cycle.

In the next unit (2 h), the inquiry that urged students to work was to successfully accomplish an online carbon cycle game, which showed how a carbon atom moves among the subsystems. They were first introduced to the game and then each group worked on experiments, concept maps, virtual laboratories, and interactive online activities, concerning photosynthesis, respiration, food chain, and decomposition, using paradigms from land, as well as ocean life. They were asked to discuss and model how these processes move carbon and are connected to create a carbon cycle. They also had to find out which are the sources and the sinks of carbon. Finally, they played the online carbon cycle game.

In the next unit (3 h), the inquiry that motivated students was the animation story of a small crab, the problem of its survival, the cause of it, and possible ways for its amelioration. The groups made assumptions and, thereafter, the activities of the intervention helped them test their hypotheses. They studied different sources, i.e. articles from print and electronic media, as well as before and after ocean acidification photos from real ocean life such as clams and corals, so as to pinpoint the problem and make assumptions for it. They run experiments concerning pH and ocean acidification and worked in virtual laboratories and interactive online activities to understand these concepts. They had also to think and justify how anthropogenic CO_2 increase is linked to ocean acidification. Lastly, each group had to give a justified answer to the problem of the crab and discuss how ocean acidification should be included in the carbon cycle.

During the last hour of the intervention, groups were asked to draw the carbon cycle including ocean acidification.

Research Tool

Students of each group were asked to draw the carbon cycle using rich pictures at the beginning and the end of the project. Rich pictures are a free form of a chart or image that is drawn by an individual or a group of people (Bell & Morse, 2013), offering a way of global communication that far exceeds the limitations of text and speech (Berg & Pooley, 2013), and is primarily used to help them illustrate complex issues (Bell et al., 2016; Berg & Pooley, 2013). In order to know how well someone understands systems, we should be able to understand what this person is thinking. In other words, the mental model of the person should be made external (Cox et al., 2018). With the use of rich pictures, this mental model is expressed both by drawing and using text to explain, as it is shown in the example given (Fig. 1). Considering that the drawing result may be limited with one's drawing skills, especially when the drawing concerns a complex system, giving details by an accompanied text or

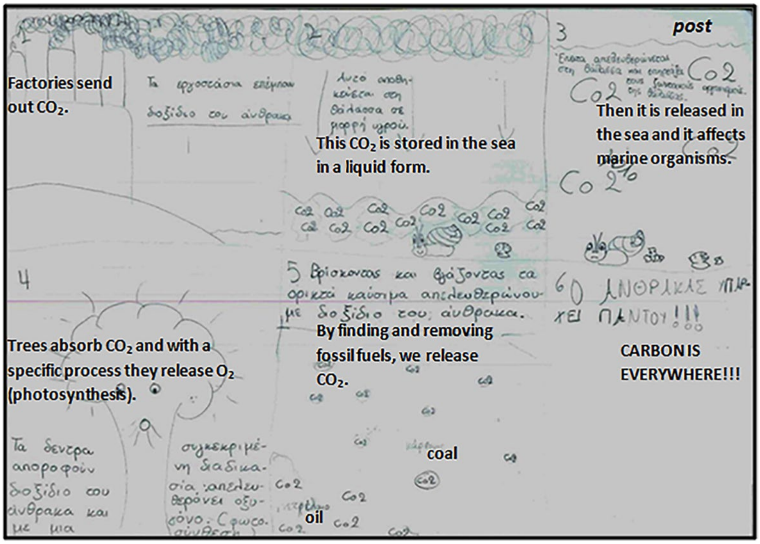

Fig. 1 Example of a Rich Picture of the present study (annotated in English)

phrase of words can help the person better express the mental model he has in mind. The effectiveness of this tool is based on the fact that drawing/explaining by words and thinking are frequently so simultaneous that the graphic image appears almost as an extension of the thinking process (Fathulla, 2008). Moreover, capturing the nature of students' mental representations and how they change with learning is a primary goal in science education research (Jee et al., 2014). Rich pictures can be and frequently are drawn by individuals. By providing an opportunity for groups to draw together and create a combined drawing, it can be argued that the rich pictures can assist the exploration of different world views, including in one form multiple perspectives. They encourage discussion and debate whilst aiding students' understanding from differing perspectives (Bell et al., 2016).

Data Analysis

All pre- and post-rich pictures of the 20 groups were content analyzed by the first and second author individually. Both authors have worked as mainstream teachers in Greek primary education and are experienced in teaching science and analyzing student assessment data at this age level. Thereafter, the researchers compared their individual results, and a few discrepancies were discussed until a complete agreement was reached. Content analysis was run with two different coding frameworks based on Bell and Morse (2013) and Ben-Zvi Assaraf and Orion (2005b) for a more thorough analysis of the pictures.

The first coding framework, according to Bell and Morse's (2013) study, included criteria which helped the authors understand whether students perceive the carbon cycle as a "story" and furthermore as a system, and gave information to answer the first research question. Specifically, it included the following criteria: kinetic, mood, and evidence for information/indicator use incidence.

Kinetics: It refers to use of words, symbols, and variation in line width. It is assumed that greater use of words, connectors, lines, and arrows suggests better connectivity and thinking through relationships. When the picture has no comments or comments to less than half of the elements included in it, then it is described as a picture with "no or limited use of words." In the other case, it is described as a picture with "great use of words." If there are no arrows and lines or the existing ones show connection between less than half of the elements, then the picture is characterized with "no or poor use of lines and arrows." When there are lines and arrows which connect half and more of the elements of the picture, then it is described as a picture with "rich use of lines and arrows."

Mood expression: It relates to the coherence of a "story" in the picture and how it is expressed. Are there clear visual metaphors to draw the story together? When the picture has elements stuck with no evidence, symbol, or arrow of how they relate in a coherent sense or less than half of the elements has a clear connection between them, then the picture is characterized "without a story." When all the elements of the picture or half and more of them are clearly related to each other with arrows in a way that suggests "thinking through," then the picture is described having a "coherence of a story."

Evidence for information/indicator use incidence: It studies whether the group has remained focused on the issue at hand (indicator use) or there is evidence of drift into related/unrelated domains. Has the group managed to sustain task focus? When the picture refers to concepts which are not related to the carbon cycle, or refers to no more than two processes of the five processes of the carbon cycle (i.e. photosynthesis, respiration, food chain, decomposition, and ocean acidification), the picture is described as "drift into related/ unrelated domain." In the other case, it is described as remained focused on the issue.

The use of words which explain processes, the use of arrows and lines which present fluxes, and the connection between the elements and between the earth systems without drifting to other domains showed how students tried to interrelate the topics of the carbon cycle. This depiction presents students' effort to say the story of the carbon cycle.

The second framework was based on the criteria Ben-Zvi Assaraf and Orion (2005b) used to analyze students' drawings about the water cycle. The codes were binary, indicating the presence or absence of each criterion. These were (a) the appearance of the earth systems, i.e. atmosphere, biosphere, hydrosphere, and geosphere; (b) the appearance of the processes, i.e. photosynthesis, respiration, food chain, decomposition, and ocean acidification; (c) the appearance of human impact; and (d) the cyclic perception of the biogeochemical cycle according to the connection point among the components of the cycle. This last criterion was adapted to the carbon cycle to serve the needs of the present study, and the coding was also binary. The carbon cycle components were determined as follows: (1) CO_2 goes from the atmosphere to the plant, (2) CO_2 goes from the atmosphere to the sea, (3) CO_2 turns into organic matter and inserts food chain, (4) CO_2 is released by respiration, (5) carbon is released during decomposition, and (6) CO_2 is released into the atmosphere due to combustion of fossil fuels.

These criteria helped the authors understand how students acknowledge the processes that take part in the carbon cycle, among which the ocean acidification, and the relationships between them. Also, these criteria helped the authors understand the progress of students' systems thinking concerning the carbon cycle, which refers the first research question. Moreover, the reference to human impact gave evidence about whether students realize the effects of human interference on the health of the environment.

The coded data of each pair (pre- and post-) of rich pictures were used to describe each group's progress in systems thinking as well as the correct inclusion of ocean acidification in the carbon cycle, which concern the first and second research question. Afterwards, the entire set of coded data was used to figure out the progress that most groups followed in their systems thinking progress, thus addressing the first research question.

Results

Table 1 contains the results of all teams, drawing the pattern across all pairs (Table 1). Pre-rich pictures were poor in words and use of connectors, lines, and arrows. From the teams, 40% showed a coherence of a story, but 80% of them referred mostly only to two processes of the carbon cycle, photosynthesis, and carbon transfer in the food chain, and less to decomposition, totally ignoring respiration. Thus, they mostly mentioned the atmosphere and biosphere, as well as the CO_2 transfer from the atmosphere to the plant and to the sea, and carbon insert in the food chain. The connections were single and linear, indicating that one component had a relationship with another component but were not cyclic. The grouped elements in the pictures were static constructs, trying to describe the characteristics and processes of the carbon cycle components. Except for one, all the other pictures did not mention the human impact on the carbon cycle (Table 1).

Post-rich pictures were richer in drawings and comments, and all groups remained focused on the issue discussed. All of them mentioned almost all of the earth systems which participate in the carbon cycle. More teams included the processes of food chain and decomposition compared to the pre-pictures, while 80% of the teams included the ocean acidification and had clear comments or drawings of human effect on the carbon cycle. Also, there were a highly increased number of teams which referred to the 2nd, 4th, 5th, and 6th components. Thus, the teams replaced the initial perception of the carbon cycle, which was restricted to the inclusion of one or two processes, with a broader, more balanced perception which included more earth systems and processes, while they presented more relationships among the system's components. The use of arrows showing relationships, the use of numbers showing the sequence of processes, and the use of stages in their drawings is great evidence of their effort to describe a story, a system. The respiration and the cyclic component that refers to the release of CO_2 by respiration are the least mentioned processes of the carbon cycle, both in pre- and post-pictures.

Considering it is practically difficult to present pre- and post-rich pictures of all 20 groups, pre- and post-pictures of two groups are presented as illustrative of the larger patterns across the entire data set.

Team 1: The rich picture of Team 1 before the intervention reported the existence of carbon in three of the earth systems, namely, the atmosphere, biosphere, and hydrosphere, with poor use of words and accompanied single pictures (Table 2; Fig. 2). There was an implication of a narrative theme, and the concepts mentioned are related to the issue, but there was no connection between them. There was only a simple reference to the process of photosynthesis, without explaining its connection to the carbon cycle (Table 2; Fig. 2), while there was no mention to the human effect on it, nor to any of the cyclic components.

Their rich picture after the intervention, although it maintained the same pattern, it contained more word expressions, richer pictures, and metaphors, and there was an effort to explain the mentioned concepts (Table 2; Fig. 2). The elements are related to the issue and are more explicitly discussed, and the arrows ended up in earth components related to carbon. The students apart from the atmosphere, biosphere, and hydrosphere which had been mentioned in the pre-picture also mentioned the geosphere, referring to fossil fuels. As for the processes, they reported photosynthesis, CO_2 dissolution in seawater, ocean acidification, and decomposition, without providing connections between them. The oversized car implied the human impact, while the oversized snail in the ocean illustrated the impact of ocean acidification on marine organisms having a shell, which was mentioned in the accompanying

Table 1 All teams' perceptions of carbon cycle as shown in their pre- and post-rich pictures

Criteria	Pre-pictures $n=20$	Post-pictures $n=20$
Bell and Morse (2013)		
Kinetic		
No or limited use of words	18	10
Great use of words	2	10
No or poor use of lines and arrows	18	8
Rich use of lines and arrows	2	12
Mood expression		
"Without a story", elements stuck with no thought of how they relate in a coherent sense	12	5
"Coherence of a story", elements of the picture clearly related to each other in a way that suggests "thinking through"	8	15
Indicator use of incidence		
Remained focused on the issue	4	14
Drift into related/ unrelated domain	16	6
Ben-Zvi Assaraf and Orion (2005b)		
Earth systems		
Atmosphere	19	20
Biosphere	19	20
Hydrosphere	10	20
Geosphere	8	18
Processes		
No mention of processes	2	0
Photosynthesis	16	16
Respiration	1	2
Food chain	13	16
Decomposition	6	11
Ocean acidification	0	16

Table 1 (continued)

Criteria	Pre-pictures $n=20$	Post-pictures $n=20$
Human impact		
No mention	19	7
Mention	1	13
Cyclic components		
No mention of components	3	0
1st: CO_2 goes from the atmosphere to the plant	15	16
2nd: CO_2 goes from the atmosphere to the sea	6	20
3rd: CO_2 turns into organic matter and inserts food chain	11	16
4th: CO_2 is released by respiration	0	2
5th: Carbon is released during decomposition	3	11
6th: CO_2 is released into the atmosphere due to combustion of fossil fuels	1	11

Table 2 Team 1 students' perceptions of carbon cycle as shown in their pre- and post-rich pictures

Bell and Morse (2013)		Ben-Zvi Assaraf and Orion (2005b)	
Pre	Post	Pre	Post
Kinetic		Earth systems	
Limited use of words and pictures	Wide use of word expressions, rich pictures and metaphors	Atmosphere, biosphere, hydrosphere	Atmosphere, biosphere, hydrosphere, geosphere
Mood expression		Processes	
Implication of a narrative theme	Same elements, more explicitly discussed, evidence of a story	Photosynthesis	Photosynthesis, decomposition, ocean acidification
Indicator use incidence		Human impact	
Related to the issue, few concepts of carbon cycle without connection between them	Related to the issue, many discussed concepts without connection between them	No mention	Mention
		Cyclic components	
		No mention	1st, 2nd, 5th, and 6th components

For cyclic components see "Data analysis" section

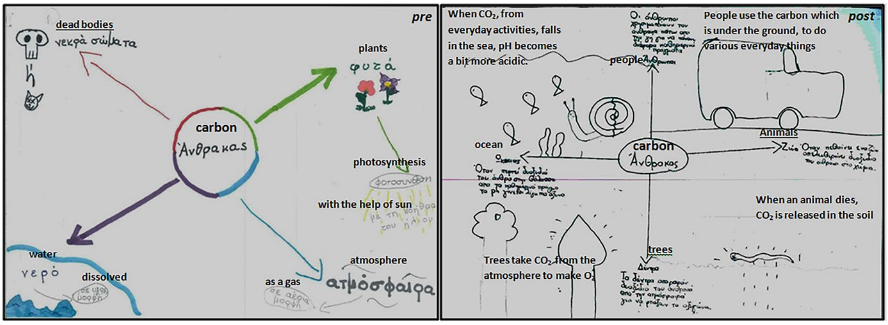

Fig. 2 Team 1: Pre- and post-rich picture of the carbon cycle (annotated in English)

comment. However, they incorrectly mentioned that during decomposition, CO_2 is released in the soil and not into the atmosphere (Table 2; Fig. 2).

Team 2: Their rich picture before the intervention had a small group of drawing elements accompanied by a wide use of words, without any connections between them. However, all elements were related to the issue (Table 3; Fig. 3). They referred to CO_2 existence in the atmosphere, biosphere, and hydrosphere, to the process of photosynthesis on land and in seawater, to the process of human respiration, as well as to the food chain and decomposition, which they did not relate them to the carbon cycle. They did not mention the human effect, while they referred to the 1st and 4th components, i.e. CO_2 goes from the atmosphere to the plant, and CO_2 is released by respiration (Table 3; Fig. 3).

In the post-rich picture, the students retained the same pattern using multiple enriched group-elements of drawings and wide comments, which were related to the issue but they had no connection among them (Table 3; Fig. 3). They referred to all earth systems, all processes, i.e. photosynthesis, respiration, food chain, decomposition, and ocean acidification revealing, however, their misconception, regarding the seawater pH. They included the human effect with the image of the factory, and they mentioned all cyclic components of the carbon cycle. However, they neither connected the earth systems, nor described the recycling of carbon (Table 3; Fig. 3).

Discussion

With regard to the first research question, the results indicate that although the elementary students of the present study possessed an incomplete and fragmented perception of the carbon cycle, after the intervention, they made significant progress in analyzing the carbon cycle to its components and processes and in including relationships between them and, thus, also presenting progress in their systems thinking skills.

Particularly, as for their system thinking progress, most teams initially had difficulties even in the identification of the system components. They expressed little understanding about the relationships between them, using mostly linear relations.

Table 3 Team 2 students' perceptions of carbon cycle as shown in their pre- and post-rich pictures

Bell and Morse (2013)		Ben-Zvi Assaraf and Orion (2005b)	
Pre	Post	Pre	Post
Kinetic		Earth systems	
Wide use of words, some drawings	Wide use of words and enriched drawings	Atmosphere, biosphere, hydrosphere	Atmosphere, biosphere, hydrosphere, geosphere
Mood expression		Processes	
Many elements without connection between them, no evidence of a story	Sub-grouped elements, evidence of a story	Photosynthesis in land and ocean, food chain, respiration, decomposition	Photosynthesis, food chain, decomposition, respiration, ocean acidification
Indicator use incidence		Human impact	
Related to the issue	Related to the issue, including multiple grouped elements	No mention	Mention
		Cyclic components	
		1st and 4th components	1st, 2nd, 3rd, 4th,5th and 6th components

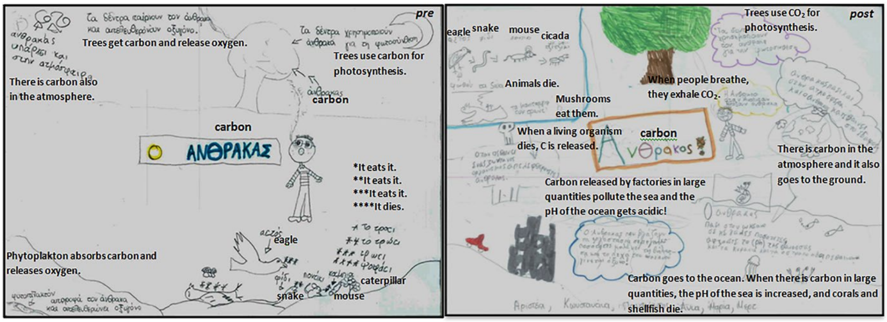

Fig. 3 Team 2: Pre- and post-rich picture of the carbon cycle (annotated in English)

After the intervention, teams included all four earth systems in the cycle, increased the number and variety of the processes, and improved their ability to identify dynamic relationships among the components and the processes. The number of concepts and the connections between them, as well as the number of concepts which were related to more than two concepts increased, presenting how students moved from linear relations to more dynamic relationships, revealing the improvement in their systems thinking. These findings indicate that under formal instruction, based on inquiry-based environment and group work that facilitates discussion, elementary students could probably develop their systems thinking, even for carbon cycle, which is considered a complex biogeochemical cycle. This supports what other studies have found concerning students' systems thinking; at this age, most students showed significant improvement in systems thinking performance through formal instruction and revealed that they can achieve a better understanding of more complex patterns in ecosystems (Ben-Zvi Assaraf & Orion, 2010; Grotzer & Basca, 2003; Sommer & Lücken, 2010; Zangori et al., 2017). Moreover, most of the teams moved away from a static view of the carbon cycle they had articulated in the pre-rich pictures, to an understanding process of its dynamic nature. However, they did not manage to understand and depict its cyclic nature, still upholding, after the intervention, some disconnected "islands of knowledge." This phenomenon has also been reported by other researchers regarding students' ability to connect processes in other biogeochemical cycles (Ben-Zvi Assaraf & Orion, 2005a; Kali et al., 2003). This could be attributed to their difficulty to sufficiently understand specific processes to be able to show their relationships to other components of the cycle. Correspondingly, Ben-Zvi Assaraf and Orion (2005b) argued that insufficient awareness of processes and locations do not allow students to create a network of relationships to describe a system. Moreover, complex environmental issues usually are not taught in ways to highlight systemic reasoning in elementary education (Sweeny & Sterman, 2007).

As for students' knowledge of carbon cycle, the pre-test findings indicate that most teams were mostly acquainted with the atmospheric and biospheric components, and they depicted the relationship between them, i.e. the transfer of carbon from the atmosphere to the plants. Half of the teams also mentioned the hydrosphere, and even fewer teams the transfer of CO_2 in the sea. Instead of presenting the carbon cycle, they presented only one or two specific processes of it, namely, photosynthesis and transfer of carbon in the food chain, and much less decomposition. Greek science textbooks include concepts concerning the carbon cycle, namely, photosynthesis, respiration, fossil fuels, acids and bases, energy flow, matter cycling, food chains and decomposition, and, thus, a sixth grader is expected to know about them (Hellenic Pedagogical Institute, 2003). However, these topics are taught fragmentarily, and they are not incorporated into the carbon cycle context. Moreover, students used mostly themes from terrestrial life, reflecting the general phenomenon that school education presents a terrestrial bias in science curricula (Fauville, 2017). This fact results in incomplete or inaccurate treatment of many fundamentally important concepts concerning the ocean life, and leading to a situation where students better understand terrestrial than marine environmental issues.

Moreover, the students articulated a general sense of the structure of the food chain without depicting the role of the food chain in the carbon cycle and the function of food as a carbon-containing material (Lin & Hu, 2003). Additionally, their knowledge about the process of decomposition is perplexed, failing to show that decomposition releases carbon into the atmosphere. Indeed, children believe either that matter from dead animals and plants simply disappear (Sequeira & Freitas, 1986), or decay is a state that simply happens to materials, and no explanation is needed (Smith & Anderson, 1986).

Additionally, the teams almost totally ignored the process of respiration and its contribution to the carbon cycle. Previous studies showed that students do not comprehend the nature and function of plant respiration and have little understanding of the relationship between photosynthesis and respiration (e.g. Dimec & Strgar, 2017; Marmaroti & Galanopoulou, 2006; Svandova, 2014). Overall, before the intervention, students depicted a static view of only two processes of the carbon cycle, photosynthesis, and carbon transfer through the food chain, namely, they referred to inputs of carbon, ignoring the mechanisms of outputs. Accordingly, Düsing et al. (2019) found that secondary students used a low number of components to construct carbon cycle, without any references to fossil fuels and only a few references to cars and industry, and were largely unaware of the fundamental role of decomposers and the release of CO_2 into the atmosphere through cellular respiration. On the other hand, in a respective study, Zangori et al. (2017) found that secondary students, in their initial models for the carbon cycle, included inputs and outputs such as plants taking in CO_2 and animals breathing out CO_2.

After the intervention, teams identified clearly that carbon is being transferred from the atmosphere to the earth systems, that it cycles through biotic factors and that it is being held by carbon sinks. They also highlighted that excess anthropogenic carbon outputs cause carbon accumulation in the atmosphere, which is transferred to the sea and brings the carbon system out of balance. However, although they have understood the input of carbon, they still have difficulties to understand and include the output mechanisms of the carbon cycle, mostly respiration and less decomposition. This knowledge gap makes it difficult for them to understand the cycling nature of the carbon cycle, and thus, they did not manage to fully present it.

As for our second research question, it was expected that students would not make any mention to ocean acidification in their pre-rich pictures since they had never been taught about it. The post-rich pictures indicate that students achieved to understand and integrate ocean acidification into the carbon cycle. They highlighted human's impact on the carbon cycle, which indicates that they realized that humans' everyday actions concerning CO_2 emissions may affect ocean acidification and, consequently, the health of the ocean. This is potentially a crucial first step towards taking responsibility to make informed lifestyle choices to minimize this impact. Overall, their significant progress reassures the suggestion of Scope and Sequence for Ocean Literacy (NMEA, 2010) that this subject can be taught in primary education. Considering that in primary education a core concern is when to introduce the issue of climate change, which is an important decision in order not to frighten children and young people (Bangay & Blum, 2010), the present study constitutes a tribute that young children could be empowered to understand and critically engage with environmental change.

Our study shows that systems thinking can help primary students engage with complex environmental issues. It is not only the fact that they understood the ocean acidification process and depicted it in the post-pictures, but it is also very encouraging that they integrated it successfully in the carbon cycle, highlighting human impact on it. Thus, it could be suggested that the complex environmental issues should not be taught fragmentarily, but as parts and consequences of a dynamic system and its unbalanced relationships, so that students not only develop their cognitive knowledge about them but from the beginning perceive the dynamics of relationships and equilibriums. Thus, earth system approach can serve as an effective prospective to help children not only understand but also engage in complex environmental issues. Our study confirms Ben-Zvi Assaraf and Orion's (2005b) suggestion that elementary school instructional efforts concerning elementary systems thinking development should focus on cultivating students' ability to identify processes and components of a system and to identify relationships between at least two components, as well as dynamic relationships in the system.

Moreover, the intervention highlighted misconceptions and gaps that should be considered thoroughly before the next implementation. Gaps in respiration underline the need for educators to focus on this process. The present intervention aimed to challenge students' knowledge of ocean acidification in a carbon cycle context. Respectively, it could be suggested that respiration could be approached in a carbon cycle context, focusing on the sub-system photosynthesis-respiration. In addition, the process of decomposition remained ambiguous even after the intervention, as students drew that matter ends up in the environment, usually as part of the soil. These difficulties could be attributed to the fact that these processes are not evident to the unassisted eye, and children's knowledge seems firmly anchored in things they can directly see (Ero-Tolliver et al., 2013). Thus, additional educational material, such as videos and animations, should be used, to help children understand this process. Moreover, although students understood that seawater becomes more acidic, a few of them interpreted acidification as an increase in pH values and not as a decrease; this misunderstanding implies that more activities concerning the pH scale should be added.

In conclusion, the outcomes of the present study provide compelling evidence that primary students can engage in systems thinking, supporting earlier arguments that young children are able to develop their systems thinking in the context of the earth system approach. Particularly, we highlight the below contributions to the field. Students' fragmented content knowledge about elements and processes of a biogeochemical cycle are necessary but not sufficient to help them put together the individual pieces to represent the whole. Therefore, domain-general patterns of systems interrelationships and patterns of causality should be emphasized in the science curricula, so as to help them interrelate the topics. In this context, the present study underlines the effectiveness of inquiry-based environments and group work, which enhance discussion and argument about patterns of causality, supporting a meaningful learning and the gradual engagement of learners with systemic complexity. Group rich pictures could serve as an effective teaching and evaluating tool especially at the elementary level, which can enforce discussion among the students and make their system thinking visible. Last but not least, the findings of the present study support the idea that students should learn concurrently about complex systems and about specific scientific topics as part of the learning activities. They understood a newly taught complex environmental issue such as ocean acidification in a systems thinking perspective, as well as the human impact on it, which is a crucial first step towards taking responsibility to make informed lifestyle choices to minimize this impact. However, more studies are needed to show that systems thinking prospective can serve as an effective approach to help children not only understand but also engage in complex environmental issues.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s10763-023-10431-5.

Acknowledgements The authors would like to sincerely thank the students who participated in the study, and their teachers for permitting to use their classes.

Author Contribution All authors contributed to the study conception and design. Material preparation, data collection, and analysis were performed by Theodora Boubonari and Despoina-Niovi Papazoglou, and analysis was performed by Theodora Boubonari and Athanasios Mogias. The first draft of the manuscript was written by Theodora Boubonari, and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Funding Open access funding provided by HEAL-Link Greece.

Data Availability Pre and post rich pictures of all teams are available as a supplementary file.

Declarations

Ethics Approval and Consent to Participate Written informed consent was obtained from the parents or legal guardians. The non-sensitive collected data cannot be rated as "personal data," according to EU General Data Protection Regulation (EU 679/2016, article 4, paragraph 1).

Competing Interests The authors declare no competing interests.

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