

Interplay between Conceptual Knowledge and Systems Thinking Skills: Undergraduate Biology Students Evaluating the Effects of Climate Change on Ecosystems

Tomi Kiviluoma^{1*}, Antti Laherto², Ilona Södervik¹

¹Faculty of Educational Sciences, Centre for University Teaching and Learning, University of Helsinki, Helsinki, Finland,

²Department of Education, Faculty of Educational Sciences, University of Helsinki, Helsinki, Finland

*Corresponding Author: tomi.kiviluoma@helsinki.fi

ABSTRACT

Systems thinking skills complemented with domain-specific conceptual knowledge are necessary to mitigate the ecological crisis caused by climate change. This cross-sectional study adapts the biology systems-thinking (BST) framework to evaluate systems thinking skills and their potential associations with knowledge related to core concepts in biology. This study is among the first to apply the BST framework while using a scenario-based case focused on the effects of climate change on boreal forest ecosystems. Forty-two 2nd-year biology undergraduate students with no specific training on systems thinking participated. They read the scenario and answered an open-ended task designed to require both application of prior knowledge and systems thinking skills. Responses were analyzed through the protocol of deductive qualitative content analysis to reveal differences in systems thinking skills and the extent of conceptual knowledge. Results highlight the potential role of conceptual knowledge in supporting systems thinking. Particularly, the quality of knowledge about evolutionary processes was higher among the students who exhibited reasoning across systems, the highest skill level in the BST framework. By integrating systems thinking into domain-specific curricula, educators can enhance students' ability to address complex ecological challenges. Scenario-based tasks seem effective in revealing differences in systems thinking skills. Educational implications are discussed, specifically highlighting the need for instructional strategies that foster robust conceptual understanding of evolutionary processes as a key component of advanced systems thinking.

KEY WORDS: Biology education, climate change, evolution, systems thinking, undergraduate education

INTRODUCTION

Planet Earth is facing an ecological crisis, exacerbated by unprecedented rates of global climate warming and biodiversity loss (Ripple et al., 2024). Mitigating the dire consequences of such complex global challenges requires multidisciplinary collaboration in which life scientists play a key role by providing expertise on ecosystem functions and evolutionary processes. This discipline-specific conceptual knowledge needs to be complemented by the skills to navigate and interpret the complex interactions between climate change and ecosystems, which is challenging even for researchers in the domain of climate science (Holme and Rocha, 2023). These skills form an integral part of systems thinking, one of several key competencies for sustainability (Brundiers et al., 2021). Multiple disciplines have argued for the importance of systems thinking in understanding the complexities of their respective phenomena of interest (Rousseau, 2014). These include engineering (Dugan et al., 2022), Earth systems sciences (Ben-Zvi Assaraf and Orion, 2005; Mehren et al., 2018) and climate change education (Liu, 2023). This importance only becomes more relevant today as the intertwined wicked problems of climate change and biodiversity loss call for educational transformations (Voulvoulis et al., 2022).

Given the emphasis on systems thinking within sustainability competencies and its inclusion in university learning objectives, there is an urgent need for research on the state of systems thinking skills in domain-specific educational contexts (Voulvoulis et al., 2022). Life sciences provide a fruitful domain for studying systems thinking, as biological systems emerge from properties such as feedback loops, hierarchical organization and dynamic relationships (Verhoeff et al., 2018). Only a few empirical studies in science education research have focused on students' utilization of systems thinking skills (Grohs et al., 2018). In biology, systems thinking has been studied using contexts such as ecosystem interactions with an example species (Sommer and Lücken, 2010), a botany course (Zangori and Koontz, 2017), and human physiology as a model system (Tripto et al., 2017). Little attention has been paid to the interaction between conceptual knowledge and systems thinking when reasoning about real-world wicked problems related to ecology and climate (Redman et al., 2021; Seher Budak and Defne Ceyhan, 2024). Furthermore, despite decades of research developing frameworks for environmental and sustainability science education, there is still a lack of consistency in assessing key competences in these contexts (Redman et al., 2021). This study responds to this gap by exploring the levels of systems thinking skills undergraduate

biology students are exhibiting when presented with an authentic scenario rooted in the real world.

LITERATURE REVIEW

A major challenge when navigating the research literature on systems thinking is the diversity of language and the fact that no clear consensus on its definition exists (Checkland, 2012). The development of systems thinking perspectives began through multidisciplinary collaboration, and the articulation of the first form of general systems theory (GST) is attributed to biologist Ludwig von Bertalanffy, who focused on defining the organism as a hierarchical open system (Gilbert and Sarkar, 2000; von Bertalanffy, 1968). The ambitious, larger objective of GST at that time was to unify relevant aspects of separately operating domains to better understand the complexities of both bio-physical and social systems (Rousseau, 2014). With the advent of network science, two other systems theories, cybernetics and dynamic systems theory, each emphasizing slightly different focal points, have emerged (for review, see Verhoeff et al., 2018). Instead of contradicting, these theories complement each other; the discourse on systems thinking today is indebted to the conceptual contributions from all of them. Below, we provide a brief synthesis on the interplay between system characteristics and the necessary skills to describe and analyze those characteristics. By the end of the literature review, we will hopefully have clarified our definition of systems thinking and how we seek to assess it in this study.

Systems exist and are indeed ubiquitous both in artificial contexts and in, for lack of a better term, the natural world. Looking for commonalities applying to systems in general, three higher-order constructs emerge from the literature. A system possesses an internal organization, or structure. The components of this structure form and maintain relationships with each other and with external (f)actors, giving rise to the function of the system (Meadows, 2008; Rousseau, 2014; Sweeney and Sterman, 2000; Verhoeff et al., 2018). We reiterate that these constructs can broadly be used to describe any system, but for the sake of clarity, we will, from now on, refer to biological systems. Complex structures exist at all levels of biological organization, and these systems can impact one another across the levels, giving rise to emergent properties (Herring and Radick, 2019). While the unpredictable emergence of novel properties from interactions between system structures is of course not unique to biological systems, it is uniquely central to them (Kitano, 2002).

While these constructs form the foundations of the representational language to reason about systems, more fine-grained concepts are needed for a comprehensive understanding. Systems biology experts and biology teacher educators agree on eight essential distinct characteristics that make up a biological system: Boundary, components, hierarchy, feedback loops, input and output, interactions, emergence, and dynamics (Gilissen et al., 2019). It is necessary

to understand all eight characteristics conceptually to explain how a system functions. This entails identifying its components and boundaries or structural elements and describing their relationships, which can take multiple forms such as direct interactions and feedback loops, positive or negative. Yet, one must also acknowledge that predicting the function of a system solely based on the properties of its structure and relationships is complicated and often impossible due to emergence. These notions are supported by literature and align with the systems theories mentioned above (Sweeney and Sterman, 2000; Verhoeff et al., 2018). Recent competence frameworks with subtle differences converge on the notion that systems thinking should be viewed and assessed as a holistic competence that can be divided into subsets of skills (Grohs et al., 2018; Mehren et al., 2018; Momsen et al., 2022). Perhaps due to the varying foci of systems theories and the differing domains and contexts, educational research has produced many lists of systems thinking skills with often complementary iterations (Boersma et al., 2011). Sometimes, these kinds of skills have been advocated without an explicit reference to systems theories or the term “systems thinking” (Jacobson and Wilensky, 2006).

Fostering systems thinking is crucial in biology education. Two of the five core concepts for undergraduate biology education, structure and function (SF) and systems, are explicitly related to the ability to reason about systems (Brewer and Smith, 2011). Ecosystems with their complex interactions between species and abiotic factors, provide a valuable context for using domain-specific conceptual knowledge together with systems thinking skills. Should students engage in systems thinking while answering problems related to ecosystems, they must first organize and apply their available conceptual knowledge that is relevant to the context of the task at hand (Meadows, 2008). Educators and researchers alike know this is no easy feat. There are multiple nested hierarchies to navigate in terms of causal interactions and feedback loops. Results have repeatedly demonstrated challenges in explaining complex feeding relations and the role of energy and matter when modelling food webs (Hogan, 2000; Wennersten et al., 2023). In a similar vein, conceptual knowledge about pathways of energy transformations at cellular levels is often insufficient (Bergan-Roller et al., 2020), as is knowledge about the emergent process of natural selection (McLure et al., 2020). Comprehensive systems thinking in biology thus requires cognitive navigation across the levels of organization, which in turn requires application and integration of prior conceptual knowledge (Mambrey et al., 2022).

Research into systems thinking must therefore consider the relevant aspects of domain-specific conceptual knowledge and incorporate them into both the research instruments and research questions, but this has rarely been the case (Redman et al., 2021). If systems thinking is being assessed through self-reporting methodology, conceptual knowledge isn't necessarily taken into account at all (Ratinen et al., 2024). There is still a need to build a unified model for assessing

systems thinking while incorporating domain-specific content (Mambrey et al., 2020). We believe that a promising candidate can be found in the biology systems-thinking (BST) framework intended for both research and instructional purposes. Developed by Momsen et al. (2022), based on an extensive literature review building on previously developed models to characterize systems thinking in biology (Ben-Zvi Assaraf and Orion, 2010; Sommer and Lücken, 2010), the BST framework organizes systems thinking into four hierarchical levels, each composed of three skills. The framework describes these skills using the common representational language of system structures, relationships, and functions. The lower levels contain the foundational skills to identify and describe system structures, and the higher levels require more comprehensive skills to analyze indirect effects, emergent properties, and relate different levels of biological organization with one another.

Broadly defined, systems thinking represents the necessary conceptual knowledge and cognitive skills to describe and explain systems, and to predict consequences to their function resulting from dynamic changes. Table 1 provides a synthesis of the literature review, aligning the three conceptual constructs, eight characteristics, and some selected examples of related systems thinking skills. This is not intended as a novel framework but merely as a visual aid to provide an overview of the many concepts and skills, along with their relations with one another.

Aims of the Study

This cross-sectional study explores the interaction between systems thinking competence and domain-specific conceptual understanding of life science undergraduates through a scenario-based task by adopting the recently developed BST framework (Momsen et al., 2022). The study answers the following two research questions:

1. Which systems thinking skills do students demonstrate when engaged in a case-based scenario task (on the effects of climate change on vegetation)?
2. How are the demonstrated systems thinking skills associated with differences in conceptual knowledge?

MATERIALS AND METHODS

Research Instrument

Using a scenario rooted in a real-world context can reveal how students exhibit systems thinking skills (Redman et al., 2021). We developed a scenario text (Appendix) which begins by describing results on the increased global vegetative cover and biomass growth in boreal forests and simultaneously occurring high rates of biodiversity loss (Jaureguiberry et al., 2022; Zhu et al., 2016). We chose the boreal forest ecosystem as an example due to its local context and familiarity to the students. The context is suited to address our research questions, since climate change will cause alterations and disruptions in ecosystems through multiple pathways, which involve all the characteristics of a system. Finally, the scenario presents paleo-historical evidence of plants' potential to adapt to changing environmental conditions, followed by examples of current changes in these conditions.

After reading the scenario, students were asked to complete an open-ended, multifaceted task which required them to evaluate the information in the scenario and think about both the vegetation changes in ecosystems and their consequences. Responses in vegetation were chosen as the focal point because plants form the foundation for energy flow in terrestrial ecosystems. In identifying responses in vegetation, students need to establish relevant structures with their boundaries (e.g., leaf, example organism, population), which is considered a foundational systems thinking skill (Momsen et al., 2022). While describing responses in stomatal regulation of leaves would be a well-justified example, it alone would not be adequate since the task prompts students to also consider the macro-level of ecosystems (locally vs. elsewhere in the globe). Finally, the task requested students to predict consequences resulting from the responses and changing conditions, which is directly aligned with skill 3c predict and explain consequences to system function resulting from changes to system boundaries, structures, or relationships. Reasoning about some consequences also required students to explain interactions between biological levels of organization, which represents skill 4c, and identify how systems intersect to

Table 1: Alignment of system constructs, characteristics, and corresponding systems thinking skills

System construct (and synonym) ^a	Characteristic ^b	Systems thinking skill example ^c
Structure	Boundary Components	Identify the system boundaries and the structures relevant to a particular function.
Relationships (behavior, mechanisms)	Hierarchy Feedback loops Input and output Interactions	Predict and explain direct effects of relationships on system structures. Describe indirect effects and feedback loops.
Function (model, phenomena)	Emergence Dynamics	Predict and explain consequences to system function resulting from change to system boundaries, structures, or relationships. Recognize that emergent properties of systems often cannot be predicted based on knowing the structures and relationships of that particular system.

^aE.g., Hmelo-Silver et al., 2017; Meadows, 2008; Momsen et al., 2022; Sweeney and Sterman, 2000; Verhoeff et al., 2018, ^bGilissen et al., 2019, ^cModified from Momsen et al., 2022

explain the ways that one system's function can impact another system across biological levels of organization. The translated task is presented below:

Based on your prior knowledge and the information in the text, describe responses in vegetation to the changing conditions both locally and elsewhere around the globe over the next few decades. What kinds of challenging consequences could result from these changes?

As part of the instrument, we developed a model answer representing a comprehensive answer that would exhibit systems thinking skills at higher levels as well as provide evidence of reasoning across different ecosystems and levels of biological organization (Appendix). All authors are active trainers of pre-service teachers, and two hold master's degrees in biology. Two faculty experts in ecology and evolutionary biology provided feedback during the development of the model answer, which was refined until consensus was reached between the authors and the experts.

Participants

The sample consisted of 42 undergraduate students enrolled in the bachelor's program in biology at the Faculty of Biological and Environmental Sciences, University of Helsinki. The data were collected during the fall semester of 2020, as the participants had entered the 2nd year of their 3-year undergraduate program. Although small, we think that the sample demographics represented the average cohort of undergraduate students in a life science program at a North European university. The sample also represents 68% of the total enrolled cohort of that year.

Procedure

Participants attended the session individually, accompanied by a researcher. All participants provided their informed consent in written form at the beginning of the session. In

providing their informed consent, the participants confirmed their understanding that the research material may lead to publication in a way that no published material can be traced to the identity of any individual. All participants were assigned a randomized pseudonym code before data collection, and identification keys were stored separately from the raw data. The whole test was administered on a computer and took between 30 and 45 min. The test included other measurements which are beyond the scope of this paper. Only the results from the task outlined above will be reported. Participants wrote their answers in a separate document. The researcher did not intervene in the test procedure. The study followed the ethical principles and instructions set by the Finnish National Board on Research Integrity (TENK). The research did not require ethical review as the conditions of the research design do not meet the conditions set out by TENK.

Data Analysis

All answers were read twice, and both research questions were addressed through the protocol of deductive qualitative content analysis using the software Atlas.ti, version 25 (Braun and Clarke, 2006; Cohen et al., 2018). To address research question 1, the answers were analyzed based on the BST framework proposed by Momsen et al. (2022). From the 12 skills listed in the original framework, we identified eight skills, two from each level, that were relevant to our research design and which could be identified from the students' answers (Table 2). We formulated task-specific assessment criteria that align with the relevant systems thinking skills at each level. Table 2 presents our modified assessment rubric.

To address research question 2, we analyzed students' domain-specific conceptual knowledge based on the conceptual elements framework (Cary and Branchaw, 2017), which is a detailed extension of the five core concepts presented in

Table 2: Rubric for assessing systems thinking skills based on Momsen et al. (2022), and contextualized for this study

Level	Assessment criteria for student answers	Systems thinking skill ^a	Task excerpt
1. Identifying and describing the system	Student identifies relevant changes based on the scenario (e.g., biomass growth). The student identifies relationships without expanding or predicting their effects beyond what was stated in the scenario.	1a: Identify the system boundaries and the structures relevant to a particular function. 1b: Identify relationships among system structures relevant to a particular function.	Describe responses in vegetation to the changing conditions locally
2. Analyzing within the system	Reasoning about the properties of relationships, the student predicts direct effects of one structure on another.	2b: Reason about the quantitative (or relative quantitative) properties of relationships. 2c: Predict and explain direct effects of relationships on system structures.	Describe responses in vegetation to the changing conditions both locally and elsewhere around the globe
3. Analyzing the whole system	Student predicts and explains consequences resulting from identified responses as perturbations. Student describes indirect effects and feedback loops.	3a: Describe indirect effects and feedback loops. 3c: Predict and explain consequences to system function.	What kinds of consequences could result from these changes?
4. Reasoning across systems	Student recognizes patterns across systems to make generalisations when predicting consequences. Student identifies how consequences might emerge from interactions across biological levels of organization.	4a: Recognize patterns across systems to make generalizations about systems with similar underlying structure or function. 4c: Identify how systems intersect in order to explain the ways that one system's function can impact another system across biological levels of organization.	What kinds of consequences could result from these changes?

^aThe numbering is a direct reference to the original biology systems-thinking framework

the vision and change document (Brewer and Smith, 2011). Table 3 presents the core concepts, selected conceptual elements relevant to our task, and a sentence from the model answer to illustrate the analysis. We read through the answers and assigned codes denoting the conceptual elements that each sentence contained (e.g., Pathways and transformations of energy and matter [PTeM]5, SF1). All five core concepts could be represented in a single comprehensive answer. Due to the complex, open-ended nature of the task, a single answer could contain overlapping core concepts. Multiple conceptual elements belonging to the same core concept could also be represented. Hence, we ultimately counted how many answers (i.e., students) demonstrated each of the five core concepts.

During the analysis process, we added two inductive codes under the core concept of evolution to quantify instances of recurring naïve conceptions related to the phenomenon. This data-driven addition was necessary to consider the well-studied naïve conceptions that involve misinterpretations of the concept of relative fitness and the process of natural selection (Cooper, 2017; Gregory, 2009). If a student referred to the paleo-historical evidence of plants' ability to adapt to justify that plants will adapt and evolve in response to changing conditions in the future, we coded these instances as "*Intentional adaptation*" and counted their occurrences. If a student described the survival of vegetation from an all-or-nothing perspective where unfit individuals categorically die, we coded these instances as "*Survival of the fittest*" and counted their occurrences. No similarly common naïve conceptions recurred in other core concepts.

RESULTS

All 42 students provided answers with enough substance and coherence to analyze the systems thinking skills evident

in their reasoning. Over half of the students ($n = 26$; 62%) reached only the first two levels, exhibiting the skills to identify relevant changes and relationships (Level 1), and to describe direct effects of relationships (Level 2). Sixteen students (38%) provided a comprehensive answer exhibiting the skill to predict and explain consequences as a result of perturbations to system structures or relationships (Level 3). Six students (14%) were able to reason across systems and biological levels of organization, exhibiting systems thinking skills at the highest level. Table 4 summarizes the results of the first research question with selected excerpts from individual answers.

The analysis of conceptual knowledge to answer research question 2 revealed that overall, SF and systems (S) were the most common core concepts identified from the answers ($n = 28$; 67%). Information flow, exchange, and storage (IFES) and evolution (E) were identified from 23 answers (55%). Sixteen (38%) answers referred to PTeM, and these instances were relatively more frequent at the higher systems thinking skill levels. Conceptual knowledge varied slightly across the reached systems thinking skill level (Figure 1). Students who demonstrated more demanding systems thinking skills at the two higher levels also more readily used conceptual elements from all five core concepts.

Finally, the occurrence of naïve conceptions related to the core concept Evolution (E) was higher among students who exhibited systems thinking skills at lower levels (Table 5). None of the six students at level 4 demonstrated these naïve conceptions despite the high frequency of conceptual elements related to Evolution (E). For students who remained at level 1, it was common to demonstrate both naïve conceptions in their explanations:

"Vegetation will adapt to the new conditions over the coming decades. The fittest and strongest individuals

Table 3: The vision and change core concepts, selected conceptual elements, and corresponding sentence examples from the model answer

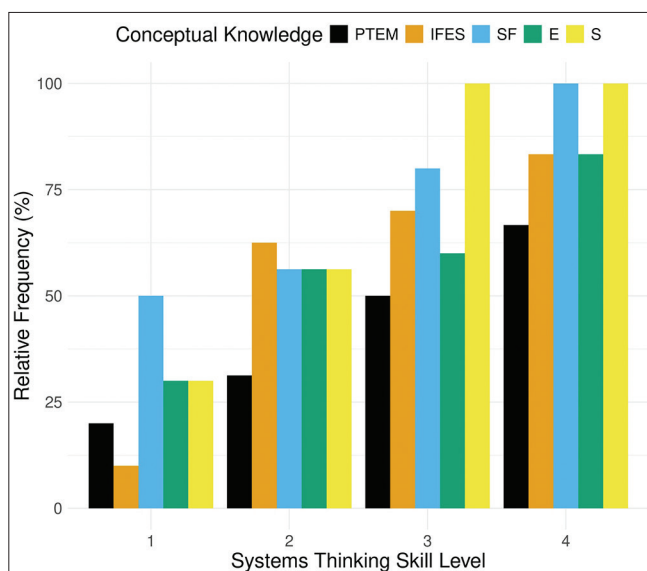
Core concept (Brewer and Smith, 2011)	Conceptual element (Cary and Branchaw, 2017)	Model answer excerpt
Pathways and transformations of energy and matter (PTeM)	PTeM7: Matter can transfer between the abiotic and biotic components of biological systems.	Plants can more effectively uptake nutrients from the soil due to the increased activity of decomposers.
Information flow, exchange, and storage (IFES)	IFES4: Information from the environment regulates protein synthesis and activity, which control cellular processes and thereby organismal and population-level activity	As photosynthetic capacity increases, plants allocate resources to growth at the expense of other functions, such as defence.
Structure and function (SF)	SF1: Biological structures from the molecular to the ecosystem scale, and their interactions are determined by chemical and physical properties that both enable and constrain function.	[...] increased temperatures and carbon dioxide concentration enhance the photosynthetic capacity only up to a certain point/limit.
Evolution (E)	E4: Phenotypes, based on underlying genotypes and environmental factors, can be subject to selective pressure. E5: Organisms have greater fitness if they have a phenotype that increases their ability to survive and reproduce in a particular environment.	There are already evident changes in plant phenology. The decrease in snow cover threatens many wintering plants. Globally, plant species adapted to dry and temperate conditions will thrive and become more numerous.
Systems (S)	S1: Biological entities interact through chemical and physical signals that can be transient, depend on spatial organization, and are influenced by environmental factors.	Accelerated warming and lengthier growing seasons can have consequences that threaten biodiversity.

Table 4: Number of students who reached each level of the biology systems thinking framework

Level	Skill description	n (%)	Example answer excerpt
1. Identifying and describing the system	1ab: Identify the system boundaries, structures, and relationships relevant to a particular function.	10 (24)	"I believe that vegetation will increase and grow more efficiently in northern regions. It is also likely that the longer growing season will lead to the appearance of new species in areas where they have not been seen before." id56
2. Analyzing within the system	2b: Reason about the quantitative (or relative quantitative) properties of relationships. 2c: Predict and explain direct effects of relationships on system structures.	16 (38)	"Vegetative cover increases as the growing season lengthens. The number of stomata in leaves decreases, as there is so much carbon dioxide in the atmosphere that fewer are needed to absorb it. The number of plants adapted to nutrient-poor environments decreases as the amount of nitrogen and phosphorus increases." id75
3. Analyzing the whole system	3a: Describe indirect effects and feedback loops. 3c: Predict and explain consequences to system function.	10 (24)	"Rising temperatures also pose challenges: conditions are likely to improve for various pest insects. Globally, warming will have varying effects in different places. In some countries, droughts will increase, posing major challenges for vegetation. In other countries, global warming may even prove beneficial for vegetation as the growing season lengthens." id102
4. Reasoning across systems	4a: Recognize patterns across systems to make generalizations about systems with similar underlying structure or function. 4c: Identify how systems intersect to explain the ways that one system's function can impact another system across biological levels of organization.	6 (14)	"As plants form the foundation of ecosystems, changes in their growth can affect entire ecosystems. Changes in the length and timing of the growing season can also affect the structure of ecosystems and the relationships between the organisms that inhabit them." id99

Table 5: Number of occurrences of the inductive codes denoting naïve conceptions related to the core concept evolution

Level	Intentional adaptation n (%)	Survival of the fittest n (%)
1. Identifying and describing the system	5 (55.6)	4 (50.0)
2. Analysing within the system	2 (22.2)	3 (37.5)
3. Analysing the whole system	2 (22.2)	1 (12.5)
4. Reasoning across systems	-	-
Total	9 (100)	8 (100)

**Figure 1:** Distribution of core concepts demonstrated by students at each systems thinking skill level

will cope best with the changing conditions, while the weakest will be eliminated." [id103, Level 1].

DISCUSSION

This study aimed to explore differences in systems thinking skills and their connections to domain-specific conceptual knowledge among undergraduate biology students completing a scenario-based task on vegetation responses and the resulting consequences in boreal forest ecosystems in the face of climate change. At the time of writing and to the best of our knowledge, this is among the first studies to utilize the BST assessment framework proposed by Momsen et al. (2022). The value of this framework is evident in its attempt to organize systems thinking skills into hierarchical levels to inform both instruction and assessment. The framework is also easily adaptable to scenario-based case tasks, which also consider relevant elements of domain-specific conceptual knowledge. These types of tasks provide important qualitative insights into the way in which systems thinking skills are actualized (Redman et al., 2021). The task used in this study was designed to require both the application of conceptual knowledge and the use of systems thinking skills formulated in the BST framework. The open-ended and multifaceted nature of the task enabled us to qualitatively analyze a wide range of conceptual elements related to all five core concepts in undergraduate biology (Brewer and Smith, 2011). Compared to previous studies, this study involved a unique sample of undergraduate students, all of whom had completed the same introductory 1st-year courses covering these central topics.

Differences in Systems Thinking Skills

All eight systems thinking skills under assessment were exhibited with an expected degree of variation between individuals. Ten students remained only at the first level of the framework,

exhibiting the foundational skills of identifying and describing system structures and relationships between them, which is a reasonable expectation already in younger students (Eilam, 2012; Sommer and Lücken, 2010). The descriptions and explanations they provided were declarative in nature, reflecting reliance on the information provided in the scenario text. The largest proportion of students exhibited skills belonging to the second level, meaning that they identified relevant system characteristics based on the scenario and predicted direct effects of the responses on the vegetation they identified. Understanding the causal effects between increased temperature, carbon dioxide concentration, and photosynthetic efficiency is essential in explaining the increases in vegetative biomass (Zhu et al., 2016). In our study, this was demonstrated in students identifying and describing the causal relationships between increased atmospheric carbon dioxide, warming climate, and biomass growth with ease. This aligns with previous research showing that learners more readily reason consequences resulting from monocausal relationships (Perkins and Grotzer, 2005; Plate, 2010).

The interactions between climate change, biodiversity loss, and ecosystem functions are complex and often result in emergent challenges that are not directly evident or observable (Davila et al., 2021; Shepardson et al., 2011). To identify and analyze such challenges, students should be operating at the two highest levels of the BST framework (3. Analyzing the whole system and 4. Reasoning across systems). These levels include skills that are demanding for students, as reasoning about multiple consequences requires the ability to predict indirect and emergent effects (Averdunk et al., 2025; Gilissen et al., 2021). This has been established as a key distinction between novices and experts (Chi and VanLehn, 2012; Hmelo-Silver and Pfeffer, 2004). Our result that slightly over a 3rd of 2nd-year undergraduate biology students exhibited these skills is encouraging. Linking concepts and processes across the levels of biological organization, navigating coherently between the micro and the macro, is a skill at the fourth level that only six students exhibited. Acquiring this demanding skill could benefit from instructional teaching where interrelations between levels are explicitly integrated (Asshoff et al., 2020).

The BST framework allows both researchers and teachers to assess the quality of systems thinking and distinguish at which levels students might be operating. The scenario-based case design was effective in revealing important qualitative differences in the systems thinking skills students demonstrated. The present study adds to the field by highlighting that in a sample of undergraduate students, both novice- and expert-like systems thinking skills exist.

Conceptual Knowledge and Systems Thinking

The diversity of student conceptions about climate change and its effects has been well documented (Holt et al., 2021; Shepardson et al., 2009; Varela et al., 2020). These studies, while important, have been limited in scope given that the perturbations to ecosystems and the repercussions across levels of biological organization require conceptual

knowledge covering the whole range of core concepts in biology, as the results of this study demonstrate. All five core concepts were present at each systems thinking skill level, though understandably, the more comprehensive answers contained more conceptual elements. The lower frequencies of conceptual elements related to PTEM and IFES were most likely due to their primary focus on processes at the levels of cells and organs. Students who integrated these conceptual elements while exhibiting only the lower-level systems thinking skills did not elaborate on consequences at the macro-level of ecosystems. In identifying and describing relationships between and within biological system structures at the macro level, students rely on their conceptual understanding of ecological processes (Grotzer and Basca, 2003; Mambrey et al., 2022). This was reflected in the high frequency of conceptual elements related to SF and systems, especially in students who exhibited systems thinking skills at the higher levels.

Applying knowledge of evolutionary processes became evident when students explained why certain traits increase the ability to survive and reproduce under the changed conditions of increased temperature, carbon dioxide concentration, and nutrient availability in the soil. These explanations were also where the naïve conceptions tended to occur. As the scenario text did not explicitly mention concepts natural selection or relative fitness, the task effectively revealed the students' underlying conceptual models about these crucial phenomena. Integrating scientifically accurate conceptual knowledge of evolutionary processes was clearly necessary for exhibiting more advanced systems thinking skills. This connection speaks for the usefulness of knowledge about biological evolution (Borgerding and Kaya, 2022; Kiviluoma et al., 2024).

Domain-specific conceptual knowledge should be considered an inseparable component of systems thinking. The extent of domain-specific conceptual knowledge can limit students in constructing explanations that would exhibit higher systems thinking skill levels (Jin et al., 2019). Our results support the notion that the ability to integrate knowledge of the core concepts and their elements forms a foundation for more advanced systems thinking skills. These connections should be brought to the forefront of future research. Having strong and integrated conceptual knowledge of biological phenomena may support students in reasoning about and analyzing systems in relation to one another, a skill that is arguably needed for effective sustainability transformations (Brundiers et al., 2021; Hofman-Bergholm, 2018; Södervik et al., 2021).

Limitations and Future Directions

The cross-sectional design and small sample size limit the generalizability of the results presented in this article. In addition, the study's focus on a specific ecological scenario may not fully capture the breadth of systems thinking skills applicable to other biological contexts. Based on the result that students did not exhibit systems thinking skills beyond the foundational ones at the first level, we cannot infer that they would not possess these skills in different contexts. This

is a clear shortcoming of open-ended tasks such as the one we used, and could be remedied by complementary data, such as semi-structured interviews where students are asked to provide justifications for their written answers.

The scenario text did not include source information, and thus, we are unable to infer how students evaluated the credibility of the information provided. Assessing systems thinking skills with the analysis method employed in this study is labour-intensive and subject to interpretative biases. However, we believe the scenario-based case design to be appropriate to assess undergraduate students to capture qualitative differences which might elude other previously utilized methods, such as concept mapping and multiple-choice questionnaires (Khajeloo and Siegel, 2022; Mambrey et al., 2020). We acknowledge that using the same task to measure both systems thinking skills and conceptual knowledge may conflate crucial aspects of the two. This study provides a valuable starting point to continue the discussion on the role of conceptual knowledge in reasoning about complex real-world natural phenomena via systems thinking skills.

While the BST framework proved useful in this context, ongoing refinement and validation of the framework are necessary to ensure its broader applicability and effectiveness. Future research could build on this study by utilizing similar scenario-based designs across diverse educational settings and with different student populations. Conceptual knowledge could be measured with a distinct instrument to enhance validity. This would also allow for much-needed correlational analyses between conceptual knowledge and systems thinking skills. Longitudinal studies are also needed to capture the learning progression of systems thinking skills.

Educational Implications

Higher education needs to address the gap in learning progression from lower to higher levels of systems thinking (Jacobson and Wilensky, 2006). Younger students already demonstrate the capacity to operate at the lower levels of systems thinking (Ben-Zvi Assaraf and Orion, 2010; Mambrey et al., 2022). However, operating at the higher levels of systems thinking remains challenging, as students often focus on monocausal and direct relationships rather than complex feedback loop networks (Grotzer and Basca, 2003; Perkins and Grotzer, 2005). By integrating systems thinking into the curriculum, educators can better prepare students to tackle real-world wicked problems such as climate change, where understanding the complexity of ecological interactions is crucial (Moore-Anderson, 2023). This could involve interdisciplinary teaching strategies that link biological core concepts with other scientific domains (Liu, 2023; Monroe et al., 2019). Interdisciplinary instructional approaches also emphasize the interconnectedness of natural systems. These connections should be made explicit, and one starting point is to pay attention to the language used. Practical instructional strategies for facilitating knowledge transfer have talked about moving from surface-level understanding to deeper structures

and sequential relationships (Chi and VanLehn, 2012). This is akin to the language of systems thinking skills (Gilissen et al., 2021; Momsen et al., 2022). If we are to foster and assess systems thinking skills in our students, we should clarify and unify our use of systems language in the classroom (Fanta et al., 2020; Gilissen et al., 2020).

The BST framework provides a promising tool for educators aiming to enhance systems thinking skills in their educational practice. The framework's hierarchical organization of skills allows for targeted instructional strategies that can address specific areas of weakness identified in this study. For instance, incorporating more scenario-based tasks that require students to explore indirect and long-term ecological consequences may foster the crucial understanding of complex system interactions (Grotzer and Basca, 2003). Concept mapping also appears to be an effective instructional strategy for visualizing students' systems thinking (Khajeloo and Siegel, 2022). Teaching concepts related to ecosystems together with the skills to organize the ecosystem structures and dynamics seems to be effective in promoting a more comprehensive understanding of complex processes (Grotzer and Basca, 2003; Mambrey et al., 2022). Combining the BST framework with such strategies could provide valuable avenues for more integrated education. Educators need to be aware of these interactions when designing lessons and learning materials, as scaffolding and dedicated time for reflective exercises are crucial to allow for engagement with systems thinking (Riess and Mischo, 2010).

CONCLUSION

This article set out to address two research questions, the first of which focused on describing the diversity of systems thinking skills among undergraduate biology students. Most students exhibited the basic skills of recognizing and articulating salient interactions within the system. Only six students exhibited the higher-level skills to reason across different systems and biological levels of organization. The second research question expanded on these results by exploring how the exhibited systems thinking skills were associated with students' conceptual knowledge. Higher-level systems thinking was associated with more diverse and integrated use of biology core concepts, particularly about evolutionary processes. Lower-level systems thinking was more frequently accompanied by naïve conceptions of evolution (e.g., deterministic language, uniform adaptation, survival of only the "fittest"). These results highlight that systems thinking presents a unique kind of challenge for learning in higher education.

ETHICS AND DISCLOSURE STATEMENT

The study followed the ethical principles and instructions set by the Finnish National Board on Research Integrity (TENK). The research did not require ethical review as the conditions of the research design do not meet the conditions set out by TENK. The authors report there are no competing interests to declare.

FUNDING DETAILS

This work was supported by Research Funds of the University of Helsinki via the project of Cultivating Expertise in the Learning of Life Sciences, CELLS Grant HY/716/05.01.07/2018; and The Finnish Cultural Foundation under personal working grant for the first author.

REFERENCES

- Asshoff, R., Düsing, K., Winkelmann, T., & Hammann, M. (2020). Considering the levels of biological organisation when teaching carbon flows in a terrestrial ecosystem. *Journal of Biological Education*, 54(3), 287-299.
- Averdunk, C., Zabel, J., & Bergmann-Gering, A. (2025). From individuals to populations to cyclic interactions: Investigating secondary students' descriptions of food web interactions. *Journal of Biological Education*, 60, 402-428.
- Ben-Zvi Assaraf, O., & Orion, N. (2005). Development of system thinking skills in the context of earth system education. *Journal of Research in Science Teaching*, 42(5), 518-560.
- Ben-Zvi Assaraf, O., & Orion, N. (2010). System thinking skills at the elementary school level. *Journal of Research in Science Teaching*, 47(5), 540-563.
- Bergan-Roller, H.E., Galt, N.J., Helikar, T., & Dauer, J.T. (2020). Using concept maps to characterise cellular respiration knowledge in undergraduate students. *Journal of Biological Education*, 54(1), 33-46.
- Boersma, K., Waarlo, A.J., & Klaassen, K. (2011). The feasibility of systems thinking in biology education. *Journal of Biological Education*, 45(4), 190-197.
- Borgerding, L.A., & Kaya, F. (2022). Is knowledge of evolution useful? A mixed methods examination of college biology students' views. *International Journal of Science Education*, 44(2), 271-296.
- Braun, V., & Clarke, V. (2006). Using thematic analysis in psychology. *Qualitative Research in Psychology*, 3(2), 77-101.
- Brewer, C.A., & Smith, D. (Eds.). (2011). *Vision and Change in Undergraduate Biology Education: A Call to Action*. United States: American Association for the Advancement of Science.
- Brundiers, K., Barth, M., Cebrián, G., Cohen, M., Diaz, L., Doucette-Remington, S., Dripps, W., Habron, G., Harré, N., Jarchow, M., Losch, K., Michel, J., Mochizuki, Y., Rieckmann, M., Parnell, R., Walker, P., & Zint, M. (2021). Key competencies in sustainability in higher education-toward an agreed-upon reference framework. *Sustainability Science*, 16(1), 13-29.
- Cary, T., & Branchaw, J. (2017). Conceptual elements: A detailed framework to support and assess student learning of biology core concepts. *CBE Life Sciences Education*, 16(2), 1-10.
- Checkland, P. (2012). Four conditions for serious systems thinking and action. *Systems Research and Behavioral Science*, 29(5), 465-469.
- Chi, M.T.H., & VanLehn, K.A. (2012). Seeing deep structure from the interactions of surface features. *Educational Psychologist*, 47(3), 177-188.
- Cohen, L., Manion, L., & Morrison, K. (2018). Coding and content analysis. In: *Research Methods in Education*. 8th ed. London: Routledge, pp. 668-685.
- Cooper, R.A. (2017). Natural selection as an emergent process: Instructional implications. *Journal of Biological Education*, 51(3), 247-260.
- Davila, F., Plant, R., & Jacobs, B. (2021). Biodiversity revisited through systems thinking. *Environmental Conservation*, 48(1), 16-24.
- Dugan, K.E., Mosyjowski, E.A., Daly, S.R., & Lattuca, L.R. (2022). Systems thinking assessments in engineering: A systematic literature review. *Systems Research and Behavioral Science*, 39(4), 840-866.
- Eilam, B. (2012). System thinking and feeding relations: Learning with a live ecosystem model. *Instructional Science*, 40(2), 213-239.
- Fanta, D., Braeutigam, J., & Riess, W. (2020). Fostering systems thinking in student teachers of biology and geography - an intervention study. *Journal of Biological Education*, 54(3), 226-244.
- Gilbert, S.F., & Sarkar, S. (2000). Embracing complexity: Organicism for the 21st century. *Developmental Dynamics*, 219(1), 1-9.
- Gilissen, M.G.R., Knippels, M.C.P.J., & Van Joolingen, W.R. (2021). Fostering students' understanding of complex biological systems. *CBE Life Sciences Education*, 20(3), 1-15.
- Gilissen, M.G.R., Knippels, M.C.P.J., & Van Joolingen, W.R. (2020). Bringing systems thinking into the classroom. *International Journal of Science Education*, 42(8), 1253-1280.
- Gilissen, M.G.R., Knippels, M.C.P.J., Verhoeff, R.P., & Van Joolingen, W.R. (2019). Teachers' and educators' perspectives on systems thinking and its implementation in Dutch biology education. *Journal of Biological Education*, 54(5), 485-496.
- Gregory, T.R. (2009). Understanding natural selection: Essential concepts and common misconceptions. *Evolution: Education and Outreach*, 2(2), 156-175.
- Grohs, J.R., Kirk, G.R., Soledad, M.M., & Knight, D.B. (2018). Assessing systems thinking: A tool to measure complex reasoning through ill-structured problems. *Thinking Skills and Creativity*, 28, 110-130.
- Grotzer, T.A., & Basca, B.B. (2003). How does grasping the underlying causal structures of ecosystems impact students' understanding? *Journal of Biological Education*, 38(1), 16-29.
- Herring, E., & Radick, G. (2019). Emergence in biology: From organicism to systems biology. In: Gibb, S., Hendry, R., & Lancaster, T., (Eds.), *The Routledge Handbook of Emergence*. London: Routledge, p352-362.
- Hmelo-Silver, C.E., Jordan, R., Eberbach, C., & Sinha, S. (2017). Systems learning with a conceptual representation: A quasi-experimental study. *Instructional Science*, 45(1), 53-72.
- Hmelo-Silver, C.E., & Pfeffer, M.G. (2004). Comparing expert and novice understanding of a complex system from the perspective of structures, behaviors, and functions. *Cognitive Science*, 28(1), 127-138.
- Hofman-Bergholm, M. (2018). Could education for sustainable development benefit from a systems thinking approach? *Systems*, 6(4), 43.
- Hogan, K. (2000). Assessing students' systems reasoning in ecology. *Journal of Biological Education*, 35(1), 22-28.
- Holme, P., & Rocha, J.C. (2023). Networks of climate change: Connecting causes and consequences. *Applied Network Science*, 8(10), 1-20.
- Holt, E.A., Heim, A.B., Sexton, J., & Hinerman, K. (2021). Undergraduate student conceptions of climate change impacts on animals. *Ecosphere*, 12(8), e03706.
- Jacobson, M.J., & Wilensky, U. (2006). Complex systems in education: Scientific and educational importance and implications for the learning sciences. *Journal of the Learning Sciences*, 15(1), 11-34.
- Jaureguiberry, P., Titeux, N., Wiemers, M., Bowler, D.E., Coscieme, L., Golden, A.S., Guerra, C.A., Jacob, U., Takahashi, Y., Settele, J., Diaz, S., Molnár, Z., & Purvis, A. (2022). The direct drivers of recent global anthropogenic biodiversity loss. *Science Advances*, 8(45), eabm9982.
- Jin, H., Shin, H.J., Hokayem, H., Qureshi, F., & Jenkins, T. (2019). Secondary students' understanding of ecosystems: A learning progression approach. *International Journal of Science and Mathematics Education*, 17(2), 217-235.
- Khajeloo, M., & Siegel, M.A. (2022). Concept map as a tool to assess and enhance students' system thinking skills. *Instructional Science*, 50(4), 571-597.
- Kitano, H. (2002). Systems biology: A brief overview. *Science*, 295(5560), 1662-1664.
- Kiviluoma, T., Savolainen, R., Åström, H., & Södervik, I. (2024). Diverse paths, stable differences role of prior knowledge in learning biology over undergraduate years. *International Journal of Science Education*, 48(7), 933-952.
- Liu, S.C. (2023). Examining undergraduate students' systems thinking competency through a problem scenario in the context of climate change education. *Environmental Education Research*, 29(12), 1780-1795.
- Mambrey, S., Schreiber, N., & Schmiemann, P. (2022). Young students' reasoning about ecosystems: The role of systems thinking, knowledge, conceptions, and representation. *Research in Science Education*, 52, 79-98.
- Mambrey, S., Timm, J., Landskron, J.J., & Schmiemann, P. (2020). The impact of system specifics on systems thinking. *Journal of Research in Science Teaching*, 57(10), 1632-1651.
- McLure, F., Won, M., & Treagust, D.F. (2020). Students' understanding of the emergent processes of natural selection: The need for ontological conceptual change. *International Journal of Science Education*,

- 42(9), 1485-1502.
- Meadows, D.H. (2008). In: Wright, D., (Ed.), *Thinking in Systems: A Primer*. London: Earthscan Dunstan House.
- Mehren, R., Rempfler, A., Buchholz, J., Hartig, J., & Ulrich-Riedhammer, E.M. (2018). System competence modelling: Theoretical foundation and empirical validation of a model involving natural, social and human-environment systems. *Journal of Research in Science Teaching*, 55(5), 685-711.
- Momsen, J., Speth, E.B., Wyse, S., & Long, T. (2022). Using systems and systems thinking to unify biology education. *CBE Life Sciences Education*, 21(2), es3.
- Monroe, M.C., Plate, R.R., Oxarart, A., Bowers, A., & Chaves, W.A. (2019). Identifying effective climate change education strategies: A systematic review of the research. *Environmental Education Research*, 25(6), 791-812.
- Moore-Anderson, C. (2023). Designing a curriculum for the networked knowledge facet of systems thinking in secondary biology courses: A pragmatic framework. *Journal of Biological Education*, 57(2), 370-385.
- Perkins, D.N., & Grotzer, T.A. (2005). Dimensions of causal understanding: The role of complex causal models in students' understanding of science. *Studies in Science Education*, 41(1/2), 117-165.
- Plate, R. (2010). Assessing individuals' understanding of nonlinear causal structures in complex systems. *System Dynamics Review*, 26(1), 19-33.
- Ratinen, I., Kashani, J.S., & Linnanen, L. (2024). Challenges in modelling and measuring sustainability competencies crucial to successful sustainability transitions. *Environmental Education Research*, 31(3), 548-565.
- Redman, A., Wiek, A., & Barth, M. (2021). Current practice of assessing students' sustainability competencies: A review of tools. *Sustainability Science*, 16(1), 117-135.
- Riess, W., & Mischo, C. (2010). Promoting systems thinking through biology lessons. *International Journal of Science Education*, 32(6), 705-725.
- Ripple, W.J., Wolf, C., Gregg, J.W., Rockström, J., Mann, M.E., Oreskes, N., Lenton, T.M., Rahmstorf, S., Newsome, T.M., Xu, C., Svenning, J.C., Pereira, C.C., Law, B.E., & Crowther, T.W. (2024). The 2024 state of the climate report: Perilous times on planet Earth. *BioScience*, 74, 812-824.
- Rousseau, D. (2014). Systems philosophy and the unity of knowledge. *Systems Research and Behavioral Science*, 31(2), 146-159.
- Seher Budak, U., & Defne Ceyhan, G. (2024). Research trends on systems thinking approach in science education. *International Journal of Science Education*, 46(5), 485-502.
- Shepardson, D.P., Niyogi, D., Choi, S., & Charusombat, U. (2009). Seventh grade students' conceptions of global warming and climate change. *Environmental Education Research*, 15(5), 549-570.
- Shepardson, D.P., Niyogi, D., Choi, S., & Charusombat, U. (2011). Students' conceptions about the greenhouse effect, global warming, and climate change. *Climatic Change*, 104(3), 481-507.
- Södervik, I., Nousiainen, M., & Koponen, I.T. (2021). First-year life science students' understanding of the role of plants in the ecosystem—A concept network analysis. *Education Sciences*, 11(8), 369.
- Sommer, C., & Lücken, M. (2010). System competence - are elementary students able to deal with a biological system? *Nordic Studies in Science Education*, 6(2), 125-143.
- Sweeney, L.B., & Sterman, J.D. (2000). Bathtub dynamics: Initial results of a systems thinking inventory. *System Dynamics Review*, 16(4), 249-286.
- Tripto, J., Assaraf, O.B.Z., Snapir, Z., & Amit, M. (2017). How is the body's systemic nature manifested amongst high school biology students? *Instructional Science*, 45(1), 73-98.
- Varela, B., Sesto, V., & García-Rodeja, I. (2020). An investigation of secondary students' mental models of climate change and the greenhouse effect. *Research in Science Education*, 50(2), 599-624.
- Verhoeff, R.P., Knippels, M.C.P.J., Gilissen, M.G.R., & Boersma, K.T. (2018). The theoretical nature of systems thinking. Perspectives on systems thinking in biology education. *Frontiers in Education*, 3, 1-11.
- Von Bertalanffy, L. (1968). *General System Theory: Foundations, Development, Applications*. United States: Braziller.
- Voulvoulis, N., Giakoumis, T., Hunt, C., Kioupi, V., Petrou, N., Souliotis, I., Vaghela, C., & binti Wan Rosely, W.I.H. (2022). Systems thinking as a paradigm shift for sustainability transformation. *Global Environmental Change*, 75, 102544.
- Wennersten, L., Wanselin, H., Wikman, S., & Lindahl, M. (2023). Interpreting students' ideas on the availability of energy and matter in food webs. *Journal of Biological Education*, 57(1), 3-23.
- Zangori, L., & Koontz, J.A. (2017). Supporting upper-level undergraduate students in building a systems perspective in a botany course. *Journal of Biological Education*, 51(4), 399-411.
- Zhu, Z., Piao, S., Myneni, R.B., Huang, M., Zeng, Z., Canadell, J.G., Ciais, P., Sitch, S., Friedlingstein, P., Arneeth, A., Cao, C., Cheng, L., Kato, E., Koven, C., Li, Y., Lian, X., Liu, Y., Liu, R., Mao, J.,... & Zeng, N. (2016). Greening of the earth and its drivers. *Nature Climate Change*, 6(8), 791-795.

APPENDIX

Scenario

Slide 1. You work as an intern at the Natural Resources Institute Finland (Luke). Together with other experts, your task is to discuss the growth of Finnish forests and possible changes in them. Read the following text carefully to ensure that you understand the content. After each section of the text, you will be presented with questions. You are asked to answer using your own knowledge and reasoning, without relying on the text. Even if you are unsure of the answer, try to explain what you think the question is referring to. You can proceed at your own pace and use the arrow key to move forward. Please note that you will not be able to return to the previous page.

Slide 2. According to studies by Luke, the growth of Finnish forests has increased over the past decades. Similar results have been obtained when studying the extent of the global vegetated area. In most terrestrial regions, the proportion of vegetated area has grown considerably over the past 20 years. In Finland, this means that forest farming is expanding northwards into increasingly marginal areas. On the other hand, we hear almost daily about climate change and biodiversity loss. The information provided above confuses the discussants, and you are asked to comment.

Slide 3. According to studies, the length of the growing season in northern regions has increased significantly over the last decade. On average, the growing season begins five days earlier and ends two days later than before. The warming climate accelerates photosynthesis and the growth of trees, as well as the overall circulation of matter in the ecosystem. A warming environment increases the release of nutrients from the soil, which further promotes the growth of trees. The increased carbon dioxide concentration in the atmosphere explains most of the changes in vegetated areas. Other reasons include increased nitrogen concentrations, other climate changes, and unknown factors.

Slide 4. However, research on plant fossils has shown that plants have adapted to increased atmospheric carbon dioxide levels and a warming climate in the past. When carbon dioxide concentrations were even higher and the climate warmer than today, trees used carbon dioxide and water as efficiently, or even more efficiently, than trees today. At present, plant leaves seem to be using water more and more efficiently. Together, carbon dioxide and heat accelerate photosynthesis, resulting in faster tree growth. It seems that plants have multiple ways of adapting to changing conditions. The discussants ask clarifying questions. Answer the questions on the next page.

Task: Based on your prior knowledge and the information in the text, evaluate how vegetation will respond to the changing conditions both locally and elsewhere around the globe over the next few decades. What kinds of challenging consequences might arise from this situation?

Model Answer

In Finland, the relationships between species will change significantly. Deciduous trees will spread from the south and occupy more land area, while coniferous trees will become increasingly abundant in the north. However, north of the Arctic Circle (sub-Arctic), plants will no longer have any habitats to retreat to. Globally, plant species adapted to dry and temperate conditions will thrive and become more numerous. As photosynthetic capacity increases, plants will allocate resources to growth at the expense of other functions, such as defence. The current climate change is occurring significantly faster than previous ones, which undermines/weakens the ability of plants to adapt. It is also worth remembering that increased temperatures and carbon dioxide concentrations enhance the photosynthetic capacity only up to a certain point/limit. Accelerated warming and lengthier growing seasons can have unpleasant consequences, and there are already evident changes in plant phenology. The decrease in snow cover threatens many overwintering plants. As a result of warming, previously non-native species are spreading from the south. Various pests and parasites pose a particular threat to native plant species.