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The repertory grid as a tool for evaluating the development of students' ecological system thinking abilities

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ABSTRACT

Comprehension of complex systems is essential for in-depth understanding of environmental issues. This study assessed the impact of a place-based ecological learning unit on development of junior high school students' systems thinking skills. It implemented, in a paired pretest–posttest design with 20 students, a qualitative approach using the Repertory Grid-Technique. Qualitative data analysis used the Systems Thinking Hierarchy (STH)-model.

Data indicate that most of the students advanced to a higher level within the STH-hierarchy, and developed the ability to generalize ecological phenomena.

Findings support that in relation to system thinking, the repertory grid is an effective tool for assessing learners' conceptual models and they broaden the implementation of RG as a research tool to the context of ecological complexity.

Introduction

Biodiversity issues are recognized as one of the major components of the global environmental crisis (Intergovernmental Panel on Biodiversity and Ecosystem Services, 2013). The Millennium Ecosystem Assessment clearly outlines the dependence of human well-being on ecosystem services derived from Earth's biodiversity (Millenium Ecosystem Assessment, 2005). In response to the importance of drawing humanity's attention to the ongoing biodiversity crisis, 2010 was pronounced by the UN 'Year of Biodiversity'.

The role of education in addressing the challenges of biodiversity is undisputed (Millenium Ecosystem Assessment, 2005). While biodiversity has become a part of the curriculum from pre-school throughout secondary school (K-12), it is often addressed from a narrow perspective, focusing primarily on anthropogenic influences, with the aim of developing the environmental awareness and responsible behavior necessary for sustaining biodiversity (UNESCO, 1993; World Resource Institute, The World Conservation Union/United Nations Environmental Program, 1992). There is accumulating evidence that comprehension of complex systems is essential for in-depth understanding of environmental issues, such as those related to human impact on biodiversity and the behavioral changes required at the individual and societal level (Eilam, 2012). In-depth understanding of ecosystem function – the mechanisms which are the essence of the self-organization of ecosystems and render them sustainable systems – is a crucial component for the comprehension of biodiversity issues (Hmelo-Silver et al., 2008; Nguyen & Bosch, 2013). Comprehension of the structural and behavioral aspects of complex systems is a challenging cognitive endeavor for science students (Jacobson & Wilensky, 2006). Ecosystems are inherently characterized by their complexity, and studies with learners have demonstrated a wide range of difficulties in their understanding of concepts and ideas that are attributed to the ecosystem properties (Booth Sweeney & Sterman, 2007; Eilam, 2002). Place-Based Education, by integrating the local physical environment, community and authentic environmental challenges, may provide a meaningful environmental educational framework to achieve this goal (Endreny, 2010; Glasson, Frykholm, Mhango, & Phiri, 2006).

The aim of this study was to investigate the influence of a place-based environmental learning unit that implements the earth system approach (Orion & Ault, 2007) on development of junior high school pupils' systems thinking skills in the context of ecology, as this is reflected in their advancement to higher levels within the System Thinking Hierarchy (STH) model (Ben-Zvi Assaraf & Orion, 2005). To this end, this study implemented the

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Repertory Grid tool to evaluate system thinking abilities. While this tool has been previously used for evaluating learners' system thinking in other contexts (Ben-Zvi Assaraf & Orion, 2005, 2010a,b), the present study broadens this to the context of ecology.

Theoretical framework

Developing system thinking as a challenge for Science and Environmental Education

Fostering an environmentally literate citizenry is a major key to achieving sustainability. The Tbilisi Declaration (UNESCO-UNEP, 1978) – one of the seminal documents in environmental education (EE) – defined "a basic understanding of the environment" as a component of the knowledge objective of EE. With respect to curriculum development in EE, Hungerford, Peyton, and Wilke (1980) synthesized a set of hierarchical target levels. The first target level is the *Ecological Foundations Level*, which aims to provide sufficient ecological foundations knowledge, and thus enable individuals to make ecologically sound decisions with respect to environmental issues. This target level states that learners should be able to apply major ecological concepts to the analysis of environmental issues, and predict the consequences of proposed solutions to environmental issues using their knowledge of ecological concepts. Roth, who coined the term Environmental Literacy, includes the understanding of a number of ecological processes (for example: population dynamics, interactions and interdependence, energy transfers, biogeochemical cycling, succession, thinking in terms of systems, thinking in terms of time frames and scales) as crucial components of the knowledge strand of the Functionally Environmentally Literate individual (Roth, 1992). The above examples of keystone literature in the field of EE support the claim that an understanding of ecosystem structure and function is a fundamental component in the developing of the environmental literacy required to understand complex multidimensional environmental issues and make responsible behavioral choices. Current guidelines for excellence in EE (NAAEE, 2010) explicitly state system thinking as one of its underpinnings.

Sauvé (2005) identified the 'systemic current' as one orientation in the pedagogical "landscape" of EE, according to which systemic analysis is indispensable to the recognition and understanding of environmental realities and problems. Systemic analysis, according to this typology, includes the relations among biophysical and social elements. This approach to environmental realities is cognitive by nature and its perspective is of enlightened decision. A pedagogical example of this approach is that of Keiny and Shachack (1987) in the context of outdoor ecology study: a field trip in an arid environment, for example, enables direct observation, in situ, of a concrete environmental reality or phenomenon, and the analysis of its component parts and relations, in order to develop a systemic model leading to a global understanding of the related issue in the arid climate. They argue that the development of a systemic model of the related issues enables the learners to identify and select more enlightened solutions.

In light of increased recognition of the importance of an understanding of ecosystems, the literature suggests that comprehension of the structural and behavioral aspects of complex systems has become a challenging cognitive endeavor for science students (Jacobson & Wilensky, 2006). Research has unveiled many difficulties that students of all ages face when dealing with complex systems (Ben-Zvi Assaraf & Orion, 2005; Hmelo-Silver & Pfeffer, 2004; Plate, 2010). For example, students have difficulty developing a coherent and comprehensive perception of the structure and multi-variable web of relationships (Jacobson, 2001) that exist in systems. Other difficulties result from the fact that complex systems are characterized by multilevel organization, interconnections, heterogeneous components, and invisible dynamic processes (Ferrari & Chi, 1998; Hmelo-Silver & Azevedo, 2006; Wilensky & Resnick, 1999). Learners have difficulty understanding multiple levels and making connections between them (Duncan & Reiser, 2007). This derives from the fact that relationships across different levels of such systems are often implicit, with indirect causality (Hmelo-Silver & Azevedo, 2006; Jacobson, 2001), and therefore the relationships among the various system agents are not intuitively obvious (Duncan & Reiser, 2007). Such characteristics present cognitive barriers that make complex systems difficult to understand (Feltovich, Coulson, & Spiro, 2001). Another characteristic of systems is 'emergence' (Jacobson & Wilensky, 2006): The unpredictable and non-intuitive macroscopic-level expression of a system's self-organization, resulting from the processes occurring within its subsystems, shows emergent and complex properties not exhibited by the individual components. Students, however, tend to believe there is a linear relationship between the salience of a phenomenon and its corresponding effect, and ignore the fact that in complex systems, a non-salient phenomenon may contribute a significant influence (Hmelo-Silver & Pfeffer, 2004; Jacobson, 2001; Kaneko & Tsuda, 2001).

What are the implications of comprehending complex systems in the context of ecology? Ecosystems are inherently characterized by their complexity, and studies with learners have demonstrated a wide range of difficulties in their understanding of concepts and ideas that are attributed to the ecosystem properties. For example, some studies report about learners' misconceptions related to food web, ecological adaptation, carrying capacity, feedback cycles, and ecosystem and niche concepts (Booth Sweeney & Sterman, 2007; Eilam, 2002; Munson, 1994). Studies addressing pupils from the elementary to the high school level report that pupils do not see ecosystem function as an interrelated whole. For example, photosynthesis, respiration and decay are not related to cycling of matter in ecosystems (Leach, Driver, Scott, & Wood-Robinson, 1996). Furthermore, when describing relationships in nature, children tend to use simple linear causality, in which only one population directly affects another, rather than several different pathways forming a food web (Booth Sweeney & Sterman, 2007; Dor-Haim, Amir, & Dodick, 2012; Grotzer & Bell-Basca, 2003). In view of this, Grotzer and Bell-Basca (2003) point out that there is a need to provide students with structural knowledge that refers to "the way that experts in a domain deal with the foundational concepts, such as causality or categorization, that impact how we frame experience or information" (p. 27). Perkins and Grotzer (2005) claim that understanding and reasoning effectively about ecosystems involves comprehending a variety of causal patterns in nature, for instance domino like, cyclic, or reciprocal patterns between organisms, as well as between organisms and abiotic components. Without a grasp of the behavior of such patterns, students are likely to impose a simple linear form to organize new information. Along this line, more recently, Eilam (2012), based on her study of system thinking and feeding relations among junior high school pupils, identified the following interrelated deficiencies: (a) feeding relations are perceived in a linear rather than a web configuration; (b) understanding of webs was also constrained by deficiencies in temporal and spatial thinking; (c) causality and implicit interactions were not evident, thus strengthening the students' perception of distinct components rather than whole systems. Eilam (2012) concluded that "Such linear and unidirectional views and temporal and spatial thinking deficits also impeded students' ability to understand that matter and energy cycles are an inherent part of the larger biosphere system and at the same time partly occur within and interact with the biotic organisms involved in the feeding web subsystem" (p. 232).

Another aspect of systemic thinking was addressed by Magntorn and Helldén (2007) in their study of Swedish secondary school students' ability to generalize the knowledge of ecosystems:

to what extent can the students apply their understanding in order to "read nature" in the aquatic ecosystem after studying the ecology of a terrestrial ecosystem? Despite the lack of knowledge of the different organisms on a species level, many students were able to generalize about the functional groups of the organisms they observed in the pond, which is an important part of reading the new environment and can be considered transferable schemata. On the other hand, the study found that not a single student noted that the lake will change over time, pointing to the students' problems of predicting changes in the environment, reflecting deficiency in dynamism and temporal thinking.

Some of the literature recognizes system thinking as an essential component for Science Literacy (Booth Sweeney & Sterman, 2007; Hmelo-Silver et al., 2008), while other researchers relate system thinking to Ecological Literacy (Magntorn & Helldén, 2005; Puk & Stibbards, 2012). According to Puk and Stibbards (2012), Ecological Literacy provides the capacity to make changes "about the future of life based on a comprehensive, gestalt-like understanding of the reciprocal relationships among natural systems and human systems". Ecological consciousness – the human condition in which all daily behaviors are viewed through a lens of Ecological Literacy, such that these behaviors form an ecologically beneficial lifestyle-requires acting on that capacity" (Orr, 1992; Puk & Stibbards, 2012).

A pedagogical approach gaining recognition as potential in achieving the goals of environmental education is Placed-based education – an approach to curriculum development and instruction that acknowledges and makes use of the places where learners live to address school subjects (Smith, 2013). Placed-based education, through direct and multi-dimensional encounters with the local environment, contributes to developing the learner's attachment to the "place", which, in turn, enhances their concern and leads to responsible environmental behavior. As described by Sobel (2005), Placed-based education "*...helps students develop stronger ties to their community, enhances [their] appreciation for the natural world, and creates a heightened commitment to serving as active, contributing citizens. [Furthermore] community vitality and environmental quality are improved through the active engagement of local citizens, community organizations and environmental resources in the life of the school*" (p.7). Associated with Placed-based education is the outdoor learning environment, which, in the context of science and environmental education, is the natural environment or the environment in which the phenomena occur. Quay and Seaman (2013) ground the rationale for outdoor learning in John Dewey's theory of learning: Dewey claimed that by nature, learning is experiential; therefore learning about nature cannot be achieved without concrete experience within the natural environment. Dewey emphasized the cognitive aspects of this experience, and specifically addressed observation, data collection and evaluation. Smith (2013) claims that Placed-based education, as well, addresses one of Dewey's central concerns – the separation of classroom learning from the learners' lives. Kellert (2002) stressed the role of physical experience in the natural environment to the cognitive, emotional and moral development of elementary school students. Furthermore, outdoor learning has been found to influence cognitive as well as social and behavioral outcomes (Falk, 2005; Orion & Hofstein, 1994; Tal & Morag, 2009). One of the cognitive outcomes significantly developed as a result of outdoor inquiry learning is development of system thinking skills (Ben-Zvi Assaraf & Orion, 2005, 2010a,b).

Methodological frameworks for exploring system thinking

Systems Thinking Hierarchy

An exploration of learners' system thinking capacities should be based on a theoretical framework that enables identification of differences in the extent of individuals' system thinking capacity, as well as of the development of these capacities within each learner. One such framework is the Systems Thinking Hierarchy (STH) model developed by Ben-Zvi Assaraf and Orion (2005), following a study of junior high school students in the context of Earth Systems. They suggest that thinking about and understanding a system can be categorized according to eight hierarchical characteristics or abilities:

(1) Identifying the components and processes of a system (level A).
(2) Identifying simple relationships among a system's components (level B).
(3) Identifying dynamic relationships within the system (level B).
(4) Organizing the systems' components, processes and their interactions within a framework of relationships (level B).
(5) Identifying matter and energy cycles within the system (level B).
(6) Recognizing hidden dimensions of the system (i.e. understanding phenomena through patterns and interrelationships not readily seen) (level C).
(7) Making generalizations about a system and identifying patterns (level C).
(8) Thinking temporally (i.e. employing retrospection and prediction) (level C).

These eight characteristics can be arranged in ascending order of advancement into three sequential levels: (A) analyzing the system components (characteristic 1); (B) synthesizing system components (2, 3, 4, 5); and (C) implementation (6, 7, 8). Each lower level is the basis for developing the next level's thinking skills. This is the model used in the present study to assess students' understanding of the ecological system.

Each of the eight characteristics of the STH-model appears in the literature on system thinking. For example, at the Analysis level, the object of the first characteristic (the components of a system) is identified in the Structure-Behavior-Function model of system thinking as *structures* which refers to the elements of a system in all organizational levels (Hmelo-Silver & Pfeffer, 2004). At the synthesis level, the second and third characteristics (the ability to identify relationships among the system's components) are identified in the SBF-model as *Behaviors*, which refer to mechanisms that enable the structures of a system to achieve their outcome or function. In the STH model, relationships have been differentiated into 'simple' and 'dynamic' in order to reflect students' difficulties in comprehending those interactions which specifically involve the transformation of matter (molecules) within the system. These relationships are termed 'dynamic'. For example, in relation to understanding of photosynthesis, a dynamic relationship refers to CO_2 and O_2 transfers between the plant and atmosphere. The ability to identify dynamic relationships is identified by Booth Sweeney and Sterman (2007) and Eilam (2012) as components of system thinking. Those dynamic relationship that occur at the molecular or cellular level are termed invisible dynamic processes (Duncan and Reiser, 2007; Hmelo-Silver & Pfeffer, 2004; Verhoeff, Waarlo, & Boersma, 2008). At the implementation level, the eighth characteristic (thinking temporally: retrospection and prediction) was identified by Hmelo-Silver and Pfeffer (2004), Wilensky and Reisman (2006), and Booth Sweeney and Sterman (2007). Prediction, in relation to temporal phenomena, refers to the ability to perceive future phenomena that result from processes and interactions that are taking place currently.

The Repertory Grid Technique

The data for analysis using the STH framework was obtained through the Repertory Grid Technique. The Repertory Grid (RG) method is based on Kelly's Theory of Personal Constructs (Kelly, 1955). In describing how concepts are acquired and organized within an individual's cognitive structure, Kelly drew explicit parallels between the processes that guide scientific research and those involved in everyday activities. Like scientists, people seek to predict and control the course of events in their environment by constructing mental models (i.e. personal construct system) of the world based on past experience. This personal construct system enables individuals to formulate testable hypotheses about future events and then test and revise them against their experience (Bradshaw, Ford, Adams-Webber, & Boose, 1993; Edwards, McDonald, & Young, 2009). The technique developed by Kelly to study personal construct systems is the Repertory Grid. While originally developed for the field of psychology, there is wide consensus that the RG technique can reliably depict a person's way of thinking (Ben-Zvi Assaraf & Orion, 2010a,b; Bencze, Brown, & Alsop, 2006; Bezzi, 1999) and it has been applied in a number of other domains. The constructivist key message of Kelly's personal construct theory is that the world is 'perceived' by a person in terms of whatever 'meaning' that person applies to it (Kelly, 1955). The bases on which persons develop their personality, attitudes, and concepts and perceive reality are their systems of personal constructs.

In view of its focus on understanding peoples' ways of thinking, the RG technique is a phenomenological approach suited for qualitative, interpretive research (Edwards et al., 2009), including education research. Prediger and Lengnink (2003) grounded the RG technique as a method within qualitative research, as follows: In the methodology of qualitative social research, a large variety of methods have been developed to identify implicit theories and belief systems. The test procedures and methods for knowledge elicitation mainly differ in their degree of standardization. One extreme is the completely standardized questionnaire offering multiple choice answers only. The missing possibility for participants to express their thoughts in their own language produces reductive results which sometimes cannot adequately explore their implicit theories. The other extreme is the free interview without any structured guidelines. This kind of knowledge elicitation is not reductive, the results are not easily comparable and the processes of interpretative analysis are, in some cases, too sophisticated for evaluating learning processes. Kelly developed a methodology for exploring systems of personal constructs by so-called repertory grids (1955). This technique is a form of highly structured interview, formalizing the interactions of interviewer and interviewee and putting into relations personal constructs and given objects of discourse. Repertory grids try to combine the advantages of both extremes: having a structured way of data collection in order to simplify the analysis afterwards, without imposing the language in which the participants express their implicit theories and personal constructs.

Some examples of education research applications of the RG technique include: perceptions of geoscience university students (Bezzi, 1999); higher education pedagogy (Nicholls, 2005); free choice learning environments in museums (Canning & Holmes, 2006); relationships between teachers' conceptions of science and the types of inquiry activities they use (Bencze et al., 2006), environmental literacy of junior high school pupils (Goldman, Ben-Zvi Assaraf & Shaarbani, 2013). In relation to system thinking, Latta and Swigger (1992) argue that the RG can identify those aspects of a system that are most commonly misunderstood. Accordingly, Ben-Zvi Assaraf and Orion (2010a,b) have applied the RG to provide insight into elementary level pupils' capacity to identify dynamic relationships and hidden dimensions of systems, and to make generalizations regarding systems. One advantage of using the RG to explore individuals' ways of thinking is that it supports the gathering of the research participants' ideas in a relatively unbiased manner (Hunter & Beck, 2000).

The aim of this study was to investigate the influence of a place-based environmental learning unit on the development of junior high school pupils' systems thinking skills, as this is reflected in their advancement to higher levels within the System Thinking Hierarchy (STH) model. What distinguishes this study is its implementation of the Repertory Grid as a tool for evaluating the development of system thinking abilities in the context of ecology, and its combined use of the RG tool and STH framework. In view of the theoretical framework, the assumption of this study is that effective EE requires an in-depth comprehension of ecological systems, which, in turn, is facilitated through the development of system thinking capacities. In this context, the RG may provide a sensitive research tool.

Methodology

Research setting

The study was conducted in a paired pre-test–post-test design with 20 junior high school pupils who voluntarily participated in an extracurricular science program on a local ecological system (Shezaf Nature Reserve in the Arava Valley). The program, developed for the study and extending throughout the school semester, was based on the constructivist approach and included three labs and three field trips for inquiry, interspersed with knowledge integration activities. Table 1 provides an outline of the Shezaf Reserve Ecosystem learning unit.

The Shezaf Nature Reserve is located in the northern part of the extremely arid Arava Valley with a mean annual winter rainfall of 35 mm, that occurs in a range of 6–9 days with large annual variations in total rainfall and temporal and spatial distribution. Mean summer temperature is 38 °C often reaching 49 °C (Goldreich & Karni, 2001). Despite being a desert, the reserve is very rich in fauna and flora, some species of which are rare or endangered. The flora of the reserve is dominated by Acacia trees (*Acacia tortilis* and *A. raddiana*) and scattered shrubs (*Zilla spinosa*, *Lycium shawii*, and *Haloxylon persicum*) which grow in the dry riverbeds (wadis). This concentration of vegetation has gathered around it a diverse biosystem which includes different species of carnivores and herbivores (Keynan & Yosef, 2010). There are more than 20 species of reptiles and mammals (including hyenas, wolves and foxes) and alongside these, the Babblers-extraordinary song birds with highly organized communities. Two major current anthropogenic influences on this ecosystem are agriculture (on the border areas of the reserve) and tourism (organized ecotourism, as well as unmanaged jeep activity).

From a pedagogical perspective, in accordance with the Place-based education approach (Glasson et al., 2006; Sauvé, 2005; Sobel, 1996), the Shezaf Nature reserve was chosen as the ecosystem for study since it is the natural ecosystem closest to where the students live and they are familiar with it as a component of their local environment. Moreover, the concrete learning encounters in the ecosystem of the nature reserve, which addressed environmental challenges relevant to the students' community, provide the potential for significant environmental education.

Research approach

The research approach of this study is framed in two strands of literature: science education and environmental education. In relation to science education, the research tools implemented in the study aimed to reveal difficulties the students were confronted with when dealing with the Shezaf Nature Reserve as an exemplar complex ecological system. Moreover, use of the STH-model for the fine-grain analysis of data, enabled to identify which components

Table 1
Outline of the Shezaf Reserve Ecosystem learning unit.

Chapters	Subject – authentic question	Educational resources	Educational activity
1 (2 h)	(1) What do I know about Shezaf Reserve? (2) What influences the Reserve? (3) What components and relationships exist in Ecosystems?	(a) Pictures, maps, and aerial and satellite images of the reserve environment in different seasons. Visual material presents phenomena such as winter flooding, human artifacts (ancient roads), and various natural and human activities occurring in the reserve. (b) Chapter 1 (From Pole to Pole) of the BBC documentary Planet Earth	(a) Categorize material into groups and justify categorization in a group discussion; Identify Earth System components in the reserve and support with evidence from the materials. (b) Identify relationships among ecosystems and components in the movie; Enrich relationships among the Shezaf ecosystem components via knowledge integration activity.
2 (3 h)	What characterizes the Shezaf environment?	Soil and rock identification kit; Electronic equipment for measuring temp./humidity; Botanical and zoological field guides.	Short field trip in Shezaf Reserve which included: (a) Comparison of rock/soil properties from different habitats in the reserve (example: wadi versus cliff); (b) Monitoring and comparing abiotic variables among different habitats (example: dens versus nests); (c) Identifying evidence for water and exploring the relationship between water and plant and animal distribution.
3 (2 h)	1. How are water and soil connected? 2. How do humans influence the hydrosphere?	Three-dimensional models (columns) for water infiltration into soil/rock.	(a) Water lab: Inquiry study of water infiltration; (b) Knowledge integration activity – drawing the water cycle.
4 (2 h)	What relationships exist between plants and their environment in the desert?	Lab equipment for plant physiology (light microscope; slides); computer based model of photosynthesis.	Plant morphology identification with focus on adaptation to arid conditions; computer simulated lab on photosynthesis.
5 (3 h)	What is the relationship between habitats and plant biodiversity in the Shezaf reserve?	Botanical field guides; Cameras.	Short Field trip on plant biodiversity in Shezaf Reserve: Compare plant diversity among three different habitats (wadis; grazing area; nature – agriculture transition zone).
6 (24 h)	What are the temporal aspects of different interactions in specific ecological niches in the Shezaf reserve?	Laptops; Animal track field-guides; Rodent-traps; Binoculars; Electronic equipment for monitoring temp and humidity.	24 h fieldtrip in Shezaf Reserve: (a) The students became acquainted with two Acacia tree species which are typical of the area and demonstrate diverse ecological interactions (such as: parasitism, competition); (b) In teams, students investigated a specific ecological niche and monitored for 24 h selected abiotic and biotic variables. This included activities such identifying animal tracks; trapping and identifying rodents; monitoring of abiotic conditions. The aim was to learn how organisms are adapted to their habitat conditions.
7 (4 h)	What did we learn about Earth Systems in the Shezaf Reserve?	Computers; Audo-visual equipment for presentation; Official documents regarding Development plans in the Shezaf Reserve.	Summary of learning unit, conducted in inquiry teams (a) Analysis of collected data in relation to hypotheses and conclusions; (b) Present outcomes to classmates; (c) Students received official plans for development in the reserve and wrote positions papers concerning the implications of such development for the biodiversity of the reserve and evaluated alternate courses of action.

of system thinking were developed and refined as a result of the learning process. Placed based education, as a pedagogical approach for environmental education, provided a learning environment that supports meaningful environmental education (Sobel, 2005).

Multiple case study

We choose to use Multiple Case Narrative methodology, which allows for collecting data from a large number of people within a single study. Similar to the conventional quantitative study in the purpose of collecting data from multiple people, it nevertheless preserves its narrative-qualitative nature and produces narrative-qualitative findings (Shkedi, 2005). According to Shkedi (2005), combining a relatively large population with the narrative-qualitative form allows researchers to identify the presence of broad patterns recurring within a wide variety of case narratives. In this study, the Multiple Case Narrative methodology provides a comprehensive view of the students' world, as it emerges from their many individual stories. The students' repertory grids, along with the accompanying interviews, reveal different angles of the students' experience of system thinking.

This study also employed a phenomenographic approach. Phenomenographic study examines each participant's experience with respect to a phenomenon, in order to determine how individuals construct the meaning of the phenomenon and how these meanings differ qualitatively across the group of individuals (Hales & Watkins, 2004).

Research tools and their analysis

The study implemented a qualitative approach, combining the Repertory Grid (RG)-technique and System Thinking Hierarchy (STH) model to evaluate system thinking capacities. The RG technique, based on Kelly's personal construct theory (1955), is used in educational research to explore learners' ways of thinking through the personal constructs they create. Regarding system thinking, the RG has been used to provide insight about subjects' capacity to identify dynamic relationships within systems, make generalizations and identify hidden dimensions of systems (Ben-Zvi Assaraf & Orion, 2010a,b; Ben-Zvi Assaraf, Dodick & Tripto, 2012).

The building blocks of the RG are *elements* (the topics of study), *constructs* (the participants' ideas about these elements) and *ratings* (relations among elements and constructs as viewed by the participants). Elements are the objects that are the focus of the investigation. There are two ways to obtain the elements. In one way, the researcher supplies the elements to the participants who focus only on creating the constructs. The second approach is to request the participants to provide the elements themselves (Latta & Swigger, 1992). In this study, the elements were 15 terms related to the Shezaf ecosystem (addressing: geosphere, hydrosphere, biosphere, human influence), provided by scientists. The reasoning for using elements provided by experts in the field of ecology was to provide the content anchors for exploring the development of the students' understanding of complex systems.

Constructs represent the participants' interpretations of the elements and the relationships between them. There are different processes to elicit constructs. This study employed the most common method – the triadic elicitation process by which the participants are asked to compare three elements and describe in what ways two are alike and differ from the third (Edwards et al., 2009; Hunter & Beck, 2000). The pupils were asked to randomly choose three elements and explain to the interviewer some aspects in which two of the elements are similar and the third is exceptional. This triad game process was repeated eight times for each participant. Throughout all 8 cycles, the students were interviewed regarding the answers they provided – the interviewer asked questions to clarify the differences and similarities between the elements as these students perceived them. Thus, the constructs were derived, during the interview, by the researchers, from the pupils' explanations of similarities and differences.

A construct, according to Kelly, is a complex image or idea, and understanding the nature of a construct requires knowledge of both the similarity and the contrast regarding a triad of elements. The word or phrase used to describe the similarity and the contrast is determined by the research participant and together, it represents a bipolar description relating to one component of the investigation (Hunter & Beck, 2000). It is important to emphasize that when using the RG technique in educational research, bipolarity can refer to one of two situations. First, it can be used when describing a phenomenon using a characteristic which is bipolar by nature. For example, with respect to the phenomenon 'lake', exemplar characteristics which are bipolar by nature are: cold versus warm water; saline versus fresh water; flowing versus standing water. The other instance of bipolarity refers to characteristics that are not bipolar by nature, and the strength stated by the participant refers to how much this characteristic is expressed or not expressed. For example, tourism influences/does not influence the lake; evaporation is related to/not related the lake. In both situations, the constructs reflect the participants' views and understandings, allowing the researchers to identify what the participants mean without putting words in their mouths (Jankowicz, 2004).

In the last step of collecting grid components, pupils were presented with the elements and the personal constructs they previously constructed from these elements, and were requested to rate (from 1 to 5) the strength of relation between each element and their constructs. For each participant, the elements, constructs they created and their ratings for linkages between elements and constructs were mapped on the grid, using the RepGrid&RepNet software (2013). Fig. 1 presents exemplar grids constructed from the pre-test and post-test results of one student (Gaya). The vertical list is the elements (components of the Shezaf Nature Reserve provided by the scientist), horizontal statements are the (bipolar) constructs she created, and the ratings of linkages she created between the elements and constructs are the central grid numbers. From these ratings for the strength of relation between each element and their constructs, the software calculates correlations among the elements and among the constructs and presents them as a tree of relations (a tree of relation for the elements and a tree of relations for the constructs).

Analysis of RG data

Analysis of the elicited data included three stages. The first stage was the elicitation of the constructs from the students' explanations about the similarities and differences among the three elements of each triad game. Construct elicitation is demonstrated by the following examples from Gaya. In her pre-test, for the triad of elements 'agriculture', 'travellers' and 'desert,' she provided the explanation: "*Agriculture and travellers are both related to human activity, whereas the desert is a place*". The bipolar construct elicited from this explanation was *Nature is influenced/is not influenced by human activity*. In her post-test, for the triad of elements 'sandstone', 'habitat' and 'Acacia tree', Gaya provided the explanation:"*The Acacia tree can be considered a complete habitat within itself*." The construct elicited from this explanation was *Related to the habitat*.

In the second stage of analysis, the constructs elicited were grouped into categories and sub-categories using the STH-model (Ben-Zvi Assaraf & Orion, 2005; Ben-Zvi Assaraf et al., 2012) as the lens for categorization. The major categories are the three sequential levels of system thinking: analysis (A), synthesis (B) and implementation (C). The subcategories refer to the eight characteristics of system thinking described in the literature review. In order to investigate the influence of participation in the program on development of the students' system thinking abilities, the distribution of the number of students who demonstrated each of the three STH-levels was calculated, for the pre and post-test results (Fig. 2). To obtain deeper insight, we also calculated the number of students who expressed the different constructs included within each of the three STH-levels (Figs. 3–5). For validity purposes, analysis of the RG data and categorization according to the STH-levels was conducted separately by the researchers, and the results were compared and discussed until agreement was reached on the constructs and construct categories and sub-categories.

In the third stage of the qualitative analysis, the unit of analysis was the grid constructed by the RepGrid&RepNet software (see Fig. 1 for exemplar grid) for each of the 20 participating students. The aim of this analysis was to identify significant relations among the elements and among the constructs, as reflected in the trees of

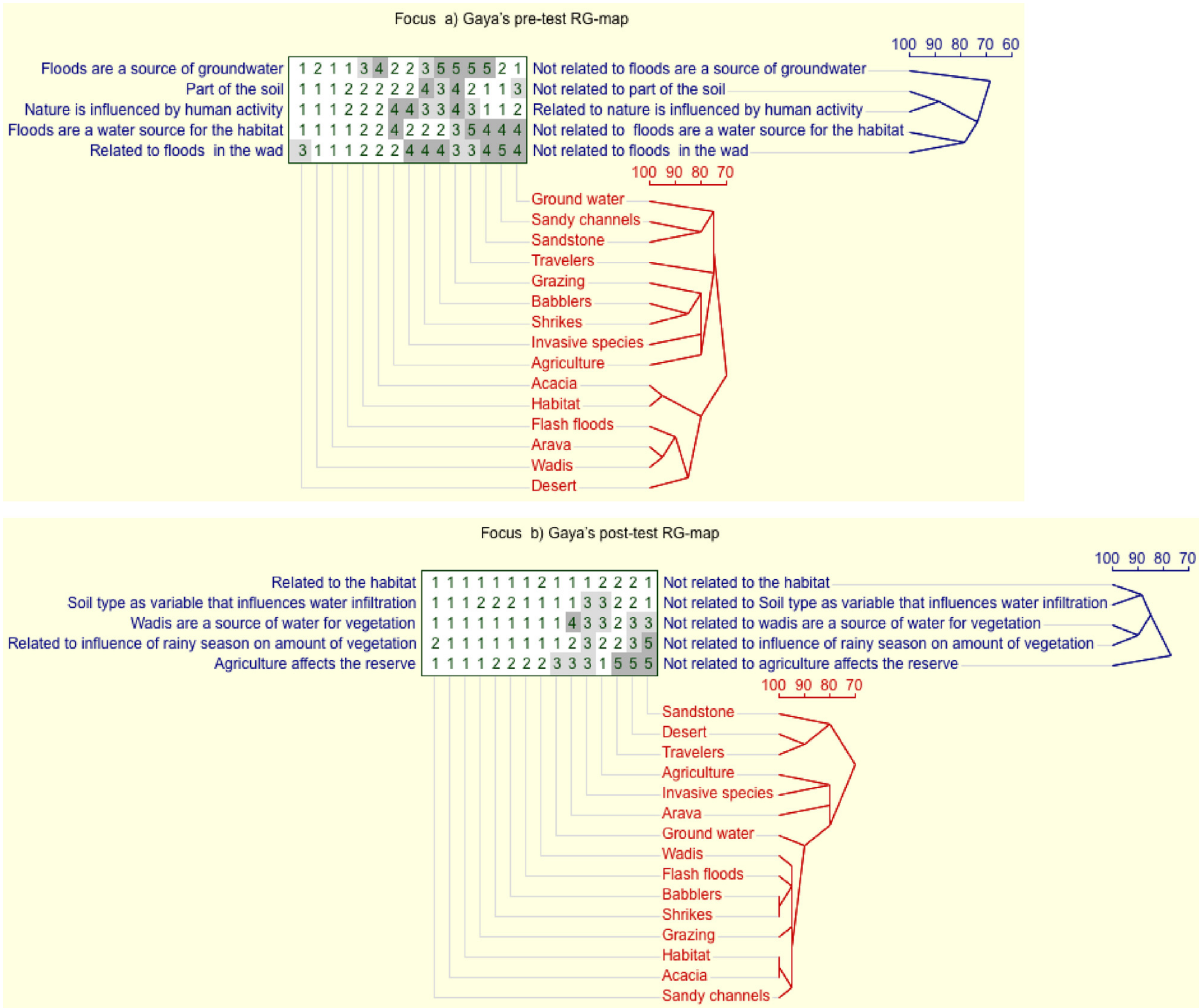

Fig. 1. Gaya's pre-test (a) and post-test (b) Repertory Grid maps.

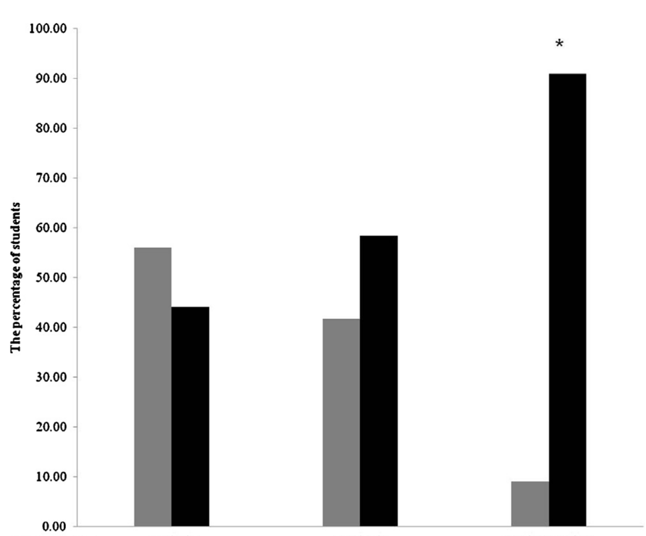

Fig. 2. The percentage of students ($n = 20$) that identified each System Thinking Hierarchy level.

relations created by the software. Only correlations of 80% and above are considered significant correlations (Jankowicz, 2004).

Results

The data is presented from two perspectives: First, the RG data obtained from the whole sample of 20 students was analyzed using the STH-model, in order to elicit a general picture of the development of system thinking skills as a result of participation in the program. Fig. 2 presents the distribution of the percentage of pupils that demonstrated constructs for each of the three major STH-levels, prior to and after studying the program. The results point to a number of findings:

(a) In the pre-test, while the majority (60%) of pupils demonstrated the analysis-level, 40% demonstrated the more advanced synthesis level and 10% demonstrated the implementation level. This suggests that the pupils entered the learning process with both affective and cognitive readiness to discuss the subject of ecological systems and were familiar with the concept. This provides good foundations to enhance development of a more complex systemic understanding of their local ecosystem during the program.

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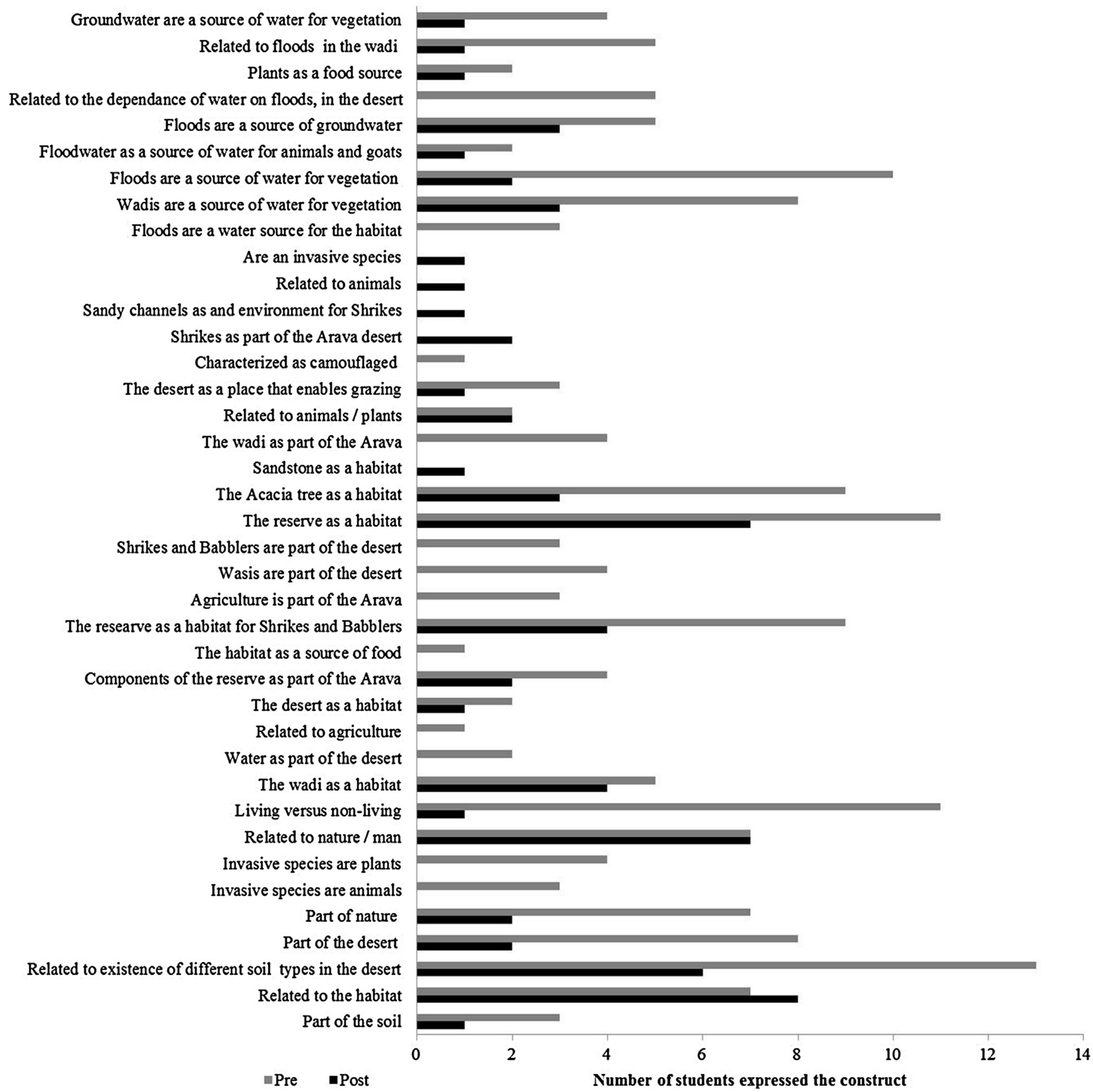

Fig. 3. The number of students that expressed each of the constructs of the Analysis Level (A) of the System Thinking Hierarchy in the pre and post-test.

(b) In the post-test, expression of the analysis level decreased while demonstration of the two more advanced levels increased.
(c) Most significantly, after studying the program, 90% of the students demonstrated the implementation level ($p = 0.001$).

The post-test results indicate that these pupils developed a significantly more complex view of the local ecosystem: The pupils demonstrated the ability to generalize some of the ecological phenomena, such as the temporal impact of flash-floods, and human interferences with the ecosystem, such as agriculture and tourism. These cognitive tools may enable them to better cope with complex, biodiversity-related environmental issues in their local environment.

The constructs created by the students within each of the three STH levels prior to and after participating in the program were also compared (Figs. 3–5). Results indicate that the program elicited changes in constructs within each STH-level. The data pertaining to the analysis level (Fig. 3) point to a number of findings: The majority of constructs (29) created by the students were related to *components* while only 9 constructs referred to *processes*. For most of the constructs that were present in both the pre-test and post-test, there was a decrease from the pre-test to the post-test. Constructs that represent elementary components, such as *Wadi is/is not part of the desert* or *Living* versus *non-living* (Wadi is the Arabic term referring to a valley or dry riverbed that contains water only during rain) were present only in the pretest or decreased very significantly between the pre and post-test. On the other hand, constructs that reflect more complex phenomena, such as *sand stone is/is not a habitat* or *invasive species*, were present only in the post-test.

A number of noteworthy findings stand out with respect to the synthesis level (Fig. 4): First, the two dominant constructs in both the pre-test and post-test relate to human activity in the reserve:

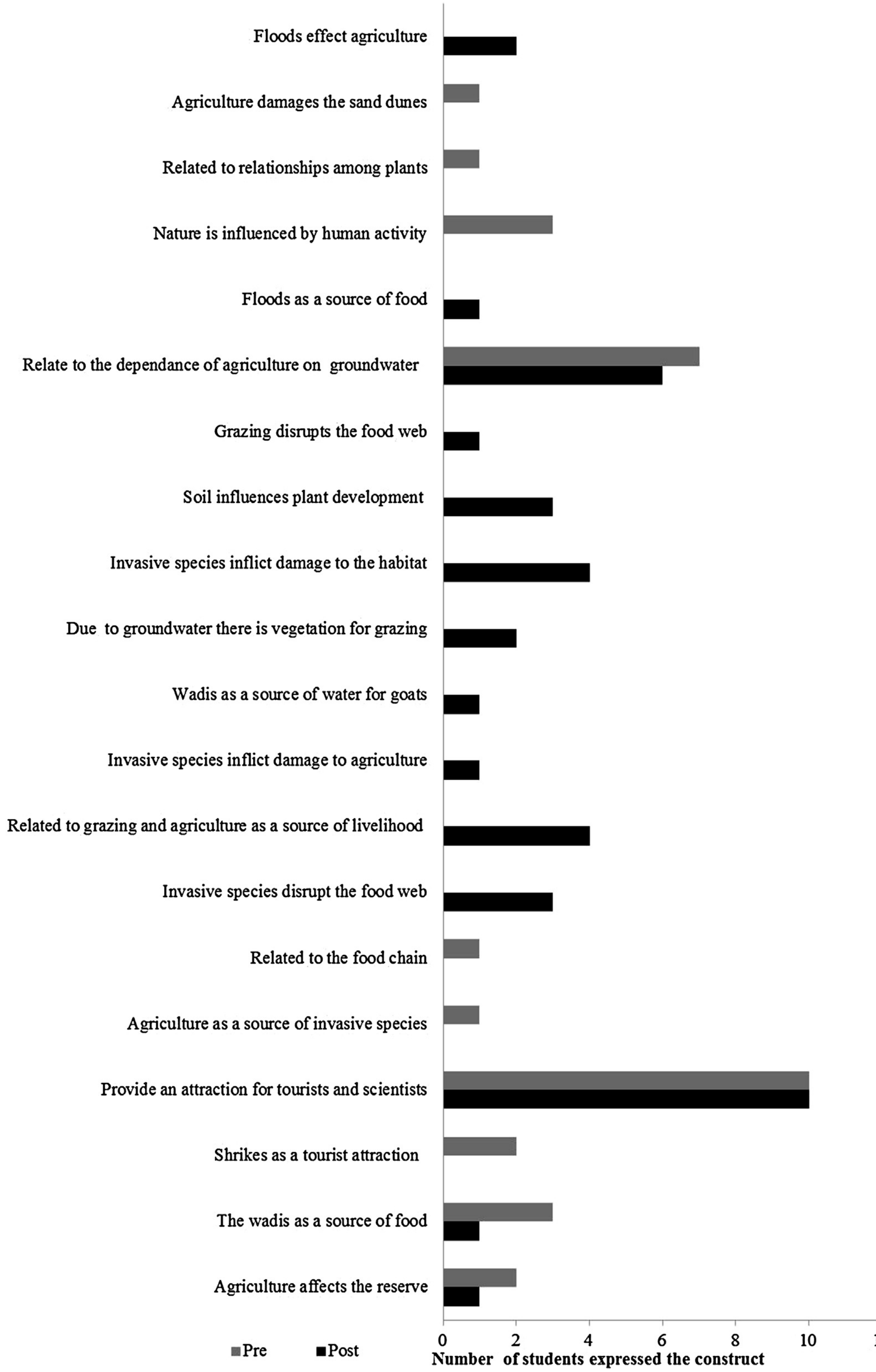

Fig. 4. The number of students that expressed each of the constructs of the Synthesis Level (B) of the System Thinking Hierarchy in the pre and post-test.

Provide an attraction for tourists and scientists and *Related to the dependence of agriculture on groundwater*. Second, ten of the twenty constructs were present only in the post-test, and these constructs reflect the students' ability to create a web of relationships, which is a more advanced understanding of systems within the synthesis level. An exemplar construct is *Due to groundwater there is vegetation for grazing*. Exemplar explanations of students leading to this construct are: "*Grazing animals eat plants that receive their water from groundwater*"; "*Usually, grazing occurs in riverbeds in which more plants grow that animals can eat, because more water*

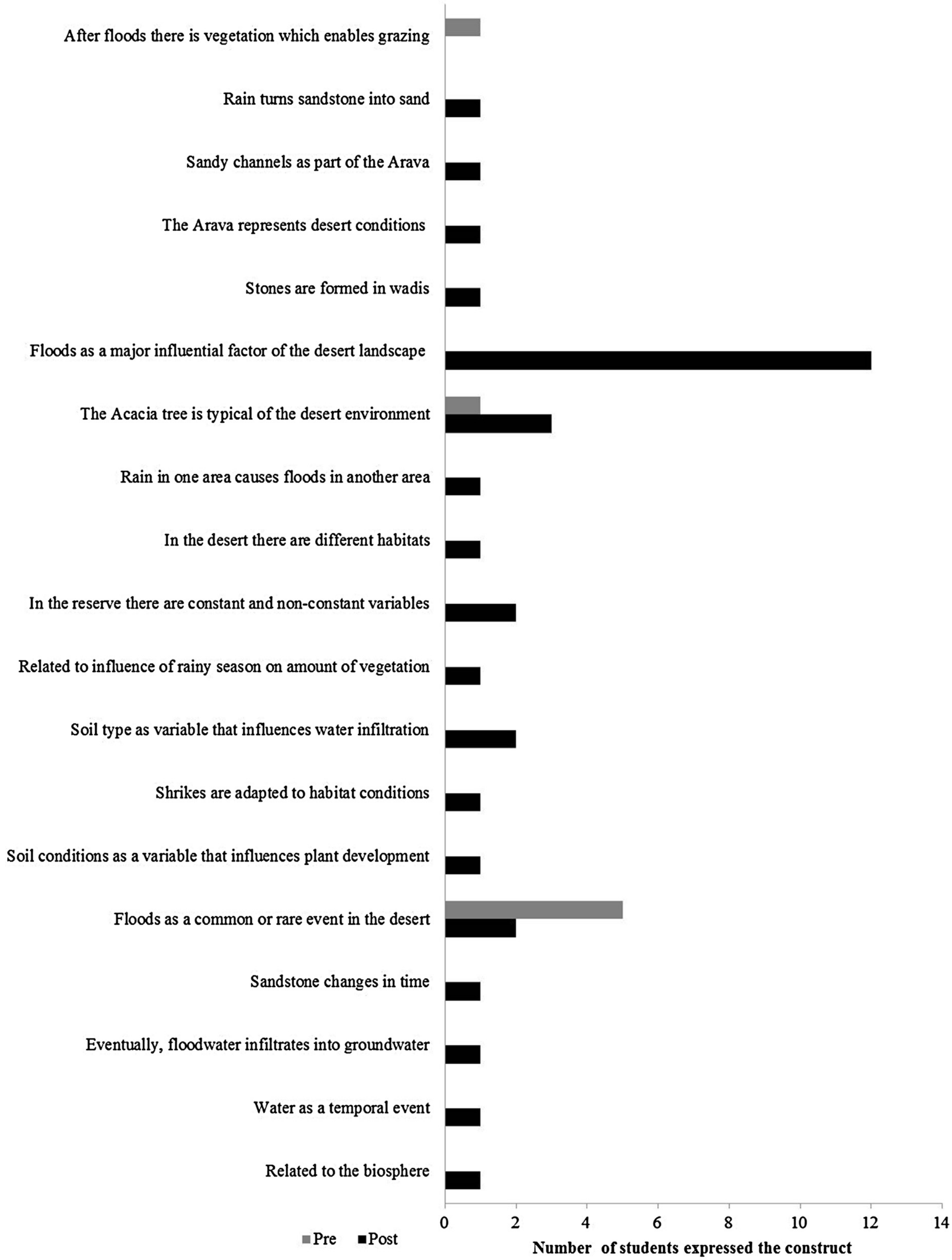

Fig. 5. The number of students that expressed each of the constructs of the Implementation Level (C) of the System Thinking Hierarchy in the pre and post-test.

flows there and plants can grow on the water that infiltrates into the groundwater". Finally, constructs that reflect the ability to identify cyclic processes were not evident in either the pre-test or post-test.

With respect to the implementation level (Fig. 5), all the constructs except three appear only in the post-test. Many of these constructs reflect temporal perception, for example: *Sand stone changes in time; Eventually, floodwater infiltrates into groundwater; Water as a temporal event*. Furthermore, most of these constructs are related to the hydrosphere in general and particularly to flooding as a phenomenon, which was one of the central topics studied in the program. Within the flood-associated constructs, the dominant construct (expressed by 12 of the 20 pupils) was *Floods* *as a major influential factor of the desert landscape*. An exemplar explanation leading to this construct was "*Sandstone turns into a sandy channel after repetitive flooding events*". The students also related time to seasonal changes. For example, the student's response "*After flooding, which occurs in the rainy season, there is more area for grazing because of the increased amount of vegetation*" led to the construct *Related to influence of rainy season on amount of vegetation*. A number of constructs within the implementation level indicated the students' ability to generalize. For example, the student's response "*Babblers and invasive species are different from sandy channels because they belong to the biosphere*" elicited the construct *Related to the biosphere*. Other constructs that reflect ability to generalize are: *In the desert there are different habitats; In the reserve there are constant and non-constant variables.*

The second part of the results comprises the individual perspective, through which each of the students' RG and transcript of the interview that accompanied construction of their RG were analyzed in-depth in order to elicit the students' mental models regarding the Shezaf Nature Reserve. Of the twenty pupils investigated, three case studies are presented here to demonstrate the potential of the RG-technique to identify qualitatively different paths of development in learners' system thinking skills as a result of the learning process. For each case study, the results will first describe the essence of the constructs constructed for the pupil before learning the educational program (pre-test), what STH levels these constructs reflect and insights from the correlations among these constructs. Examples of the pupils' explanations and resulting constructs will be provided in order to demonstrate how the students' mental models pertaining to system thinking are extracted from the RG-data. The results will then address the major changes that occurred in all these aspects after learning the program (post-test).

Case study 1 – Enhancement within earth-system comprehension of a system (Fig. 1)

Gaya's pre-test constructs describe ecosystem components and processes indicating that she entered the learning process mainly at the analysis level (i.e. level A) of STH with one construct demonstrating the synthesis level (B). Water-related phenomena are a dominant feature of her constructs, as exemplified in the construct *Floods are a source of water for vegetation*, which was elicited from her explanation "*Grazing is related to flashfloods, because after them there are plants for grazing animals and water resources*". The only significant correlation (88%) found was between the constructs *part of the soil* and *Nature is influenced by human activity*, indicating her ability to identify a relationship between human activity and the geosphere. With respect to correlations among elements, high correlations (>90%) among the elements flashfloods, Arava and streams indicate her perception of the phenomenon of flashfloods as an integral component of the ecosystem. Relatively high correlations (>80%) among grazing, bird species, invasive species and agriculture are supported by her explanation "*Agriculture damages the reserve by using its open space. Thus, birds are affected since they have less living area*". These results demonstrate that even before studying the program, Gaya was able to identify relationships between humans and earth systems.

In the post-test, Gaya created different constructs, more of which demonstrated synthesis (STH level B) and implementation (STH level C) abilities. An exemplar construct that reflects her temporal thinking (implementation level) is *Related to influence of rainy season on amount of vegetation*, elicited from her explanation: "*After the rainy season and flashfloods, there are more grazing areas as a result of the increase in amount of plants*". High correlations (>80%) among four of the five constructs, and high correlations (>90%) among the elements: groundwater, streams, flash-floods, Babblers, Shrikes, grazing, habitat, Acacia and sandy channels, indicate her perception of the ecosystem as a web of relationships among abiotic and biotic components, including processes. For example, she identified a relationship between the constructs *Related to the habitat* and *Soil type as variable that influences water infiltration*, indicating her perception of water infiltration as a process related to the habitat. Thus, she is expressing a more sophisticated understanding of the habitat to include hydrological processes. Similarly, the high correlation between the elements 'desert' and 'travelers' reflects her perception of the relevance of the desert as a tourist site. Thus, after the learning process, Gaya reflects a more advanced cognitive level of the system as a web. The following interview statement nicely illustrates this conclusion: "*...each plant or animal is crucial to the food-web, if one plant or animal is impaired it will cause a chain reaction that will effect people...in the food-web all are connected, each organism is directly or indirectly dependent on another organism*".

To summarize, comparison between Gaya's pre-test and post-test results indicates that she entered the learning process with an ability to comprehend the processes in the ecosystem. This provided the foundations for a process of refinement in her system thinking, as reflected in a better ability to perceive the complexity of the local ecological system, through the earth-system lens, after learning the educational program.

Case study 2 – From human oriented to biospheric perception of a system

Ziv's pre-test constructs (Fig. 6a) express his focus on the inclusion of humans as part of the local environment, with respect both to agriculture and tourism. For example, from his explanation "*Many travelers come to observe the birds of the reserve, such as the Babblers and Shrikes*" the construct *Provide an attraction for tourists and scientists*. In congruence with this, the two pre-test constructs that reflect the STH synthesis level (B) are connected to human activity within the local system: *Provide an attraction for tourists and scientists; Related to the dependence of agriculture on groundwater*. In Ziv's pre-test tree of relations there was no evidence for correlations between constructs. With respect to elements, correlations greater than 80% were observed within the following groups of elements: bird species-invasive species-habitat; Travelers-sandy channels; agriculture-streams and support the role he views of humans within the local ecosystem. Correlations among biotic elements of the ecosystem were only found among Acacia-Arava-Desert.

The picture emerging from Ziv's post-test RG-map (Fig. 6b) portrays a development in his system thinking abilities. His constructs reflect advancement to the synthesis level (B) and implementation level (C) of the STH. The construct *Floods as a major influential factor of the desert landscape* elicited from his explanation "*Flashfloods create sandy channels because the flow creates channels, therefore Babblers come to sandy channels because there is vegetation in them which the birds can eat*" is an example of Ziv's acquired synthesis ability to perceive a web of relationships. The construct *Shrikes are adapted to habitat conditions*, which was elicited from his explanation "*Shrikes require a habitat suitable for them, in order to survive in the environment and obtain all their necessary conditions*", represents his acquired ability for generalization (level C). Interestingly, humans, which were a dominant feature in Ziv's pre-test constructs, are absent from his post-test constructs, all of which relate to biophysical components of the ecosystem. This natural habitat perspective is also reflected in the post-test correlations (>80%) among Ziv's constructs, all occurring among biophysical components of the ecosystem (second, third and fourth constructs). Similarly, Ziv's post-test ability to correlate among many system components as groups and not as pairs is

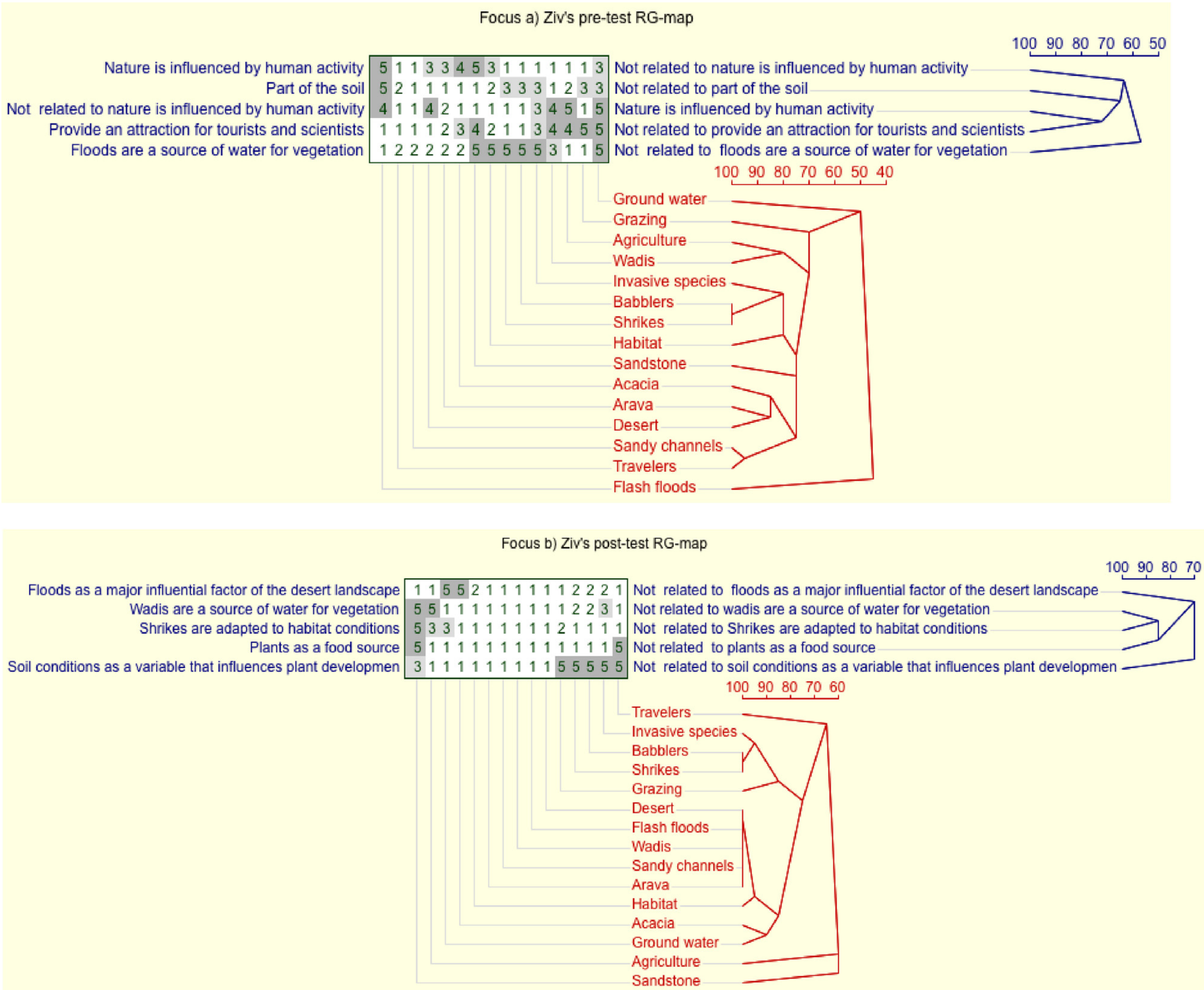

Fig. 6. Ziv's pre-test (a) and post-test (b) Repertory Grid maps.

evident in the correlation among the elements: desert-flashfloods-streams-sandy channels-Arava-habitat-Acacia-groundwater. In summary, Ziv's perspective of the ecosystem after participation in the program reflects a more biospheric perception of the local ecosystem. Within this biospheric lens, it seems that Ziv's mental model of the system is built on connections among the habitat (Arava and the desert), local vegetation (Acacias) and water resources (flash floods and ground water).

Case study 3 – From human impact to ecospheric perception of a system

Aya, who is a member of the Israeli Society for Protection of Nature (SPNI), brought environmental awareness into her learning process. This manifested itself in her pre-test constructs (Fig. 7a), which reflected her focus on humans, with emphasis on their negative impact on the natural environment. Also, her pre-test constructs demonstrate that she entered the learning process with the ability for Synthesis level (B) thinking. For example, the construct *Agriculture damages the sand dunes* was derived from her explanation "*Preparation of natural areas for agriculture eliminates the dunes, thus the dunes are disappearing*". No correlations could be found among her pre-test constructs. Correlations could be found between elements, mostly between pairs of elements, and interestingly these were between biospheric components (flashfloods-sandstone; grazing-invasive species; desert-habitat; Babblers-Shrikes). These connections reflect her prior acquaintance, as a member of the SPNI, with the local nature reserve.

In the post-test (Fig. 7b), with respect to advancement in the STH hierarchy, Aya's constructs remain reflective of the synthesis level (B) with limited progress to the implementation level (one construct). While humans are still present in her post-test constructs, her perspective has changed from a negative view of human activity to a more positive role of humans, as exemplified in the construct *Provides an attraction for tourists and scientists* which was elicited from her explanation "*Babblers attract visitors who observe them, and others who research them*". Furthermore, two constructs that refer specifically to the habitat (*Related to the habitat; Wadis are a source of water for vegetation*) are strongly correlated. After studying the program, the correlations Aya creates among elements (Travelers-Shrikes-Babblers-Acacia-Arava-desert-habitat-invasive species) suggest that she perceives the ecosystem as constructed from a larger set of interrelated components, including humans. This is supported by her explanation "*We are part of nature, we don't have the right to harm organisms. Some human activity is detrimental to the environment but there is also human activity that benefits nature. If people protect nature, then humans and nature will be able to exist alongside each other for years*". This explanation also supports

Fig. 7. Aya's pre-test (a) and post-test (b) Repertory Grid maps.

Aya's more positive perceived role for humans in the environment. In summary, while Aya did not advance to the highest level of system thinking capacity, her comprehension of systems became more refined, with humans being viewed as one component of an ecological system which is comprised of many more different components.

Discussion

This study combined, in the context of ecology, the repertory grid as a tool for exploring learners' conceptual models, and the System Thinking Hierarchy as the theoretical framework for evaluating the development of system thinking. The discussion will first address the development that occurred in the students' system thinking skills consequential to their participation in the placed-based learning unit on ecology and the environment in the Shezaf Nature Reserve. It will then focus on the strengths and limitations of the RG as an instrument for investigating system thinking abilities.

Analysis of the students' constructs through the lens of the STH provides insight regarding the conceptual understanding of systems that they brought into and attained from the learning process. Comparison of the distribution of the constructs among the three STH-levels prior to and after participating in the learning unit demonstrates the transition the students experienced to higher levels of system thinking skills: after the learning experience, 90% of the students expressed the implementation level of system thinking. Specifically, the students expressed some aspects of temporal thinking such as the long term effects of flooding, grazing and human influence. Many of the students' elaborations during their interviews reflected their recognition of changes in the reserve ecosystem that occur over time, such as the dynamics of flood-related phenomena. Studies have indicated that temporal thinking is one aspect of system thinking that is especially challenging for junior high school students (Ben-Zvi Assaraf & Orion, 2005; Booth Sweeney & Sterman, 2007; Magntorn & Helldén, 2005). The development of temporal thinking that occurred in this study can be attributed to characteristics of the outdoor learning unit. First, the unit involved three different extensive field activities that exposed the students to different physical environments throughout a period of four months. Second, one of the field trips was designed specifically to track the diurnal changes occurring in selected phenomena. Third, some of the environmental phenomena chosen for study in this unit specifically demonstrate the time dimension (for example flooding, grazing).

Another system thinking skill difficult for junior high school students to master is the ability for generalization (Hmelo-Silver & Pfeffer, 2004; Hmelo-Silver et al., 2008). In this study, participation in the ecological learning unit led to development of some of the students' ability to generalize. It is important to note that this ability was restricted to the desert environment while transfer of concepts and processes from the desert system to a broader ecological context was not evident. One explanation for this outcome can be attributed to the RG methodology: in this study the students were provided with the ecological elements which comprise the content under investigation. These elements cover diverse components enabling the students to construct a wide variety of inter relationships within the ecosystem. Although these elements were provided by specialists in the field of ecology (i.e. they are comprehensive with respect to components and processes of the ecosystem), they were all related to the Shezaf Reserve, hence they limited the students' construction of ecosystem inter-relationships to those existing in the context of the desert. The rationale for opting for this method, as opposed to the alternative RG approach in which the learners suggest their own set of elements, was twofold: (a) It has the advantage that it leads the students' to construct a specific ecosystem, which provides a concrete system model of reference (Ben-Zvi Assaraf & Orion, 2010a; Eilam, 2012); (b) It enables the pre-test–post-test comparison in the development of system thinking in relation to the same set of elements (i.e. system components). In spite of this methodological constraint, other studies, implementing the more open RG approach in which the students provide the elements, also support that they rarely developed the ability to transfer generalization beyond the system which was the focus of investigation (Ben-Zvi Assaraf et al., 2012). In relation to ecology, results of Magntorn and Helldén (2007) also indicate that the learners' ability to transfer from one system (terrestrial) to another (aquatic) was limited to the functional components of the ecosystem (different trophic groups), while the ability to transfer system thinking abilities such as temporal thinking and dynamism was non existent.

The large percentage of the constructs created by the students before studying the learning unit, that reflect the synthesis level of system thinking, indicate that these students entered the learning process with relatively advanced cognitive readiness. This may be attributed to the local context of the ecosystem chosen as a focus of the learning unit, which addressed a physical environment with which the learners are well acquainted. This finding points to the significance of the place-based approach in developing a systems comprehension of the ecosystem. Focusing on the local environment enabled the students to enter the learning process with affective and cognitive readiness to address the ecosystem and its related human–environment issues. This provided the foundations for the learning unit to develop a more complex systemic understanding of the local ecosystem. Other studies support that by enabling learners to construct a concrete model of a nearby authentic environment, the placed-based approach has an advantage in developing a more complex understanding of natural systems (Ben-Zvi Assaraf & Orion, 2005; Magntorn & Helldén, 2007; Shepardson, Wee, Priddy, Schellenberger, & Harbor, 2007). One constraint of this approach, as discussed previously, is its potential for limiting the transfer of concepts and processes.

A basic pedagogical characteristic of place-based learning is it reliance on the outdoor learning environment. According to Eilam (2012, p. 215), exploring live ecosystems is the essence of biology. Learning about systems by directly interacting with and examining live ecosystems has advantages such as contextualizing learning in real, complex, world environments, engaging students in particular environments that are meaningful and relevant to them, and triggering learners' phases of processing and reflection, from which new conceptualizations may evolve. The fact that the Shezaf Reserve learning unit included extensive outdoor learning, according the literature (Dillon et al., 2006), was, most likely, central in the development the students' understanding of ecological complexity. Dillon et al. (2006) also claim that implementing outdoor phenomenon that illustrate, in a concrete and authentic manner, the concept or processes which are the focus of learning, increases the chances for significant learning. In line with this, the outdoor phenomena specifically chosen for the learning unit, such as flooding and grazing, demonstrate very tangibly large spatial and broad temporal scales of the ecological system. The significance of these phenomena to the students is evident in their post-test constructs and elaborations in their interviews.

A skill at the synthesis level of system thinking that was not advanced through the learning unit was cyclic thinking: after studying the program, none of the students expressed processes of energy or material transfer, in spite of the fact that the learning unit included a laboratory on photosynthesis and a laboratory on soil microbiology. These results indicate that the students' advancement to higher levels of system thinking was related mainly to the influence of the learning unit on their ability to better understand the Shezaf ecosystem as an earth system, i.e. a web of inter relationships at the macro level. The unit was less effective in developing comprehension of relationships at the micro level of hidden dimensions, such as processes of respiration, photosynthesis, decay of organic material or biochemical cycling. It appears that the students had difficulty in relating between the environment as experienced in the field trips and energy and material processes that were studied in the labs. Magntorn and Helldén (2005) describe the ability to recognize organisms and relate them to material cycling and energy flow in the specific habitat is the ability to 'read nature'. 'Reading nature' requires the ability to create links between the macro and micro levels. According to Wilson et al. (2006), the lack of ability to follow matter as it is transported through a system comprises an obstacle to dynamic thinking such as cyclic thinking. Thus, these students are mirroring difficulties reported in the literature in developing system thinking with respect to the hidden dimensions of the system, such as deficient ability to link micro-level processes with macro-level phenomena, i.e. relate macroscopic observations to microscopic explanations (Ben-Zvi Assaraf et al., 2012; Hmelo-Silver et al., 2008).

Findings of this study support that in relation to system thinking, the RG is an effective tool for assessing learners' conceptual models: The RG-maps that emerged from computer analysis provide rich information regarding the pupils' capacities to identify relationships among ecosystem components (*elements*) and identify ecosystem characteristics (*constructs*). Furthermore, the outcomes of the RG maps were compatible with the System Thinking Hierarchy Model: analysis of the constructs yielded from the students' RG maps and interview enabled to explore the development of the learners' system thinking capacities within the STH framework. Other studies (Ben-Zvi Assaraf & Orion, 2010a,b; Ben-Zvi Assaraf et al., 2012; Goldman et al., 2013), which triangulated between the RG-tool and other cognitive research tools (such as concept maps, drawings and open-ended questionnaires), indicate a high level of similarity in the results obtained by the different tools, thus supporting the validity of the RG as a cognitive research tool. The outcomes of this study reinforce this conclusion and broaden the implementation of RG as a research tool to the context of ecological complexity.

The three examples of pre-post RG maps demonstrate not only different conceptual models of the Shezaf Reserve ecosystem but also different pathways of conceptual development consequential to the learning unit. These results point to the sensitivity of the RG tool in eliciting and portraying conceptual maps of systems. In accordance with the constructivist approach to learning, identifying diversity of students' conceptual models and learning styles is important not only from a diagnostic perspective but also provides the starting point for effective learning processes (Tobin & Tippins, 1993). Based on Hmelo-Silver and Azevedo's (2006) claim that students must be "scaffolded" for systems thinking, we propose the RG as a powerful instrument for knowledge integration activities upon which learning experiences can be designed that enable different students, who portray different conceptual models, to advance to higher levels of system thinking, in accordance to their individual learning styles. Interestingly, in a previous study which implemented the RG to evaluate development of system thinking skills during a learning process and its retention, Ben-Zvi Assaraf & Orion (2010b) found that the mental models (of the water cycle system) created by the learners were unique and stable even six years after the learning process. Together, these studies illuminate the instrumental potential of the RG technique as a cognitive research tool in science education. The use of the RG in the context of ecology exposed aspects of system thinking, such as spatial and temporal thinking, that were less evident in other RG studies that addressed other systems.

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