JOURNAL OF BALTIC SCIENCE EDUCATION

ISSN 1648-3898 /Print/
ISSN 2538-7138 /Online/

EXPLORING LOWER-SECONDARY SCHOOL STUDENTS' SYSTEMS THINKING PERFORMANCE IN ECOLOGICAL ISSUES

Ruying Li,
Gaofeng Li

Abstract. *Exploring students' systems thinking (ST) is essential in enhancing science learning, but existing studies have failed to understand students' ST fully as it relates to ecological issues. This study aimed to fill the aforementioned literature gap by exploring lower-secondary school students' ST regarding ecological issues. The Systems Thinking Test regarding Ecological Issues, which measures four ST skills (system organisation, behaviour, application, and evaluation), was administered to 1,092 lower-secondary school students. The results reveal low ST performance in ecological issues, with students finding it particularly difficult to identify interactions among components and understand system characteristics. Furthermore, most lacked reflective consciousness and consideration of the diverse dimensions of ecological issues, resulting in monocausal reasoning in system decision-making and evaluation. Comparatively, urban school students performed better than their rural counterparts; additionally, an item-level analysis revealed that climate warming was challenging for the students to understand. This study suggests that greater efforts should be made to address students' drawbacks and that multi-perspectival teaching is necessary in the context of ecological issues. The addition of system decision-making and evaluation in assessments can enable a broader understanding of ST.*

Keywords: *environment education, lower-secondary school, partial credit model, sustainable development, systems thinking*

Ruying Li
Shaanxi Normal University, China
Gaofeng Li
Shaanxi Normal University, China

Introduction

Human activities such as deforestation, overfishing, and environmental pollution have endangered the survival of many species; for example, commercial whaling and marine garbage have brought whales close to extinction. To achieve a harmonious co-existence of humanity and nature, the United Nations has launched a program titled 'Education for Sustainable Development'. Accordingly, understanding of ecological issues, such as climate change and biodiversity loss has become particularly stressed in environmental education and sustainable development (Mambrey et al., 2022), and the ecosystem has emerged as an important aspect in international science curricula (Australian Curriculum, Assessment and Reporting Authority, n.d.; Ministry of Education, & P. R. China, 2022; Next Generation Science Standards Lead States, 2013).

Ecological issues refer to environmental problems concerning organisms, and their interactions with each other and the environment (Ecology Center, 2023). These are complex systems that are difficult to understand, because of the inherent intricacies, and long-term effects of human actions (Fanta et al., 2020). Multiple dimensions (e.g., social, economic, and socio-cultural elements) must be considered for identifying the consequences of such issues (Fanta et al., 2020; Ke et al., 2020; Riess & Mischo, 2010; Schuler et al., 2018). However, students lacking a systematic perspective cannot fully appreciate these issues (Ke et al., 2020; Liu et al., 2011; Yang, 2005). To solve these issues effectively, students need the systems thinking (ST) skills (Hogan, 2002; Mambrey et al., 2022; Riess & Mischo, 2010) that are emphasized in international science education documents (e.g., National Research Council, 2010; Next Generation Science Standards Lead States, 2013). ST is the skill to reason about complex systems in accordance with system characteristics to create a holistic understanding of various phenomena for problem-solving and system evaluation (Fanta et al., 2020; Gilissen et al., 2020; NRC, 2010). Researchers in various fields advocate the necessity to promote students' ST in science learning (Gilissen et al., 2020; Schuler et al., 2018; Sommer & Lücken, 2010; Verhoeff et al., 2018). Moreover, complex and diverse perspectives of ecological issues would allow students to engage in ST about broader issues, and ultimately achieve global citizenship literacy (Ke et al., 2020; Lee et al., 2013; Sadler et al., 2007). Thus, it is essential to explore and develop students' ST in the context of ecological issues.

https://doi.org/10.33225/jbse/23.22.865

ISSN 1648–3898 /Print/
ISSN 2538–7138 /Online/

ST in the Ecological Context

According to previous studies, ST in science education incorporates not only the skill to identify interactions among system components and understand system characteristics (Ben-Zvi Assaraf & Orion, 2005; Brandstädter et al., 2012; Mehren et al., 2018; Sommer & Lücken, 2010) but also the skill to make predictions, decisions, and judgement based on system analysis (Ben-Zvi Assaraf & Orion, 2005; Evagorou et al., 2009; Mehren et al., 2018; Riess & Mischo, 2010) and make evaluations on the validity of system structures, decision-making, and the limitations of predictions (Fanta et al., 2020; National Research Council, 2010; Rosenkränzer et al., 2017).

Given that multiple components and interactions of ecosystems must be considered, studies have mostly focused on students' understanding of interdependent relations in ecosystems; for example, assessments of elementary school students require them to reason about food webs (Hokayem & Gotwals, 2016; Mambrey et al., 2020; Mambrey et al., 2022). At the secondary level, they focus on students' scientific explanations of ST concepts regarding ecosystems (e.g., indirect connections, feedback loops, and emergent properties) (Jin et al., 2019). However, these studies failed to cover the full range of ST skills needed by students for understanding and solving complex ecological issues, especially for making decisions and evaluating on the basis of system analysis. Although the direct impact of human actions on ecosystems has been incorporated in the assessment (Jin et al., 2019), it failed to provide opportunities for students to consider the other dimensions (e.g., society, economy, and socio-culture) indirect effects on causing or solving ecological problems.

Research on Lower-secondary School Students' ST Levels

Most studies (e.g., Hokayem & Gotwals, 2016; Jin et al., 2019; Mehren et al., 2018) have assumed that there is a gradual increase in the development of students' ST skills through learning progressions (LPs). Some researchers have defined ST using a three-level hierarchical model (from low to high), namely, analysis of system components, synthesis of system components, and problem-solving (Ben-Zvi Assaraf & Orion, 2010). Jin et al. (2019) defined a four-level LP for ST in an ecosystem based on students' response complexity patterns; the four levels are called no ideas (Level 1), individual organisms (Level 2), relationships and patterns (Level 3), and mechanisms (Level 4). Mehren et al. (2018) differentiated systems-thinking levels according to system complexity, including the number of components and interrelations, type of relations, and dealing with system properties.

Only a few ST measurements at the lower-secondary school level exist, especially for large groups of students (Brandstädter et al., 2012). Existing studies indicate a low starting point for ST among young students with regard to various fields. A small sample study of the hydro-cycle system indicated a relatively low performance of lower-secondary school students regarding ST skills in general (Ben-Zvi Assaraf & Orion, 2005). A small-scale comparison of the skill of understanding complex systems between experts and Grade 7 students using the Structure–Behaviour–Function model implied that novice students focused on the structural level (Hmelo-Silver & Pfeffer, 2004). An assessment of ST regarding ecosystems has revealed that most secondary school students tend to identify direct and indirect relationships (Jin et al., 2019). However, the specific difficulties hindering lower-secondary school students' ST in the context of ecological issues remain unclear.

Studies have also revealed a great improvement in ST performance following the introduction of teaching interventions at the lower-secondary school educational level (Ben-Zvi Assaraf & Orion, 2005; Hmelo-Silver et al., 2017; Riess & Mischo, 2010); this indicates the feasibility and potential of developing lower-secondary school students' ST.

Students' ST Performance in Different Groups

For a comprehensive evaluation of ST, it is important to detect differences in students' average performance among different subgroups. However, this question has not been sufficiently explored in ST research (Cox et al., 2019; Jin et al., 2019).

Gender science stereotypes have long been discussed; females are still considered to be underrepresented in different science fields (Brotman & Moore, 2008). However, the effect of gender on ST is unclear; research in different scientific contexts has yielded distinct results. A study conducted in engineering found that male students performed significantly better than female ones (Sweeney & Sterman, 2000). However, research on ecosystems and geographical systems has suggested no significant differences based on gender (Cox et al., 2019; Jin et al., 2019). Mambrey et al. (2020) found a similar reasoning pattern in elementary and lower-secondary school students, sug-

https://doi.org/10.33225/jbse/23.22.865

gesting that the ST of young students regarding ecosystems was independent of their age. However, a significant difference was found with respect to geographical ST between grades, especially among high school students (Cox et al., 2019). Research has found significant performance gaps in ST among schools from different locations in the United States (Jin et al., 2019). Because the above-mentioned studies have shown distinct results in different system-specific contexts, it is necessary to check the effects of the aforementioned variables on students' ST performance in the more complex context of ecological issues involving interactions between humans and ecosystems.

Research Aim and Questions

A full picture of students' ST regarding ecological issues is essential for promoting ST to achieve sustainable development. However, the existing studies failed to cover the full range of ST skills and the specific weaknesses that hinder students' development of ST. Moreover, it remains unclear in the literature whether students are able to contemplate the various dimensions involved in these complex issues. Thus, this study aimed to supplement the missing content by comprehensively evaluating on a large scale lower-secondary school students' ST regarding ecological issues. The following were the research questions for this study:

1. What is the current level of ST regarding ecological issues among lower-secondary school students?
2. In which specific aspects of ST regarding ecological issues do students experience the most problems?
3. How do students from different groups differ in their ST performance?

Research Methodology

Description of the Test to Measure Students' ST

The authors constructed a systems thinking test regarding ecological issues (STTEI) based on Mehren et al.'s (2018) ST framework; it incorporated comprehensive ST skills based on the latest insights from ST studies and was empirically validated in the context of geography and ecology (Mambrey et al., 2020). The items of the STTEI measured four skills in ST, which we regard as covering the full range of skills included in the existing literature (Ben-Zvi Assaraf & Orion, 2005; Brandstädter et al., 2012; Evagorou et al., 2009; Fanta et al., 2020; Mehren et al., 2018; National Research Council, 2010; Riess & Mischo, 2010; Sommer & Lücken, 2010), namely, system organisation, system behaviour, system application, and system evaluation. Items in system organisation refer to identifying ecosystem components and the interrelations among components. Items related to system behaviour require students to analyse the results of system changes based on the interactions involved and their understanding of the system characteristics. To apply the system, students were asked to make predictions and decisions based on a system-effect analysis. For the last skill, students were required to work on problems and determine the validity of the system structure, decisions made, and limitations of predictions. Second, these ST skills were differentiated into three levels based on performance complexity according to system-related structural and behavioural complexity, as described by Mehren et al. (2018). These levels are described below.

Level 1: Students identify low numbers of elements and isolated or monocausal relationships. Students' analysis and reasoning regarding systems are based on monocausal relations.

Level 2: Students identify a moderate number of elements and linear–indirect relationships. The analysis and reasoning are based on linear and indirect relationships.

Level 3: Students identify a large number of elements and complex or nonlinear relations. Students perform analysis and reasoning based on nonlinear and complex relations.

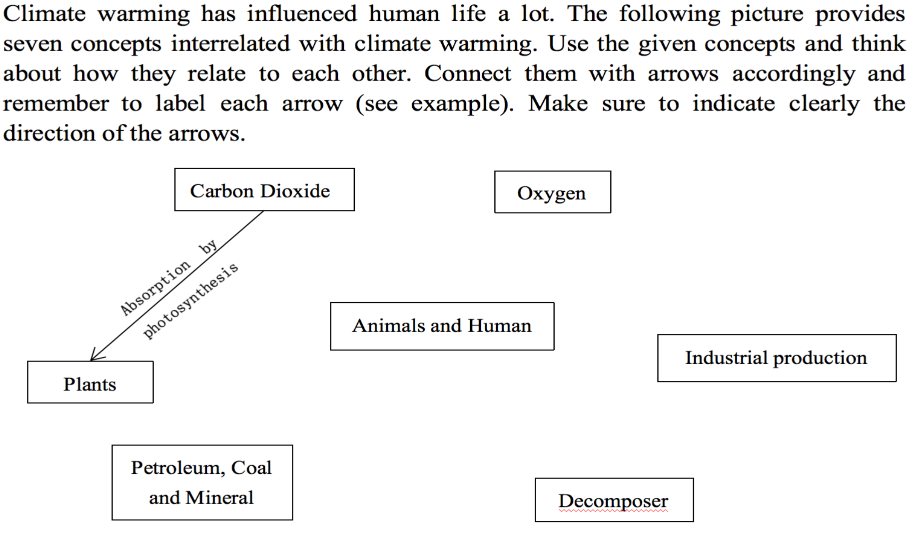
The STTEI comprised 13 items (ordered multiple choice, short answers, two-tied items, and extended response questions) to probe different levels of students' ST about ecological issues, and each item was allocated to one skill (Table 1). As climate change and sustainability problems have been the most prevalent ecological issues in the last decade (Fanta et al., 2020; You et al., 2018), the test was about issues highlighting sustainability as the context that could provide students with opportunities to explore multiple dimensions in ecological issues (e.g. climate warming, sustainable rainforest development, overfishing, industrial pollution, abuse of pesticides, and the absence of top predators). Items were scored using 0–2 or 0–3 point ranges according to the three levels of performance complexity. The two tied items and extended response questions gave students the opportunity to express their explanations of ecological issues. The concept map (CM) item is an example of an extended response question

https://doi.org/10.33225/jbse/23.22.865

ISSN 1648–3898 /Print/
ISSN 2538–7138 /Online/

(Figure 1). It was designed based on the context of climate warming to assess the extent to which students identify interrelations among components related to climate warming. The provided concepts included both biotic and abiotic components. The social element (industrial production) was included in this item. The other items of the STTEI are presented in the Appendix.

Figure 1
Concept Map Item (Item 5)



To ensure content validity, the item content and wording were evaluated and revised by expert review. A quantitative pilot test (n = 97) was conducted to validate the test instrument, and the Rasch partial credit model (PCM) was used to examine item fit statistics to address construct validity. Three items in the original version were eliminated because of low item discrimination (below .2). Subsequently, a field test (n = 456) was conducted to validate further the 13-item test. The expected a posteriori (EAP) reliability was .8, indicating acceptable internal consistency, and all items' mean-squares fell into the suitable range of .7 to 1.3 (Bond & Fox, 2007).

Table 1
Specific Information of Test Items

Skills required		Item context	Item number
System organisation	Identify system components	Pond ecosystem	Item 1
	Identify interrelations among components	Climate warming	Item 5
System behaviour	Understand emergence	Ecological equilibrium	Item 3
	Dynamic change	Absence of top predators	Item 8
	Identify feedback loop	Temperature change in forests	Item 11
	Cyclic thinking	Nutrition cycle	Item 10
System application	Make predictions	Industrial pollutant, Climate warming	Item 2 Item 6
	Make decisions	Climate warming, Sustainable development of rainforests	Item 7 Item 12
System evaluation	Evaluate the system structure	Overuse of pesticides	Item 4
	Determine the validity of the system structure, decisions, and limitations of predictions	Absence of top predators Overfishing problems	Item 9 Item 13

https://doi.org/10.33225/jbse/23.22.865

Participants and Data Collection

A sample representative of the diversity of lower-secondary school students is required to obtain more robust statistical results and meet the purpose of the study, such as the requirement of comparing students' performance across genders, grades, and school locations. Thus, six lower-secondary schools in southern and northern regions of China were purposefully sampled. These schools varied in school settings, educational resources, and socio-economic status. According to the previous study, the sample size is determined by the standard error of measures, which should exceed the minimal requirement of 267 (Liu, 2020; Wu et al., 2016). In order to improve the accuracy of measurement, the sample size is four times larger than the required minimal sample size (the standard error of Rasch measures less than .1). All participants in these schools possessed knowledge about the ecosystem; a total of 1,183 students from Grades 7 and 8 involved in the study. After eliminating blank and invalid responses, information from 1,092 students was used for the analysis (Table 2).

Data were collected from November 2022 to December 2022. The purpose of the study and test content were reported to school principals to acquire permission. All students and teachers participated in the study voluntarily, and the test was conducted anonymously to protect students' privacy. The teachers ensured that students completed the test within 45 minutes. Before the test, teachers informed students of the aim of the test and that the results would be used exclusively for scientific research purposes. The teachers also promised students that their test performance would not affect their subject grades and encouraged them to write down their honest thoughts as much as possible.

Table 2
Demographic Data of the Participants

Demographic categories		Number of students	Percentage (%)
School location	Urban schools	592	54.2
	Rural schools	500	45.7
Gender	Male	565	51.7
	Female	527	48.2
Grade	Grade 7	568	52
	Grade 8	524	47.9

Data Scoring and Analysis

The developed scoring rubrics were used to score all students' responses. Ten percent of the randomly selected tests were scored by two independent raters (a PhD student and a lower-secondary school biology teacher) to check inter-rater reliability. An inter-rater reliability analysis using kappa statistics determined the consistency between raters, and the kappa's range was .62–.85, with a median of .75 (Cohen, 1968), indicating substantial agreement for each item from different raters (Landis & Koch, 1977).

This study used PCM analysis via the Test Analysis Module package in R software (Robitzsch et al., 2021) to establish the participants' ST levels on the test, as it has been deemed suitable for analysing polytomous data. The reliability of the EAP estimates was checked, and the weighted likelihood estimates (WLEs) were used as student proficiencies. A Wright (person–item) map was generated to quantify the locations of item difficulty and student performance on the same logit scale. The *t*-test was used to compare performances between the different sub-groups of participants (e.g., male vs. female). Differential item functioning (DIF) was applied to examine differences between student groups at the item level to provide further information on weaknesses and strengths with regard to students' ST (Wu et al., 2016).

https://doi.org/10.33225/jbse/23.22.865

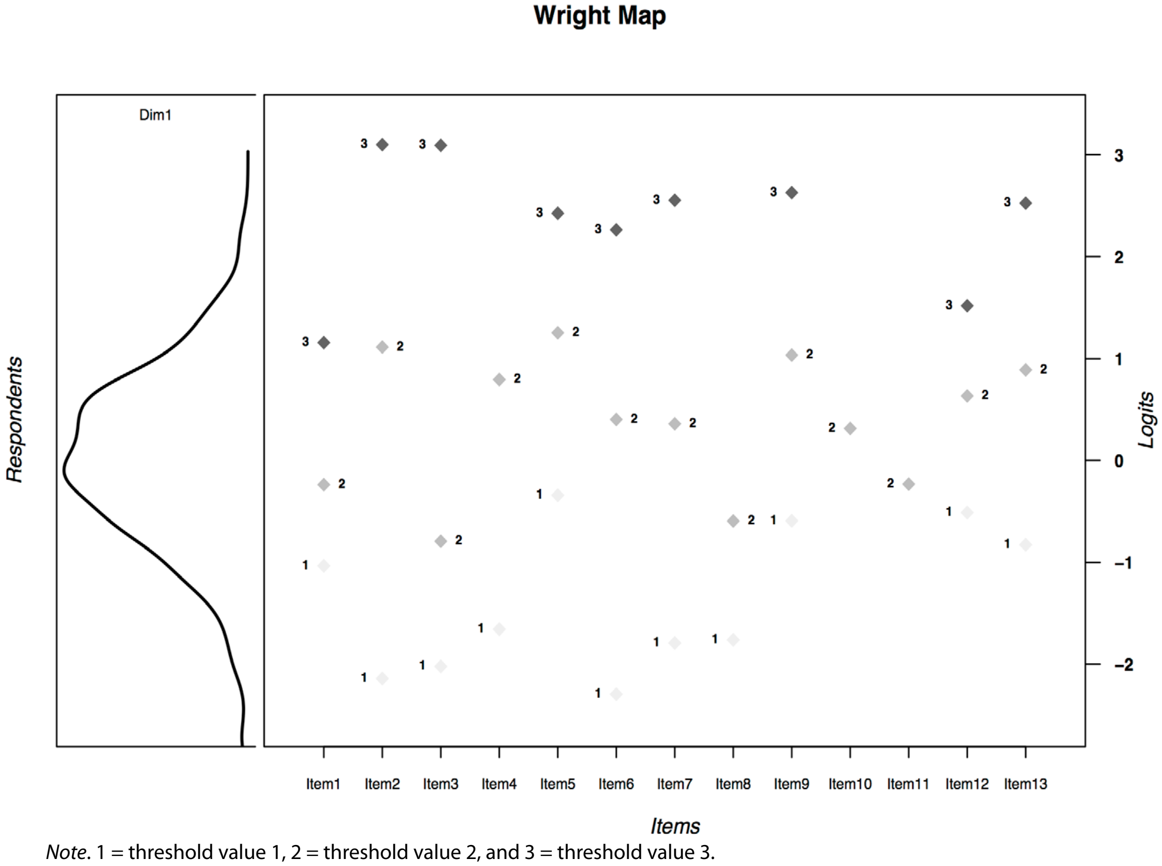
ISSN 1648–3898 /Print/
ISSN 2538–7138 /Online/

Research Results

Students' Overall Performance in ST Regarding Ecological Issues

In Figure 2, the left side of the Wright map displays the density distribution (which approximates a normal distribution) of the student performance (WLEs) on the test. The right side represents the distribution of the Thurstonian thresholds for each item. A comparison of the WLEs and item thresholds showed that only a small proportion of students had more than a 50% chance of achieving the third level (Figure 2).

Figure 2
Wright Map for ST Regarding Ecological Issues



Note. 1 = threshold value 1, 2 = threshold value 2, and 3 = threshold value 3.

The threshold values of each item level were calculated using PCM analysis (Table 3), and the mean threshold values of the item responses belonging to the same level across the ST skills were calculated (Wang & Song, 2021). The mean of the students' ability measures (WLEs) was compared with the mean threshold values of the different levels; when the mean WLEs exceeded the latter, it was determined that the student had reached a specific ST level. As shown in Table 3, the student ability measures reached, on average, Level 1 for each skill, and Level 3 was the most difficult to achieve for each skill. The students' mean ability (M = .047) for system organisation was higher than that for the other three skills.

https://doi.org/10.33225/jbse/23.22.865

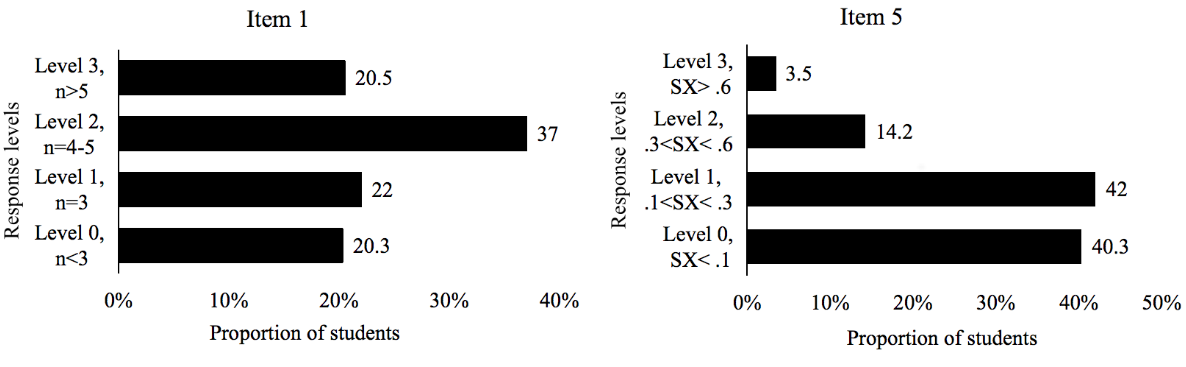
Table 3
Mean Threshold Values of Every Performance Level across ST

Skill	Level	Items and threshold values on different levels	Mean Threshold values	Participant ability
System organisation	Level1	I1(-1.034); I5(-.341)	-.688	.047
	Level2	I1(-.238); I5(1.253)	.508	
	Level3	I1(1.156); I5(2.426)	1.791	
System behaviour	Level1	I3(-2.02); I8(-1.760)	-.926	-.014
	Level2	I3(-.793); I8(-.594); I10(.313); I11(-.232)	.070	
	Level3	I3(3.092)	3.092	
System application	Level1	I2(-2.141); I6(-2.294); I7(-1.791); I12(-.512)	-1.685	-.009
	Level2	I2(1.112); I6(.402); I7(.359); I12(.633)	.627	
	Level3	I2(3.099); I6(2.263); I7(2.554); I12(1.519)	2.359	
System evaluation	Level1	I4(-1.656); I9(-.592); I13(-.828)	-.575	-.004
	Level2	I4(.794); I9(1.034); I13(.888)	1.619	
	Level3	I9(2.629); I13(2.525)	2.577	

Difficulties Experienced with Regard to Different ST Skills for Ecological Issues;
Ability to Identify Components and System Interactions

The analyses of the students' identification of components in the pond ecosystem (Item 1) indicated that most students (57.5%) correctly identified a moderate (Level 2) or high (Level 3) number of elements (Figure 3). However, one-fifth of the students could not correctly identify the system components. The analyses of students' wrong answers indicated that they had some misconceptions regarding hidden elements; for example, the students confused 'green algae' with 'bacteria' and sorted 'bacteria' into the producer and 'green algae' into the decomposer categories. Furthermore, some students misclassified 'bacteria' as an abiotic factor in the pond ecosystem.

Figure 3
Distribution of Students' Responses on Items 1 and 5



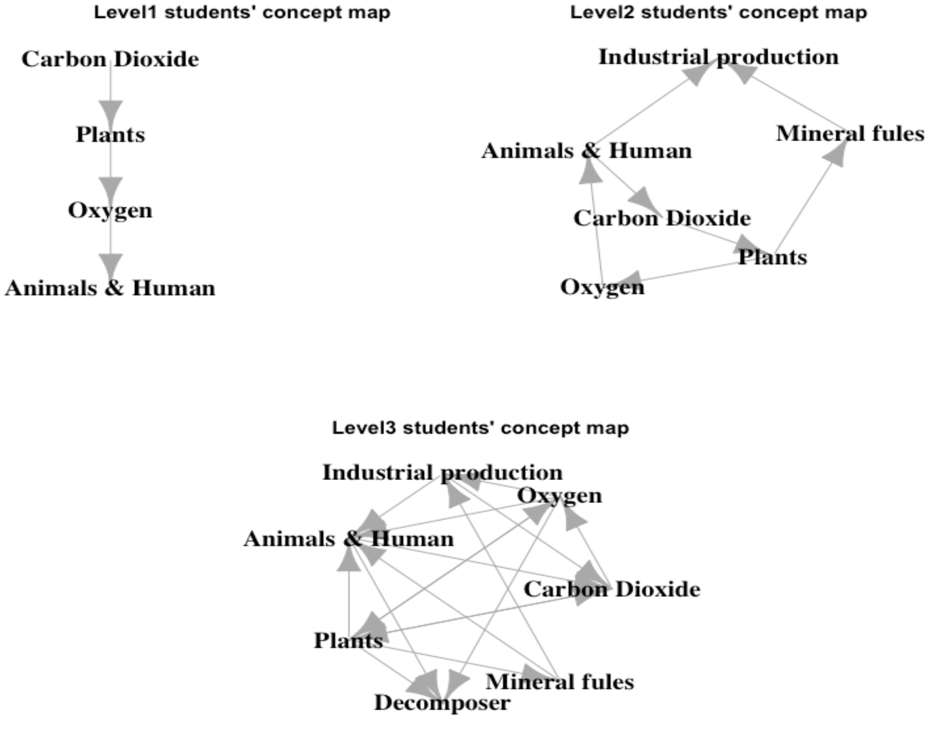
Note. n = number of components. The structural index (SX) = sum of all arrow strings, branches, and cycles / the number of concepts (Mehren et al., 2015).

https://doi.org/10.33225/jbse/23.22.865

ISSN 1648–3898 /Print/
ISSN 2538–7138 /Online/

Although the students performed well in identifying the system components, analysis of the CMs indicated that most students possessed an incomplete picture of climate warming. Students' abilities to identify interrelations among components were assessed using the structural index (SX) of the CM (see Figure 3). The results of the CMs showed that most students' (82%) SX scores in Item 5 were less than .3 (Figure 3), indicating students' low ability to identify interrelations among system components. Figure 4 shows three typical networks that visualise the structure of the students' CMs at the three levels. The first network in Figure 4 indicates that students at Level 1 could not make connections among all concepts provided in the CM and tended to identify direct linear connections among concepts; 14.2% of students reached Level 2, and students at this level could make indirect relations among concepts (e.g. branches [at least two arrows lead to/away from a concept]) and identify a simple carbon cycle via plant photosynthesis and respiration of organisms in the second network of Figure 4. Only a few students (3.5%) connected all the concepts in a networked manner. Complex relationships (e.g., different cycles and interactions among oxygen, plants, and carbon dioxide) can be identified at Level 3 (Figures 3 and 4).

Figure 4
Examples of the Networks in Students' Concept Maps at the Three Levels



Ability to Analyse System Behaviour and System Characteristics

The results of Item 3 suggest that most students (54.1%) recognised dynamic changes among the three populations (wolves, deer, and plants), which help to maintain the equilibrium of the ecosystem. Furthermore, students' responses to Item 8 also support the result that most students (64.6%) were able to explain the disappearance of grey wolves, which caused an increase in the number of deer, which, in turn, damaged plants. However, students' inability to use emergent properties (e.g., carrying capacity and energy pyramid) to explain the changes in the ecosystem suggests that incomprehension of system characteristics hindered students' analysis of dynamic behaviours in the system. Item 3 showed that only a few students (4.4%) could explain the long-term changes in the number of animals based on the conception of the energy pyramid (Table 4).

Furthermore, the *t*-test analysis of Items 10 (M = .790) and 11 (M = 1.170) revealed that students performed significantly better in recognising the feedback loop than the nutrition cycle in the forest (t (2,147.7) = -8.92, p < .001), and only 39% of students could correctly connect the process of the nutrition cycle in Item 10. These find-

https://doi.org/10.33225/jbse/23.22.865

ings indicate that a lack of cyclic thinking makes it difficult for students to combine a variety of relationships into coherent cyclic and dynamic processes. Analysis of the CM also revealed a similar result; the third network in Figure 4 suggests that different carbon cycles exist in the context of climate warming (e.g., interactions via photosynthesis and the respiration of plants, cyclical processes such as plants' photosynthesis and the respiration of organisms, and the connection of mineral fuels to industrial emissions or human consumption). However, students at Levels 1 and 2 (56.2%) only formed a fragmented perception of the carbon cycle in the context of climate warming (Figure 4).

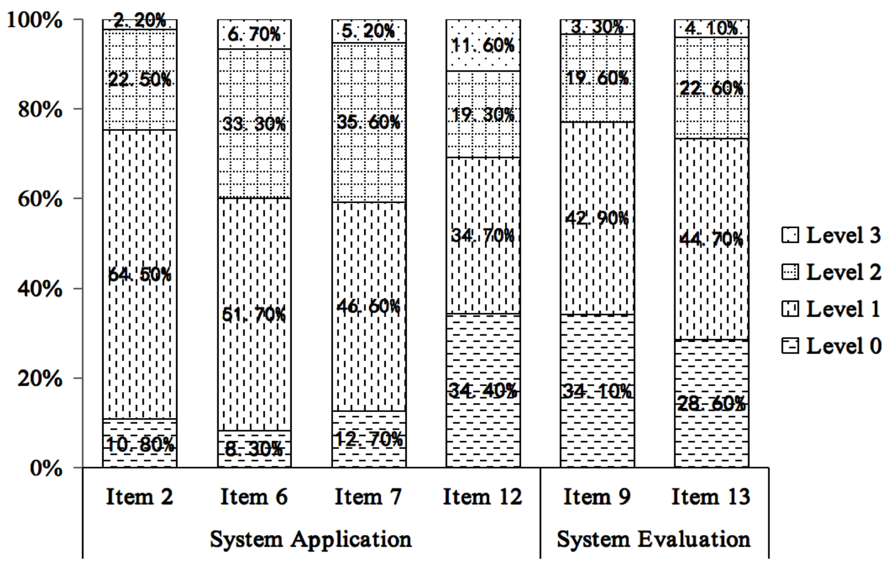
Table 4
Item 3 System Characteristics and Contents

System characteristics	Specific contents	Number of students
Direct/indirect interactions	The relations in food chains	254 (22.9%)
Dynamics and stability	Dynamic changes among populations	599 (54.1%)
Emergent property	Energy pyramid	49 (4.4%)

Ability to Make Predictions and Decisions

Figure 5 displays the proportion of student responses at different ST levels. The size of each chunk in the bar represents the proportion of the students. Figure 5 suggests that a large proportion of students' responses were at Level 1, which implies that monocausal and direct thinking dominated the students' systems application. Furthermore, students' preference to identify direct effects closely related to the environment also supports this result; see, for instance, the common responses in Item 2: 'Pollution of air and water caused the deaths of the organisms in the water'. Only a small proportion of students who formed a complex analysis at Level 3 (Figure 5) could anticipate the long-term effects based on a comprehensive understanding of the ecological, economic, and sociocultural dimensions of ecological issues (e.g., effects of industrial pollutants on residents' income in Item 2 and decision-making considering the sustainable development of the rainforest as well as the protection of local people's lifestyle in Item 12).

Figure 5
Students' Response Distribution Regarding the Items in System Application and System Evaluation



Note. Level 0 represents incorrect responses; Level 1 represents monocausal relations; Level 2 represents indirect/linear relations, and Level 3 represents complex relations.

https://doi.org/10.33225/jbse/23.22.865

ISSN 1648–3898 /Print/
ISSN 2538–7138 /Online/

Ability to Make Evaluations about the Structures and Applications of Systems

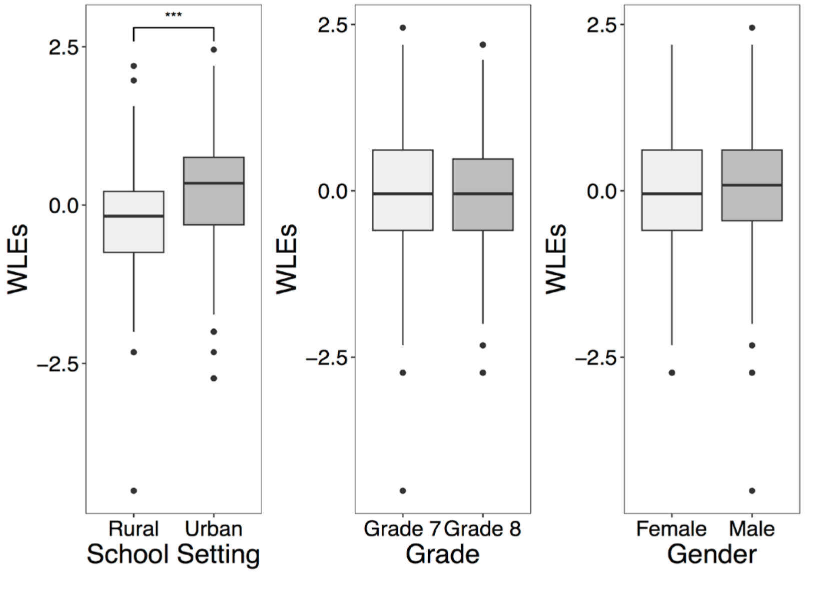
The results of Item 4 showed that holistic thinking was lacking in students' evaluation in that most students (84.3%) could find the error of isolated relations in the system, but few students (31.1%) could evaluate the relations from a system perspective. To make the right judgement about relation 9 ('human consumption of crop' is good for 'human health') in Item 4, students had to think about the whole system instead of just the parts, because the overuse of pesticides would result in crops accumulating pesticide residues. However, more than half of the students (53.2%) overlooked this whole system background. Furthermore, the results for Items 9 and 13 suggest that most students made evaluations in a monocausal (Level 1)/incorrect (Level 0) manner (Figure 5). Further analysis of students' responses indicated that these students lacked reflective consciousness about the limitations of predictions and decisions and could not make full evaluations of the validity of decisions and predictions in a time dimension; for example, they were unable to determine the long-term effects of killing grey wolves on ecosystems and that of a fishing ban on the economy and society.

Identification of Performance Gaps in Different Student Groups

The *t*-test was used to compare the means of student performances using WLEs for particular student groups (Figure 6). Students showed significantly different levels of performance based on their school location (t (1,090) = -8.388, p < .001); rural students (M = -.236) showed lower performance than urban students (M = .187). The results suggested that there was no significant difference between male (M = .033) and female students (M = -.049; t (1,090) = 1.583, p = .114), and no significant difference between Grades 7 (M = .01) and 8 (M = -.02) students (t (1,090) = .672, p = .502).

In the DIF analysis, Items 2, 5, 6, 7, and 9 appeared to be more difficult for rural school students, at a .01 significance level. The specific content and ST skills regarding these items were examined, and the analysis of students' responses indicated that rural students had more difficulties in identifying interactions among components and making predictions, decisions, and evaluations in an indirect or complex way than their urban counterparts. Furthermore, Items 5, 6, and 7 were all included under the context of climate warming, which means that this ecological issue is challenging for rural school students to understand.

Figure 6
Differences in ST Performance between Various Student Subgroups



Note. *** <. 001.

https://doi.org/10.33225/jbse/23.22.865

Discussion

This study incorporates a broader set of ST skills (e.g., system decision-making and evaluation) for assessing students' consideration of diverse dimensions of ecological issues, resulting in a more comprehensive understanding of their ST performance in ecological issues. Furthermore, this study recruited a larger sample group than previous studies, thereby yielding more reliable and representative baseline data on lower-secondary school students' performance.

Regarding RQ1, the Wright map and the comparison of students' abilities both suggest that, on average, the students reached Level 1 of ST about ecological issues. The low ST performance of the participants is not surprising because some previous studies from different contexts also found similar results (Ben-Zvi Assaraf & Orion, 2005; Mambrey et al., 2020). Among the four skills in ST, systems organisation was found to be relatively easier for students, which is consistent with the findings of Evagorou et al. (2009) and Hmelo-Silver and Pfeffer (2004), who observed that the structure of a system was the most cognitively easy for students to understand.

The analysis of the students' responses to the items in RQ2 further explained the reasons for their low performance in understanding ecological issues. Students exhibited difficulties comprehending the interrelations among system components and identifying hidden elements in the ecosystem. The microorganism is invisible and thus easily neglected, making it difficult for students to identify them (Ben-Zvi Assaraf & Orion, 2005). Results in this study align with previous research findings that emergence is the most difficult system characteristic for students to understand (Hmelo-Silver et al., 2007; Jin et al., 2019; Sommer & Lücken, 2010). However, the analysis implies that stability and dynamics are relatively easy for the lower-secondary school students in China. The ecosystem equilibrium highlighted in the Chinese lower-secondary school biology curriculum likely promotes students' understanding of the characteristics. The little to no use of system concepts in explanations also supports the necessity of imparting general system characteristics (e.g., feedback loop, emergent properties, equilibrium) to scaffold students' coherent understanding of complex systems from a system perspective (Gilissen et al., 2020; Gilissen et al., 2021). Students lacked the cyclic perception, as reported by Ben-Zvi Assaraf et al. (2005) for the water cycle, and most students were unable to draw a complete network of interactions. The lack of time dimension hinders students' ability to make predictions and decisions based on long-term effects.

Although evaluation is an essential aspect of ST (Fanta et al., 2020; National Research Council, 2010), it is usually ignored in assessment. This study's findings indicate that students were less proficient in system decision-making and evaluation. There may be several reasons for this. First, the absence of reflective consciousness made it difficult for students to contemplate the limitation of prediction and decision. Second, the lack of holistic thinking prevented most of them from deciding or evaluating from a comprehensive perspective. The results also suggest students' inability to recognise other dimensions (such as social, economic, and cultural), and the indirect effects on ecological problems in their predictions, decision-making and evaluation. This further explains the dominance of monocausal reasoning in most students' ST, and their inability to fully understand the causes of ecological problems. This led them to decide and evaluate from a unidimensional perspective.

Regarding RQ3, this study's results contradict those of Jin et al. (2019), who concluded that the average performance of urban students was statistically significantly lower than that of rural students. A major reason for this is the contrast in urban area educational resources between China and the United States. Urban schools in the United States tend to have low resources, high teacher turnover, and low-quality students (Jin et al., 2019). However, with the accelerating urbanisation in China, resources have accumulated in urban areas. In general, urban schools in China have better educational resources and more highly qualified teachers than rural schools (Wen & Gu, 2017). Given that context-specific knowledge is necessary for developing ST (Ben-Zvi Assaraf & Orion, 2005; Sommer & Lücken, 2010), the lower performance of rural students in the context of global warming implies a possible lack of knowledge about this ecological issue. To explain the differences between rural and urban education more precisely, future research should explore the extent to which possible variables (e.g., socioeconomic status, teachers' teaching quality, and students' knowledge about ecological issues) influence students' ST.

Conclusions and Implications

This study explored lower-secondary school students' system thinking performance in ecological issues. The STTEI was administered for acquiring extensive data from Chinese students. Their overall ST performance was at Level 1, and an analysis of their responses revealed that they faced substantial difficulties in understanding ecological issues. Furthermore, this study is unique in revealing that most lower-secondary school students lack reflective

https://doi.org/10.33225/jbse/23.22.865

ISSN 1648–3898 /Print/
ISSN 2538–7138 /Online/

consciousness, and are thus unable to consider the indirect impact of diverse dimensions, leading to monocausal reasoning in system application and evaluation. This study also found that Chinese rural students did not perform as well as their urban counterparts, specifically in the context of climate warming, which may be explained by rural school students' lack of the corresponding content knowledge.

These findings have significant implications, particularly for developing lower-secondary students' ST in ecological issues. First, teachers must address students' shortcomings, especially regarding emergent properties, cyclic perception, and interactions within complex systems. Second, ecological issues must be discussed from multiple perspectives for promoting ST in science classes and improving students' causal reasoning in complex systems. Third, there should be greater efforts in making rural students understand climate change. Future research must examine other variables for developing teaching strategies suited to students' backgrounds. Furthermore, qualitative methods (e.g., semi-interview) should be used for future assessments, so that the underlying causes of students' low performance are identified.

Declaration of Interest

The authors declare no competing interest.

Acknowledgements

This work was supported by the Fundamental Research Funds for the Central Universities under Grant number 2021TS062 and the Research Program Funds of the Collaborative Innovation Center of Assessment toward Basic Education Quality at Beijing Normal University under Grant number 2022–05-012-BZPK01.

References

Australian Curriculum, Assessment and Reporting Authority. (n.d.). Australian curriculum: F-10 curriculum: Science. Australian Curriculum. https://www.australiancurriculum.edu.au/f-10-curriculum/science/

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. https://doi.org/10.1002/tea.20061

Ben-Zvi Assaraf, O., & Orion, N. (2010). Four case studies, six years later: Developing system thinking skills in junior high school and sustaining them over time. *Journal of Research in Science Teaching, 47*(10), 1253–1280. https://doi.org/10.1002/tea.20383

Bond, T. G., & Fox, C. M. (2007). *Applying the Rasch model: Fundamental measurement in the human sciences*. Routledge.

Brandstädter, K., Harms, U., & Großschedl, J. (2012). Assessing system thinking through different concept-mapping practices. *International Journal of Science Education, 34*(14), 2147–2170. https://doi.org/10.1080/09500693.2012.716549

Brotman, J. S., & Moore, F. M. (2008). Girls and science: A review of four themes in the science education literature. *Journal of Research in Science Teaching, 45*(9), 971-1002. https://doi.org/10.1002/tea.20241

Cohen, J. (1968). Weighted kappa: Nominal scale agreement with provision for scaled disagreement or partial credit. *Psychological Bulletin, 70*(4), 213–220. https://doi.org/10.1037/h0026256

Cox, M., Elen, J., & Steegen, A. (2019). Systems thinking in geography: Can high school students do it? *International Research in Geographical and Environmental Education, 28*(1), 37-52. https://doi.org/10.1080/10382046.2017.1386413

Ecology Center. (2023, March 28). What are ecological problems. https://www.ecologycenter.us/ecological-problems/what-are-ecological-problems.html

Evagorou, M., Korfiatis, K., Nicolaou, C., & Constantinou, C. (2009). An investigation of the potential of interactive simulations for developing system thinking skills in elementary school: A case study with fifth-graders and sixth-graders. *International Journal of Science Education, 31*(5), 655–674. https://doi.org/10.1080/09500690701749313

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. https://doi.org/10.1080/00219266.2019.1569083

Gilissen, M. G. R., Knippels, M. P. J., & van Joolingen, W. R. (2020). Bringing systems thinking into the classroom. *International Journal of Science Education, 42*(8), 1253–1280. https://doi.org/10.1080/09500693.2020.1755741

Gilissen, M. G. R., Knippels, M. P. J, & van Joolingen, W. R. (2021). Fostering students' understanding of complex biological systems. *CBE Life Sciences Education, 20*(3), Article 37. https://doi.org/10.1187/cbe.20-05-0088

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. https://doi.org/10.1207/s15516709cog2801_7

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. https://doi.org/10.1007/s11251-016-9392-y

Hmelo-Silver, C. E., Marathe, S., & Liu, L. (2007). Fish swim, rocks sit, and lungs breathe: Expert-novice understanding of complex systems. *Journal of the Learning Sciences, 16*(3), 307–331. https://doi.org/10.1080/10508400701413401

Hogan, K. (2002). Small groups' ecological reasoning while making an environmental management decision. *Journal of Research in Science Teaching, 39*(4), 341–368. https://doi.org/10.1002/tea.10025

Hokayem, H., & Gotwals, A. W. (2016). Early elementary students' understanding of complex ecosystems: A learning progression approach: A learning progression approach. *Journal of Research in Science Teaching, 53*(10), 1524–1545. https://doi.org/10.1002/tea.21336

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. https://doi.org/10.1007/s10763-017-9864-9

Ke, L., Sadler, T. D., Zangori L., & Friedrichsen, P. J. (2020). Students' perceptions of socio-scientific issue-based learning and their appropriation of epistemic tools for systems thinking. *International Journal of Science Education, 42*, 1339–1361. https://doi.org/10.1080/09500693.2020.1759843

Landis, J. R., & Koch, G. G. (1977). The measurement of observer agreement for categorical data. *Biometrics, 33*(1), 159–174. https://doi.org/10.2307/2529310

Lee, H., Yoo, J., Choi, K., Kim, S.-W., Krajcik, J., Herman, B. C., & Zeidler, D. L. (2013). Socioscientific issues as a vehicle for promoting character and values for global citizens. *International Journal of Science Education, 35*(2), 2079–2113. https://doi.org/10.1080/09500693.2012.749546

Liu, S.-Y., Lin, C.-S., & Tsai, C.-C. (2011). College students' scientific epistemological views and thinking patterns in socioscientific decision making. *Science Education, 95*(3), 497–517. https://doi.org/10.1002/sce.20422

Liu, X. F. (2020). *Using and developing measurement instruments in science education: A Rasch modeling approach*. Information Age Publishing.

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. https://doi.org/10.1002/tea.21649

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*(1), 79–98. https://doi.org/10.1007/s11165-020-09917-x

Mehren, R., Rempfler, A., Ulrich-Riedhammer, E. M., Buchholz, J., & Hartig, J. (2015). Wie lässt sich Systemdenken messen? Darstellung eines empirisch validierten Kompetenzmodells zur Erfassung geographischer Systemkompetenz [How can systems thinking be measured? Representation of an empirically validated competence model for the assessment of geographic system competence]. *Geographie, Aktuell & Schule, 37*, 4–16.

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. https://doi.org/10.1002/tea.21436

Ministry of Education, & China, P. R. (2022). 义务教育生物学课程标准 [Biology curriculum standards for compulsory education]. People's Education Press.

National Research Council. (2010). *Standards for K-12 engineering education?* National Academies Press.

Next Generation Science Standards Lead States. (2013). *Next generation science standards: For states, by states.* National Academies Press. https://doi.org/10.17226/18290

Riess, W., & Mischo, C. (2010). Promoting systems thinking through biology lessons. *International Journal of Science Education, 32*(6), 705–725. https://doi.org/10.1080/09500690902769946

Robitzsch, A., Kiefer, T., & Wu, M. (2021). *TAM: Test Analysis Modules.* https://CRAN.R-project.org/package=TAM

Rosenkränzer, F., Hörsch, C., Schuler, S., & Riess, W. (2017). Student teachers' pedagogical content knowledge for teaching systems thinking: Effects of different interventions. *International Journal of Science Education, 39*(14), 1932–1951. https://doi.org/10.1080/09500693.2017.1362603

Sadler, T. D., Barab, S. A., & Scott, B. (2007). What do students gain by engaging in socioscientific inquiry? *Research in Science Education, 37*(4), 371–391. https://doi.org/10.1007/s11165-006-9030-9

Schuler, S., Fanta, D., Rosenkraenzer, F., & Riess, W. (2018). Systems thinking within the scope of education for sustainable development (ESD) – A heuristic competence model as a basis for (science) teacher education. *Journal of Geography in Higher Education, 42*(2), 192–204. https://doi.org/10.1080/03098265.2017.1339264

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. https://doi.org/10.5617/nordina.255

Sweeney, L. B., & Sterman, J. D. (2000). Bathtub dynamics: Initial results of a systems thinking inventory. *System Dynamics Review, 16*(4), 249–286. https://doi.org/10.1002/sdr.198

Verhoeff, R. P., Knippels, M. 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*, 40. https://doi.org/10.3389/feduc.2018.00040

Wang, Z., & Song, G. (2021). Towards an assessment of students' interdisciplinary competence in middle school science. *International Journal of Science Education, 43*(5), 1–24. https://doi.org/10.1080/09500693.2021.1877849

Wen, J., & Gu, C. (2017). 基础教育资源分配的城乡差异及其社会后果：基于中国教育数据统计的分析[The rural-urban differences in resources allocation of basic education and its social consequence: Base on the analysis of China's education statistics]. *Journal of East China Normal University: Educational Science, 35*(2), 10. https://doi.org/10.16382/j.cnki.1000-5560.2017.02.004

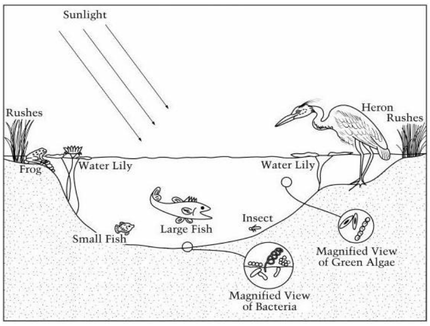
Wu, M., Tam, H. P., & Jen, T.-H. (2016). *Educational measurement for applied researchers. Theory into practice.* Springer. https://doi.org/10.1007/978-981-10-3302-5

Yang, F.-Y. (2005). Student views concerning evidence and the expert in reasoning a socio-scientific issue and personal epistemology. *Educational Studies, 31*(1), 65–84. https://doi.org/10.1080/0305569042000310976

You, H. S., Marshall, J. A., & Delgado, C. (2018). Assessing students' disciplinary and interdisciplinary understanding of global carbon cycling. *Journal of Research in Science Teaching, 55*(3), 377–398. https://doi.org/10.1002/tea.21423

ISSN 1648–3898 /Print/
ISSN 2538–7138 /Online/

Appendix



Item 1 Answer the following questions based on the information provided in the picture:

Organisms that use the energy of sunlight to produce organic matter include______________.

Abiotic factors affecting the pond ecosystem include______________.

The decomposer in the pond is ______.

(Modified from the National Assessment of Educational Progress, http://nces.ed.gov/NATIONSREPORTCARD/)

Item 2 A newly built factory near the pond emits substantial amounts of sulphur dioxide and other pollutants and discharges wastewater containing heavy metal pollutants, nitrogen, and phosphorus (nitrogen and phosphorus will cause many green algae to multiply) into the pond. What do you think this will do to the creatures in the pond and the surrounding villagers?

Item 3 A remote island is uninhabited. The main animals on the island are wolves and deer, and the island is free from external interference all year round.

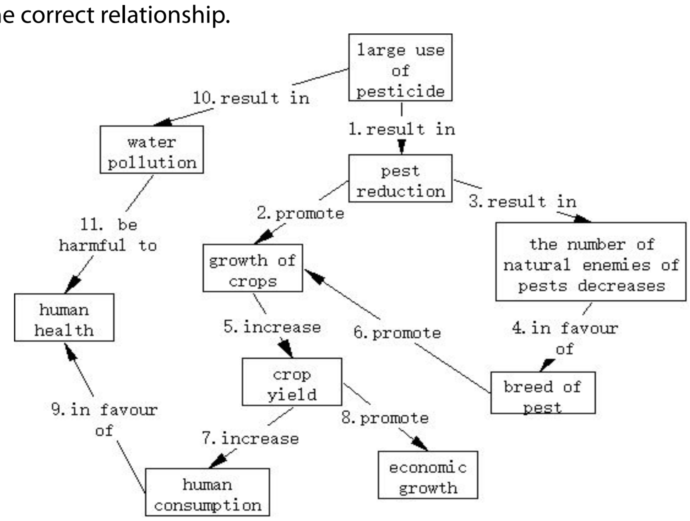
(1) Select the answer below that best describes what will happen to the average populations of the animals over time. (　　)

a) The deer will all die or be killed.
b) The wolves will all die.
c) There will be many more deer than wolves.
d) There will be many more wolves than deer.
e) The populations of each will be approximately equal.

(2) Choose the reason for your answer (　　)

a) Wolves prey on deer, and deer are eaten up by wolves.
b) Wolves prey on deer, causing the number of deer to decrease.
c) Wolves prey on deer. The number of deer decreases. Wolves die as they lack food.
d) To maintain the ecological balance of the 'plant → deer → wolf' food chain, the number of wolves and deer will fluctuate up and down within a certain range.
e) When energy is transmitted along the food chain, it decreases step by step. The population of wolves store less energy than the population of deer.

Item 4 The following concept map describes the impact of heavy use of pesticides in farmland on people and the ecosystem. There are two errors in the word relationships described in the concept map. Write the wrong serial number and explain the correct relationship.



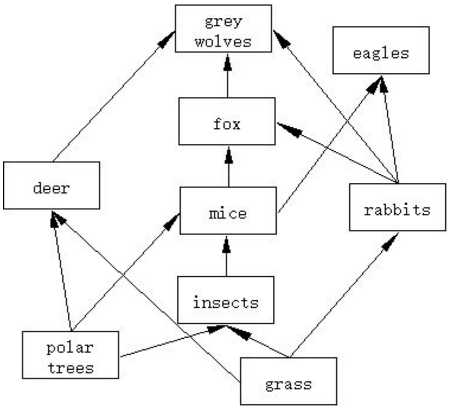
https://doi.org/10.33225/jbse/23.22.865

ISSN 1648–3898 /Print/
ISSN 2538–7138 /Online/

Item 6 Together with the concept map you have constructed, please predict what will happen if the number of plants substantially decreases.

Item 7 Everyone is responsible for protecting the Earth as our home. Please put forward specific measures to mitigate climate warming.

Please answer the following questions according to the information in the food web (the arrow in the food web points to the predator).



Item 8 If all grey wolves disappear, what will be the trend in the deer population ( )

A. It will keep growing.

B. It will grow first, then decrease.

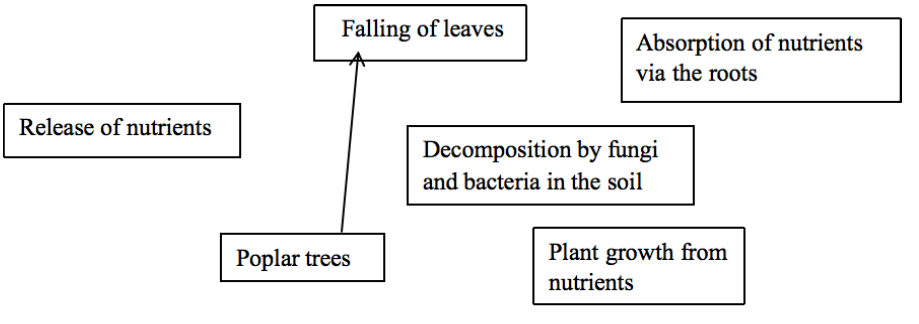
C. It will keep decreasing.

D. It will decrease first, then grow again.

Explain the reasons for your answer:

Item 9 To protect the safety of villagers near the forest, some people proposed to kill all the grey wolves in the forest, but Ming argued that 'if there are no grey wolves in the forest, the number of all herbivores in it will increase rapidly in a short period, thus damaging the stability of the ecosystem'. Do you think Ming's analysis is correct? Please explain your reasons.

Item 10 Use arrows to connect the following words to form the nutrient cycle of poplar trees in the forest. The first arrow has been provided in the picture, and the last arrow you draw must point to 'poplar trees'.

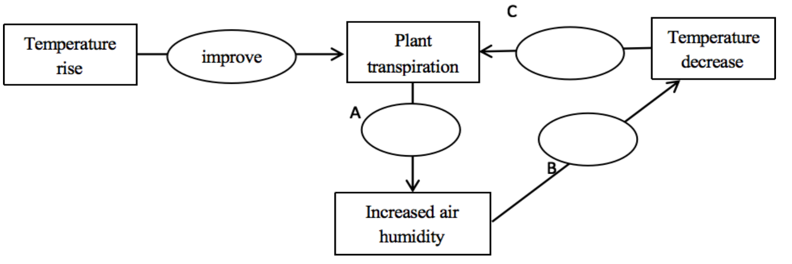


(Modified from Mehren et al., 2018)

https://doi.org/10.33225/jbse/23.22.865

ISSN 1648–3898 /Print/
ISSN 2538–7138 /Online/

Item 11 Trees and plants can reduce ambient temperature through transpiration. The higher the ambient temperature, the stronger the transpiration of plants, and the more water in plants is emitted into the air. Please judge what changes will happen to the forest environment when the temperature rises and the transpiration of plants increases. Fill in 'promote' or 'weaken' at A, B, and C in the following figure (as shown in the example below). Please fill in the blanks in the order of A → B → C.



Item 12 The Khmus people in Xishuangbanna have been using slash-and-burn cultivation in the tropical rainforest. They cut down and burn trees to clear the land for planting food. The ashes from the burning of trees can increase soil fertility. This planting method is only effective for one year, and the land fertility will decline in the next year. The rainforest includes valuable trees (with high prices) and ordinary trees. After cutting them down, it takes at least ten years to recover the trees.

(1) To achieve sustainable development of tropical rain forests and the planting activities of Khmus, which of the following measures do you think is the most reasonable?

A. Cut down all the trees in the rainforest and sell the valuable trees.

B. Only cut down the valuable trees in the rainforest and sell all the valuable trees.

C. Divide the entire rainforest area into ten equal segments. Every year, cut down trees only in a partial area and sell the resulting valuable wood.

D. Divide the entire rainforest area into ten equal segments. Every year, cut down trees only in a partial area and sell all the resulting wood.

(2) Explain the reasons for your answer.

Item 13 Zhoushan in Zhejiang Province is known as the 'Eastern Fish Warehouse' in China. People here basically rely on fishing to make a living. However, with the overfishing of yellow croakers, the number of yellow croakers has declined sharply in the past few years. One reason is that many young yellow croakers have been caught. To prevent the extinction of wild yellow croakers, the measure of 'banning fishing within three years' was proposed. Do you think this measure is feasible? Please explain your reasons.

Received: *May 05, 2023* Revised: *July 24, 2023* Accepted: *September 24, 2023*

Cite as: Li, R., & Li, G. (2023). Exploring lower-secondary school students' systems thinking performance in ecological issues. *Journal of Baltic Science Education*, *22*(5), 865-880. https://doi.org/10.33225/jbse/23.22.865

Ruying Li PhD Student, College of Life Sciences, Shaanxi Normal University, No.620, West Chang'an Avenue, Xi'an 710119, Chang'an District, China.
E-mail: lry2020sisy@163.com
ORCID: https://orcid.org/0000-0003-0896-8262

Gaofeng Li *(Corresponding author)* PhD, Professor, College of Life Sciences, Shaanxi Normal University, No.620, West Chang'an Avenue, Xi'an 710119, Chang'an District, China.
Shaanxi Normal University Branch, Collaborative Innovation Center of Assessment toward Basic Education Quality, Xi'an, China.
E-mail: ligaofeng@snnu.edu.cn
ORCID: https://orcid.org/0000-0002-5827-7112