Instr Sci (2012) 40:213–239
DOI 10.1007/s11251-011-9175-4

System thinking and feeding relations: learning with a live ecosystem model

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Received: 22 March 2009 / Accepted: 23 June 2011 / Published online: 6 July 2011

Abstract Considering well-documented difficulties in mastering ecology concepts and system thinking, the aim of the study was to examine 9th graders' understanding of the complex, multilevel, systemic construct of feeding relations, nested within a larger system of a live model. Fifty students interacted with the model and manipulated a variable within it in the course of this model ecosystem yearlong inquiry, in a laboratory/traditional learning environment. Students' written responses to 10 pretest–posttest probes underwent fine-grain analysis regarding 53 descriptors of the system of feeding relations. Overall, students exhibited initial system thinking, manifested in different levels of increased ability to identify: system components, processes, levels, and their interrelations; ecosystem patterns and control mechanisms; equilibrium shifts; and spatial and temporal aspects of feeding relations. However, many still exhibited a deficient understanding of the system studied, reflecting a deficient system thinking. Implications for systemic ecology teaching and learning are discussed.

Keywords System thinking · Live system model · Long-term inquiry · Ecology instruction and learning · Junior high school

Instruction of ecology poses great difficulties for students' learning (e.g., Hogan and Fisherkeller 1996; Reiner and Eilam 2001). These difficulties are usually attributed to ecology's interdisciplinary nature, to ecological theories' low level of generality, formalization, and verifiability (del Solar and Marone 2001), to the complex systemic nature of ecosystems (Grotzer and Bel Basca 2003; Hmelo-Silver et al. 2007), to the need to comprehend biological systems of increasing levels of complexity (Model et al. 2005), and to students' prior knowledge (Vosniadou 1994). For most biology students, learning biology mostly involves memorizing details about static components of phenomena while disregarding systemic changes in time (Wilensky and Reisman 2006). Learning about a system's components alone does not ensure students' development of system thinking.

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However, despite these difficulties, ecology constitutes an inherent part of most western countries' curriculum, because it provides opportunities to study systemic phenomena and plays a crucial role in human decision making (Sabelli 2006). To overcome some of the difficulties, diverse instructional modes are continually being developed to help students experience basic systemic concepts and principles from middle school on (Jacobson and Wilensky 2006; Penner 2000; Wilensky and Resnick 1999). Most of these instructional modes utilize models represented by various computer simulations, whereas live ecosystem models have been reported less often. Therefore, I believe students' learning with a live model—and in particular in the biology domain—has to be studied as an additional experience and a tool for acquiring system thinking. To investigate students' difficulties and draw recommendations for teaching ecology, the current research study followed ninth graders' long-term inquiry of a live ecosystem model that promoted students' gradual and simultaneous construction of complex understanding regarding not only distinct components but also the ecosystem as a whole. The study main contributions lies in the long-term interaction with the model, and in the fine grain analysis of students' responses to probes designed to reveal their system understanding.

System thinking and its inherent difficulties

Briefly, complex systems comprise numerous diverse components organized in a multilevel structure; these components interact dynamically, nonlinearly, and simultaneously, within or across levels, but such interactions are often implicit, with indirect causality (Hmelo-Silver and Azevedo 2006; Jacobson 2001). The unpredictable and non-intuitive macroscopic-level expression of a system's self-organization, resulting from processes occurring within its subsystems, show emergent and complex properties not exhibited by individual components (Hmelo-Silver and Pfeffer 2004; Jacobson 2001; Kaneko and Tsuda 2000). Therefore, system thinking requires a wide repertoire of cognitive abilities for performing general structural analysis, based on dynamic, fluent, closed-loop, and scientific thinking modes (Richmond 1993). Unsurprisingly, system thinking has been shown to seriously challenge students of different school and college age (Jacobson and Wilensky 2006).

Indeed, studies examining comprehension of different biological systems (e.g., food webs, stream ecosystems) have shown that not only students but even preservice teachers and experienced teachers reveal compartmentalized knowledge and deficient system thinking. Such comprehension problems were evident regarding the ability to interrelate system levels regarding components like cells or processes like slime growth, photosynthesis, predator–prey populations, feeding relations in ecosystems, dynamic equilibrium maintained by feedback mechanisms, or self-organization forming an emergent pattern (Jacobson and Wilensky 2006; Penner 2001; Waheed and Lucas 1992; Wilensky and Reisman 2006; Wilensky and Resnick 1999; Wilson et al. 2006).

For example, regarding the ability to relate between processes like photosynthesis and cellular respiration, Brown and Schwartz (2009) showed that after learning the topic, preservice elementary school teachers could describe some components of photosynthesis and cellular respiration processes in plants, but not the nature of their connections. Teachers' conceptions exhibited egocentrism—perceiving plants as providing services to humans; interdependency—perceiving plants as dependent on humans; and even a sociological view—suggesting that society must care for plants. The teachers justified their conceptions by citing authoritarian sources like classroom experiences, or by relying on anthropomorphism (assigning human characteristics to plants), tautology (applying circular reasoning), or just intuition (Brown and Schwartz 2009).

In light of the difficulties involved in the acquisition of system thinking, different instructional modes have been developed over recent decades to promote students' learning. Among them, model-based instruction is salient.

Model-Based learning environments for enhancing complex systems' instruction

Exploring live ecosystems (an ocean, forest, or marsh) is the essence of biology. Learning about systems by directly interacting with and examining live ecosystems has advantages like contextualizing learning in real, complex, world environments (Doberski 1998; Tessier 2004), engaging students in particular environments that are meaningful and relevant to them (Winn et al. 2006), and triggering learners' phases of processing and reflection, from which new conceptualizations may evolve (Kolb et al. 2001).

However, live ecosystems contain a much larger number of components than individuals can address, as well as mostly implicit interactions and processes, occurring at diverse microscopic and macroscopic levels over time. Manipulation of variables cannot be controlled in real ecosystems, and to explore such complexity, students must have substantial prior knowledge of the domain (Winn et al. 2006). Indeed, this very complexity may be too difficult to enable students to develop system thinking.

Modeling-based environments simulate behaviors of modeled ecosystems and afford learners opportunities to experiment and manipulate variables in controlled settings. Students actively explore concepts and phenomena and construct relevant knowledge about them, by hypothesizing and testing their hypotheses. In cases of inaccessible, dynamic systems as well as invisible interactions and processes, models enable learners' accessibility by changing scales (e.g., an aquarium instead of a lake, a bacterium modeled by a circle); by making the abstract and invisible to be concrete and visible (e.g., processes modeled by equations); by reducing costs of investigating a real large ecosystem like, a forest, to those involved in designing and managing a greenhouse, a terrarium or a computer model; and by reducing possible dangers involved in the investigation of certain live natural ecosystems.

The most frequently used models in ecology instruction are computerized models (Crawford et al. 2005; Finn et al. 2002) and, to a lesser extent, live models (Hmelo-Silver et al. 2007). Both model types are time consuming.

Computerized models (especially system dynamics simulations and agent-based simulations) offer many advantages for learning, such as engaging students in integrated explorations of complex conceptual spaces (Sabelli 2006), revealing patterns of system behavior by decreasing the number of system variables and oversimplifying reality (Bayraktar 2002), enabling learners to construct better mental models of the modeled phenomena and to continuously repair and refine them according to immediate feedback cues (Nersessian 1999), promoting students' ability to link isolated concepts, reason relationally and causally, synthesize knowledge, and explain phenomena (Stratford et al. 1998), and facilitating performance of virtual experiments that cannot be performed in reality (Bradbury et al. 2000; Kaneko and Tsuda 2000). However, in spite of these advantages, students have been shown to experience great difficulties with the manipulation of these models and with handling of the "multimedia" presented on the screen. In particular, they exhibit difficulties to relate what they perceive to the natural world.

Live models constitute simplified concrete models of real ecosystems such as an aquarium, terrarium, or greenhouse, which allow students encounters with live organisms.

Live models can foster system understanding because they contain significantly smaller numbers of components, interactions, processes, and system levels than real ecosystems; however, such models may not represent all of the ecosystems' systemic characteristics. For example, unlike natural ecosystems, such live models rarely arrive at a state of equilibrium on their own, and must receive a supply of energy and matter to maintain them (e.g., food for some organisms must be provided because food chains are incomplete). Yet, despite their simplification, these live models still constitute highly complex systems according to any criteria.

Live models enable an authentic inquiry of ecosystems (Schraw et al. 2006), including some manipulations of variables in one ecosystem as compared with a control model set. Furthermore, because they are chosen and built by students, these models are directly related to their prior knowledge and experiences, especially domain knowledge of ecology concepts and theories (Eilam 2002; Doberski 1998). Students' interactions with the live model may involve: observations of system behaviors over time, collection of data and measurements of different variables (e.g., population size, oxygen amounts), explanations of changes in measurements, and the consideration of simultaneously occurring processes by relating data to observed behaviors. Gradually, students construct dynamic mental models of their system's behavior and refine them in light of perceived macro changes in the live model and of input from new collected data. Inasmuch as students, while learning with live models, interact with both the whole system as is (e.g., bad smell, organisms die, oxygen levels of an aquarium) and with its distinct components (e.g., feeding the fish, measuring number of falling leaves), such longitudinal interactions may promote students' gradual development and refinement of system thinking. For example, students measuring oxygen levels in such model aquarium may search the reasons for the measured changes over time, hence foster their understanding that outcomes stem from several concurrent micro-level processes ongoing within the aquarium (e.g., plant photosynthesis, organisms' respiration, oxygen dissolving in and evaporating from water) whereas measurement of only a single component (e.g., oxygen discharged from a plant due to light exposure) would not lead to similar awareness. Studies suggested that students' interactions with live models promoted: (a) their awareness of some underlying implicit causes, nonlinear processes, and interactions; (b) their understanding of each involved component as embedded in the system as a whole, and (c) their ability to relate perceived macro-level phenomena to measurements of micro-level components, processes, and products (Hmelo-Silver and Azevedo 2006; Jacobson 2001; Model et al. 2005).

Despite these studies suggesting the advantages of model-based learning environments, other research has continued to demonstrate many difficulties in students' and teachers' acquisition of conceptual and system thinking in biology and ecology in general, and in feeding relations in particular (the focus of the live models investigated in the present study).

Students' difficulties and misconceptions regarding feeding relations

The major difficulty revealed by many studies of ecological and other system learning is the significant effect of individuals' prior knowledge on learning outcomes, both quantitatively and qualitatively (Brown and Schwartz 2009; Hmelo-Silver and Pfeffer 2004; Thompson and Reiman 2010; Wilensky and Resnick 1999). Such research suggests that system thinking challenges learners not only because it requires many abilities but also due to the misconceptions that students bring to classrooms, including their naïve beliefs and ontologies. In particular, some core systemic ideas have been shown as counterintuitive to students' prior knowledge and beliefs, like the "butterfly effect," randomness, decentralized interactions, self-organization, and nonlinearity (Grotzer 2005; Jacobson and Wilensky 2006). In addition, substantial differences have been demonstrated between novices and experts' system thinking (Jacobson and Wilensky 2006; Wilensky and Resnick 1999). Therefore, while examining students' understanding of a system like that of feeding relations, attention must be directed toward students' intuitive "naive system intelligence" (Booth Sweeney and Sterman 2007), which may present many possible obstructions to students' development of a system view. Research suggested that students' misconceptions involve feeding relations as a concept and as a system within ecosystems, as well as related specific concepts. The following deficits in student understanding were well-documented regarding micro and macro levels of feeding relations:

Naïve macro view of matter

Students' misperception of matter as successive constrains their understanding of dynamic processes like molecular mobility in organisms, the body, and the biosphere (Lee et al. 1990; Nakhleh et al. 2005).

Lack of a micro view of feeding relations

Students' system thinking is constrained by their failure to regard plants as essential elements in food chains, their misconception that chain sequences are determined by size and strength hierarchies (Reiner and Eilam 2001), and their naïve, egocentric placement of humans at the top of feeding chains (Dagher and BouJaoude 1997).

Deficient ability to link micro-level processes with macro-level phenomena

Students are generally unable to relate macroscopic observations to microscopic explanations and to recognize that similar micro processes underlie different macro-level processes in all live creatures (Alparslan et al. 2003; Liu and Lesniak 2006). For example, they may not understand that the prerequisite of plant placement as first in webs is due to photosynthesis, or that chains' order is due to evolutionary processes and environmental conditions.

Inaccurate plant-animal analogies

Students often misperceive plants' and animals' feeding as similar while ignoring photosynthesis, thus revealing erroneous ontologies (Ozay and Oztas 2003). Likewise, students often misconceive animals' food simply as consumed materials used to build the body and grow, disregarding possible chemical transformations of matter along chains, involving inorganic and organic materials (Hogan and Fisherkeller 1996).

Deficient understanding of matter's and energy's distinct characteristics

Junior high school students are already aware of matter conservation but mistakenly believe that matter simply breaks up in the soil, without considering its transformation by bacteria. Their lack of awareness of differences between organic and inorganic matter and their frequent confusion with energy may hinder students' comprehension of matter-energy relationships in biological or ecological phenomena, involving energy loss or transformation (Chi et al. 1994; Hogan and Fisherkeller 1996).

Clearly, these main areas of misconception may constrain students' understanding of feeding relations as a system, nested within larger systems, and nesting sub-systems (Brown and Schwartz 2009). For example, Misconception 1 excludes situations of mobility within an organism or between the biosphere's different levels, and Misconceptions 2 and 3 may seriously constrain students' ability to perceive interrelations among system levels, including its micro and macro levels. Students' egocentric beliefs about humans at the top (2) may prevent their ability to regard other chains as optional (e.g., an organism feeding on man). Finally, students' erroneous ontology concerning plants' resemblance to animals (4) and matter's resemblance to energy (5) may result in misunderstandings about the system's structure.

Basic notions enabling a system view of feeding relations

Four basic notions are necessary for development of a system view of feeding relations, but research has shown that students' understanding of them is often deficient:

(1) *Matter and energy cycles as multilevel phenomena*: to obtain a system view of feeding chains, students must recognize gasses as matter and understand that matter and energy flow through the biosphere, partially through the biotic world (e.g., gaseous cycles and light and chemical energy as part of photosynthesis and respiration) (Anderson et al. 1990; Hogan and Fisherkeller 1996). While considering such flows through the biosphere, they must avoid confusion among its system levels (e.g., cells, organisms, atmosphere) (Wilensky and Resnick 1999).

(2) *Directionality and dynamic equilibrium*: understanding that physical processes are possibly reversible and that chemical reactions reach a dynamic equilibrium (Steiff and Wilensky 2003) is necessary for students' system view of the dynamic equilibrium that underlies processes in many levels of ecosystems (e.g., population sizes, diffusion). A dynamic system equilibrium is achieved when the quality and quantity of system components are kept constant over time (although they continue changing around the equilibrium point), mostly by the action of implicit feedback mechanisms (Booth Sweeney and Sterman 2007; Draper 1993; Ossimitz 2000). Students often reveal unidirectional thinking (Leach et al. 1996), which hinders understanding of a dynamic equilibrium. From elementary school on they rarely recognize feedback processes, frequently describe them as cycles, and perceive increases in system materials as the effect of inflow only, while ignoring outflow from the system (Booth Sweeney and Sterman 2007).

(3) *Causality*: to understand system outcome behaviors, students have to identify causal relationships among its components in the same or in different system levels. Students' ability to identify causality is hindered by gaps in their knowledge about temporal and spatial processes, especially when the cause is obscure (Grotzer and Bell Baska 2003). Students tend to overlook population relationships and sizes within a system (Barmen et al. 1995) partly related to their unidirectional thinking.

(4) *Temporal and spatial facets and evolution*: to develop a system view of feeding relations, students must be able to recognize processes as occurring along the temporal dimension and of space, processes occurring simultaneously in different spaces.

> Elementary school students and older ones show deficient awareness of time delay impacts (Booth Sweeney and Sterman 2007). Older students fail to perceive evolutionary events as an "emergent" phenomenon (i.e., the unpredictable macro-level expression of a system's self-organization, resulting from processes occurring within its subsystems; Kaneko and Tsuda 2000). Instead, students tend to see a central force (e.g., god) as guiding live trends. The well-documented difficulties in comprehending evolution may stem from its counterintuitive nature, from students' deficient understanding of time frames and causality, from religious beliefs, from prior learning based on anatomy rather than on evolution (Blackwell et al. 2003; Grotzer et al. 2003), or from teleological thinking and an intuitive Lamarckism view (e.g., Crawford et al. 2005; Demastes et al. 1996; Samarapungaven and Wiers 1997). Although students do associate mutation with change, the latter is not necessarily thought to be genetic, involving organisms' DNA (Albaladejo and Lucas 1988).

In sum, the holistic system view of feeding relations involves: (a) analysis of observations as embedded in the wider context (e.g., the feeding organisms in a chain transfer matter and energy from and to their environment); (b) acknowledgment that a system's properties differ from its composites' properties (e.g., the feeding web's properties—like equilibrium—differ from the properties of the web's individual organisms); (c) recognition that a change in a single variable may cause changes in many others (e.g., extinction of one component may cause a web to change dramatically); (d) considerations of multiple cause-effect relations (e.g., amount of producers affects the number of feeding levels); (e) understanding that the system functions at the micro and macro levels (e.g., the chemical reactions involved in photosynthesis at the plant cell level affect the web structure and environment's matter and energy); and (f) pattern anticipation of a long-term effect by a present action and understanding of change over time (e.g., anticipation of order in the feeding chain according to evolutionary-determined organisms' digestive system structures or changes in webs due to evolutionary changes in its components) (Assaraf and Orion 2005; Grotzer and Bell Baska 2003; Hmelo et al. 2000; Hogan 2000).

In line with these high demands, findings unsurprisingly showed that elementary school students were mostly able to describe only those elements and factors that were within the immediate boundary of the investigated scenario (Booth Sweeney and Sterman 2007). Research on junior high school students revealed that they: (a) could only grasp the simpler, immediate, linear reasoning patterns rather than the complex patterns typifying ecosystem processes; (b) overlooked indirect or extended effects while reasoning about populations (Griffiths and Grant 1985; Webb and Boltt 1990); (c) considered a change passing along populations only for populations that were linked through direct predator–prey relations (Barmen et al. 1995; Leach et al. 1996); (d) did not relate fluctuations in population sizes to environmental factors like food supplies; and (e) had difficulties perceiving chemical equilibrium as dynamic, assuming that the forward reaction must be completed before the reverse reaction could start (Munson 1994).

The present study rationale and design

Vosniadou (2007, 2008) recently proposed that students' learning and cognitive development in terms of conceptual change should be reframed as a domain-specific process, in which naïve theories constructed from everyday experiences and lay culture (through bottom-up additive mechanisms) gradually change over time. Such changes involve both bottom-up enrichment of existing bodies of knowledge and top-down restructuring of these bodies through an intentional instructional process, thereby opening up conceptual space for new perspectives to promote conceptual reorganization. In line with these recommendations, the present study investigated the impact of students' long-term inquiry-based interaction with a live ecosystem model (terrarium, aquarium, or greenhouse) on their constructed knowledge and understanding of the system of feeding relations. This long-term inquiry is expected to initiate both top-down and bottom-up construction and restructuring processes, involving both model examinations and the learning of theory. The affect on the knowledge constructed was examined in relation to the five areas identified by researchers as deficient and while considering the four basic notions that are prerequisite to system understanding. As may be seen in the criteria for analysis, they are closely related to these 9 core ideas.

Overall, an inquiry-oriented environment has been advocated as best fitting the domain knowledge characteristics of ecology and ecosystems (National Research Council 2000). As an ill-structured and student-centered learning method, inquiry is driven by students' current state of knowledge and thus offers a level of uncertainty and ambiguity in finding solutions that facilitates students' reflective, flexible thinking (Roth 1998; Song et al. 2006). Therefore, in the current study, ninth graders interacted for an entire academic year with an ecosystem model that they planned and executed cooperatively in small groups, with the explicit aim of learning about their ecosystem's behavior.

However, in light of the complexity of the basic notions that are prerequisite for system understanding of feeding relations and the documented student difficulties, deficits, and misconceptions in achieving system understanding, as described above, the current instructional program design integrated two other components in parallel to the independent inquiry: classroom instruction and laboratory support (comprising direct teacher guidance and supportive materials). These components aimed to support students' system-oriented inquiry in three major ways: (a) by fostering their acquisition of deep knowledge of ecology and physics (energy in particular) concepts and guiding principles through traditional classroom instruction, using ecology textbooks developed from a system perspective (Eilam 1980) (see also Eilam 2002, 2008). This knowledge promote students' top-down construction processes; (b) by facilitating students' construction of deep understanding about the nature and execution of inquiries, using a textbook developed for guiding students' inquiry procedures (Eilam and Aharon 1998) as well as support from physics and biology teachers in the laboratory; and (c) by enhancing students' ability to self-regulate their long-term learning using specifically-developed supportive tools accompanied by teacher guidance in the laboratory (Eilam and Aharon 2003). This design corresponds with Kirschner et al. (2006, p. 75) call for such instruction to provide "information that fully explains the concepts and procedures that students are required to learn as well as learning strategy support that is compatible with human cognitive architecture."

Feeding relations were selected as the focus of the current study because they constitute a system nested in any ecosystem and any of the models chosen by students and therefore lend themselves to analysis regarding students' system thinking in interaction with the live models. While reading and learning about, building, manipulating, observing, and interrogating a live model of an ecosystem, students encounter most issues related to feeding relations in general and in their model in particular. For example, they could specify what item(s) each organism feeds on and recognize that plants' "feeding" (photosynthesis) differs from animals' and thus realize that plants must be first in a chain. Those working with a terrarium could observe that plants are eaten faster than they reproduce because of insects feeding on them and that insects later disappear due to lack of food, thus eliciting thoughts about population size, equilibrium, and feedback mechanisms, as well as about chain elements' sequence and consequences of one element's disappearance. Live ecosystem models enable students to measure various feeding-related systemic variables (e.g., levels of O_2, CO_2, and nitrates or number of fallen leaves) and relate the data to the feeding organisms' other functions (e.g., reproduction, death or even eutrification—the death of an ecosystem due to overpopulation of microorganisms), coming to understand that many simultaneous interactions and processes occur in the live model.

Altogether, the inquiry-based live model was expected to enable analysis of students' constructed system thinking focusing on feeding relations as a nested system example.

Method

Sample

Participants were 50 students comprising two-ninth-grade classrooms (ages 14–15) in one middle-class suburban Israeli junior high school. Students' composition regarding age and sex was similar in both classrooms (as a part of school policy).

Live model inquiry-based learning environment

Inquiry task in the laboratory

Students' explicit task (goal) was to examine a specific hypothesis in an ecosystem model, within the broader aim of learning about ecosystem behavior. They could choose any topic they wish to investigate in their model, and raise any hypothesis relevant to it, not necessarily related to feeding relations. It was assumed that the long-term investigation of the system includes the understanding of the feeding relation nested system. They worked in cooperative small groups for a weekly 3-hour independent-study session in the school laboratory, carried out throughout one academic year. This setting and time allocation allowed for gradual knowledge construction and revisions, through students' mindful discourses and decisions, in light of occurrences in the modeled ecosystems and data collected.

Guidance in the lab was provided by both a biology and a physics teacher, to enable students' concurrent access to both disciplines while dealing with concepts pertaining to both (e.g., energy) and developing cognitive flexibility by avoiding knowledge compartmentalization. In addition, teachers attempted to attend to students' aforementioned learning difficulties and misconceptions known to obstruct systemic thinking.

To perform this investigation they had to learn and independently read about different ecosystems and their components, formulate a broad topic of interest, focus gradually on possible questions, raise hypothesis based on their knowledge of ecology and biology, choose one hypothesis for examination in a live model of their choice (i.e., an aquarium, terrarium, or greenhouse), and select the model's biotic components (e.g., plants, animals) and abiotic components (e.g., sand, stones, light, heat, air). They then constructed two exact copies of this model—one for manipulation and the other as a control—and maintained both copies under exactly the same conditions.

When the models were ready, they were left as-is for more than a month, to allow them to settle as much as possible. Students did not confuse this stage with equilibrium, due to the matter and energy added to or extracted from the model (e.g., food added for some animals, water added to replace water that evaporated). During this time, students performed a series of measurements on their ecosystem models' micro and macro variables (e.g., O_2, CO_2, temperature, nitrates, phosphates, salts, acidity, evaporation, organisms' numbers, sizes, and weights), and they took samples of bacteria from various system components (like leaves, earth, or air) and counted the number of different shapes, colors, and textures of bacterial colonies as indicators of different species and their approximate amounts. Already at this stage students realized that their two systems (experimental and control), although constructed to be exactly the same, showed a wide variability in measurements, suggesting complexity. During this period, in addition to measuring and observing, students also went on reading and learning about processes in the system and about the properties of the selected components.

In the next stage of inquiry, students caused a change in one variable in the experimental model only, in line with their hypotheses. For example, one group of students who built a greenhouse inserted a large quantity of CO_2 in it, aiming to examine "the greenhouse effect." Another group added a predator to a terrarium. Other groups working with aquariums added one tablespoon of fertilizer or sugar, or covered the experimental aquarium to prevent light from entering, and so forth. From this moment on, students measured all possible variables (under school lab conditions) in both the experimental and the control live models. Needless to say, they came to the lab to "see what was happening" and to measure variables outside their weekly lesson time.

Over the course of their long-term observations, each group was required to prepare visual representations (e.g., tables, graphs, schematic drawings) of their collected data. Students evidenced different states of their model system behaviors due to changes occurring over time in it. (e.g., a gradual decrease in oxygen, only then the rise in acidity, etc.). They made attempts to explain these changes, based on their own measurements of variables in the system and on the understanding they constructed while learning ecology. Finally, they generated conclusions as to whether their hypothesis was correct or not and submitted a "paper" about their inquiry.

Classroom instruction

In addition to the laboratory sessions, students attended three traditional classroom sessions per week, one in ecology and two in physics, throughout the year. Physics classes focused on energy and its relation to ecology (e.g., conservation, thermodynamics), thus supporting meaningful deep understanding of ecosystems' structure and function principles. Ecology classes focused on open systems' structure and function, discussing concepts like input and output flows, interactions, feedback mechanisms, equilibrium, the biosphere as an open system including matter and energy transfer, photosynthesis, respiration. Ecology lessons also analyzed and discussed examples of natural and artificial ecosystems like a lake or forest, and monocultures like agricultural fields or dairy/chicken farming. The sessions activated knowledge acquired in earlier years (e.g., evolution) and related it to the students' current live models of ecosystems. This pedagogy was designed to trigger a top-down and bottom up processes of knowledge construction at students' own readiness and comprehension levels.

Data collection and analysis

Pretest–posttest probes

To reveal the knowledge students constructed about feeding relations as a nested system while interacting with their live models for a full year, a set of 10 open-ended probes was developed and administered to students before and after encountering their live models (see Appendix A). Students' expected responses are presented after each probe in relation to the analysis criteria presented next.

Criteria for analyzing students' responses to the probes

To analyze students' responses to these probes, 13 criteria were defined based on the aforementioned scientific canon and literature reports about learners' misconceptions of feeding relations and the basic prerequisite notions for system understanding. These criteria (left column of Table 1) were selected to optimally represent the structure and function of the feeding relations' nested system. To provide valid, cross-referenced data on the core criteria identified, each of the 10 probes was designed to unveil several criteria, and the different probes overlapped (see second column in Table 1).

Several values and descriptors were defined for each criterion, as relevant to feeding relations as a nested system (e.g., a chain's configuration may be described as linear or cyclic; the biotic component types may be described as plants, animals, humans, or decomposers) as presented in the third column of Table 1). A descriptor was defined as comprising at least one of the following: (i) a part of the chain's/web's structure or function; (ii) an explicit or implicit component or characteristic of a food chain/web (e.g., plant, decomposer, order, reversibility); (iii) an event or process (e.g., linearity, change, matter transformation); and/or (iv) a part of matter or energy cycles (e.g., oxygen, light, heat). Three biology and two physics experts validated the 13 criteria and their 53 descriptors as reflecting core concepts and processes in feeding relations. These criteria and descriptors then served as the coding system for content analysis of students' responses.

Students' pretest and posttest responses were analyzed for their content using each single idea as a unit of analysis. All responses to the probes were coded for correct evidence of each descriptor. An inter-coder reliability of 89% was achieved between two ecology educators who coded all descriptors for 5 randomly sampled pretest response sets to the 10 probes and 5 randomly sampled posttest sets. A correct response concerning a particular descriptor scored 1, and an incorrect or no response scored 0. Responses for each descriptor were summed, with a possible range of 0–6 (the maximum number of responses pertaining to each descriptor). Responses that did not correspond to any of the criteria were coded as "other" and were described separately. Paired *t*-tests were used to compare students' pretest and posttest responses for the various descriptors (see Table 1).

Results and discussion

Table 1 presents analysis outcomes (means, standard deviations, *t* values, and percentages) for the pretest–posttest comparisons of the feeding relations criteria and descriptors. Percentages for some criteria do not sum up to 100% because some students responded irrelevantly. The following section discusses the findings according to the various criteria and presents excerpts from students' responses to various probes.

Changes in students' understanding of feeding relations after learning

As evidenced in Table 1 (see for *t*-values), many of students' conceptions changed after their yearlong interactions with their live model ecosystem. Some of these changes suggest students' initial naïve system thinking regarding feeding relations. The large standard

Table 1 Means, standard deviations, percentages, and *t* values for pretest–posttest comparison

	Criteria	Relevant test probes	Descriptors	Pre-post comparison ($n = 50$)				
				%		*M*	*SD*	*t*
1	Configuration	1, 2, 8	Linear[a]	74	Pre	4.18	2.71	2.05*
			(non-cyclic)	88	Post	5.08	2.14	
			Cyclic	24	Pre	.72	1.69	1.55
				10	Post	.28	1.01	
2	Structure	1, 5, 6, 7, 8	Linear	64	Pre	3.74	2.92	
				38	Post	2.28	2.94	2.76**
			Branched	20	Pre	.20	.40	1.77
				8	Post	.08	.27	
			Web[a]	4	Pre	.04	1.99	
				54	Post	1.86	2.45	5.27***
3	Components	1, 4, 8	Biotic and abiotic	20	Pre	.36	1.01	.00
				10	Post	.36	1.27	
			Only biotic[a]	64	Pre	3.78	2.87	1.85
				84	Post	4.84	2.35	
4	Component type	1, 2, 3, 7	Plants[a]	44	Pre	2.04	2.76	8.26***
				98	Post	5.40	1.65	
			Animals[a]	88	Pre	4.52	2.43	2.53*
				98	Post	5.50	1.53	
			Humans[a]	38	Pre	1.90	2.74	1.63
				52	Post	2.82	2.97	
			Decomposers[a]	8	Pre	.48	1.64	
				66	Post	3.76	2.90	7.78***
5	Component types' sequence	1, 2, 3, 4, 7	First element	36	Pre	.48	.95	10.93***
			Plants[a]	96	Post	2.78	1.28	
			Others	64	Pre	1.36	1.35	4.52***
				4	Post	.36	.96	
			Intermediate elements	60	Pre	2.92	2.90	4.19***
			Consumers[a]	88	Post	4.98	2.21	
			Humans[a]	0	Pre	.00	.00	.00
				0	Post	.00	.00	
			Decomposers[a]	0	Pre	.00	.00	.00
				0	Post	.00	.00	
			Terminal element	2	Pre	.12	.85	7.41***
			Decomposers[a]	64	Post	3.16	2.90	
			Humans	10	Pre	.60	1.82	.50
				20	Post	.80	1.96	
			Others	12	Pre	.44	1.50	.85
				6	Post	.26	1.19	
			Decomposers feeding on each element[a]	0	Pre	.00	.00	4.28***
				42	Post	1.42	2.35	

Table 1 continued

	Criteria	Relevant test probes	Descriptors	Pre-post comparison ($n = 50$)				
				%		*M*	*SD*	*t*
6	Components' hierarchical order	1, 3, 8, 10	Random (evolution)[a]	4	Pre	.04	.20	2.29*
				18	Post	.58	1.64	
			Meaningful (size, strength, developmental stage)	60	Pre	1.70	2.26	3.72***
				68	Post	3.44	2.84	
7	Each element's no. of functions	1	Single	8	Pre	.40	1.46	2.16*
				30	Post	1.16	2.20	
			Single to multiple[a]	2	Pre	.04	.28	2.91**
				28	Post	.80	1.81	
8	Matter characteristics	1, 2, 3, 4, 5, 10	Type	4	Pre	.06	.31	3.33**
			Organic[a]	36	Post	.94	1.81	
			Inorganic[a]	0	Pre	.00	.00	2.32*
				26	Post	.48	1.46	
			Conservation	68	Pre	4.08	2.83	1.06
			Conserved[a]	72	Post	3.54	2.83	
			Not conserved	0	Pre	.00	.00	1.00
				4	Post	.12	.86	
			Transformation	0	Pre	.00	.00	13.62***
			Transformed[a]	86	Post	2.68	1.39	
			Untransformed	0	Pre	.00	.00	4.89***
				46	Post	.76	1.10	
9	Energy characteristics	1, 2, 3, 4, 5, 6, 8, 10	Type	0	Pre	.00	.00	5.58***
			Light[a]	62	Post	1.90	2.41	
			Heat[a]	2	Pre	.02	.14	2.05*
				18	Post	.28	.90	
			Life activities	4	Pre	.14	.86	1.94
			Metabolism[a]	30	Post	.54	1.25	
			Chemical[a]	4	Pre	.24	1.19	8.02***
				78	Post	3.64	2.74	
			Conservation	20	Pre	1.10	2.32	1.26
			Conserved	14	Post	.64	1.68	
			Not conserved[a]	4	Pre	.14	.86	5.09***
				68	Post	1.70	2.23	
10	Process characteristics	All	Reversibility	0	Pre	.00	.00	1.86
			Reversible[a]	10	Post	.32	1.22	
			Irreversible	0	Pre	.00	.00	4.69***
				36	Post	1.78	2.68	
			Direction	46	Pre	2.28	2.84	2.15*
			Unidirectional	62	Post	3.62	2.95	
			Multidirectional[a]	0	Pre	.00	.00	1.00
				7	Post	.02	.14	

Table 1 continued

	Criteria	Relevant test probes	Descriptors	Pre-post comparison ($n = 50$)				
				%		*M*	*SD*	*t*
			Frequency/timing of events	0	Pre	.00	.00	2.33*
			One at a time	10	Post	.60	1.82	
			More than one	2	Pre	.04	.28	2.34*
			Simultaneously[a]	18	Post	.60	1.65	
11	Evolution	9	Temporal	28	Pre	1.48	2.57	3.85***
			Short-term event	6	Post	.06	.24	
			Long-term event[a]	24	Pre	1.14	2.31	3.49***
				70	Post	3.04	2.80	
			Changes					
			Individuals	8	Pre	.28	1.20	.57
			Within lifetime	6	Post	.16	.87	
			Gene frequencies	0	Pre	.00	.00	2.81**
			In populations[a]	18	Post	.78	1.96	
			Mutation control	8	Pre	.28	1.20	.56
			By individuals	6	Post	.16	.87	
			No control,	0	Pre	.00	.00	2.89**
			Random[a]	20	Post	.80	1.96	
12	Chain length	10 and others	Unlimited	2	Pre	.18	.87	1.12
			Cyclic	4	Post	.04	.20	
			Limited					
			By element size,	70	Pre	.70	.46	6.09***
			Developmental stage, strength	20	Post	.20	.40	
			By energy[a]	8	Pre	.12	.14	4.78***
				64	Post	1.06	1.56	
13	Dynamic equilibrium	2, 3, 5 and 7	Populations[a]	0	Pre	.00	.00	.00
				.04	Post	.00	.00	
			Molecules[a]	0	Pre	.00	.00	.00
				.02	Post	.00	.00	

Scores range 0–6, with scores normally distributed

* $p < .05$; ** $p < .01$; *** $p < .001$

Note: Concepts marked with [a] are correct

deviations suggest a high variability, which probably reflects the many different paths taken by students for constructing their knowledge, through interactions among their prior knowledge, knowledge acquired from conceptual lessons, and inferences concerning their inquiries. The following results emerged for the 13 criteria (see Table 1):

(1) *Configuration*: a significant pretest–posttest change emerged only regarding a linear configuration. This was the common perception before learning and was even strengthened after learning. A linear chain configuration is correct as a system component in itself, but is embedded in the feeding web, when perceived through a

systemic lens. However, some students maintained their misperception of a cyclic configuration, linking the last chain component to the first one through abiotic elements still included in feeding relations ("a plant growing in the ground, eaten by a sheep, eaten by a man who dies and returns to the ground, and the chain starts all over again").

(2) *Structure*: a significant change emerged regarding food chains' structure, from a linear structure as perceived by most students before learning, to a web structure after learning. Linearity suggests a simple component view, whereas a web configuration reflects a more complex systemic one. No significant change emerged from pretest to posttest regarding number of students describing a "branched" structure, which conceived an organism as feeding on several others (e.g., "If a link is extinct, the organism will feed on anything available around it, because everyone can eat many things, not only one"). The branched view may be considered an intermediate structure. The significant increase found in the number of students exhibiting an understanding of the webs' structure suggests that students learned to recognize each organism's concurrent ability to feed on several others and to be eaten by several different others. However, the use alone of the term "web" does not ensure students' understanding, as sometimes reflected in their responses when analyzed according to other criteria. In these cases, a deficient understanding of both the spatial and temporal aspects of webs was revealed. The spatial aspect of webs entails the possibility of many simultaneous occurrences transpiring in the ecosystem space, populations achieving dynamic equilibrium, and a single organism in a web holding several concurrent roles (e.g., being both a producer and a consumer, a 2nd consumer and a 3rd one at the same time). The temporal aspect of systems entails the recognition of long-term evolutionary processes' effect on the system, including the understanding that webs are more stable than chains. For example, despite one students' use of the term "web," he responded to the 7th probe by writing: "The organisms before the extinct link will grow dramatically in number because no one will feed on them, and those after this link will disappear because they will starve," with no mention of the possibility that the element following the extinct link may be capable of feeding on other kinds of food. His response reflected no awareness of control mechanisms of population size and unidirectional perception. In contrast, a student who showed a systemic understanding of the meaning of web, as enabling the control of population sizes by implicit feedback mechanisms, stated: "If an element is extinct, the organisms that feed on it will feed on other organisms in their diet. The organisms before the extinct link—if a few were left around—may also now be able to grow in number again because nobody's left to feed on them. On the other hand, they will be more available to the organisms that fed on the extinct element. This is how populations in nature retain their size in spite of local shifts." Students' words "in their diet" may suggest awareness of the evolutionary temporal effect as reflected in structure–function fit.

(3) *Components*: the number of students who included abiotic elements in feeding relations dropped significantly after the yearlong inquiry. Most students' posttest responses indicated that only organisms are part of feeding relations.

(4) *Component type*: the feeding relations described in probe 6 were mistakenly considered to be feeding relations in the pretest, but significantly more students regarded plants and decomposers as essential elements of feeding relations after learning. Knowledge of bacteria before learning was usually limited to their agency in promoting diseases rather than in decomposition of organic matter (e.g., "Human cells are eaten by bacteria, which are eaten by white blood cells").

(5) *Component type's sequence*: after learning, significantly more students perceived plants as constituting the first element in feeding relations, and significantly fewer students perceived other components as first. After the inquiry, significantly more students regarded consumers as intermediate elements in feeding relations chains, but no student expressed a possibility that humans or decomposers may constitute an intermediate element even after learning.

Decomposers were mostly regarded as a terminal chain element, but students revealed a significant increase in understanding them as feeding on each of the chain elements after learning. The understanding of matter cycles requires the comprehension that decomposers must feed on all organic matter of any element at all levels of feeding relations, rather than only on their terminal organism (e.g., a falling leaf, secretions, dead body). Whereas some students developed such a view, others were constrained to the linear, unidirectional view and added decomposers only as a terminal chain element (e.g., "Decomposers break up the body of the human, who feeds on animals, who feed on plants"). These students' system thinking concerning several dimensions like the decomposers' role in linking the biotic and abiotic cycles, the micro and macro structure of matter, heat released in the process, etc. was still deficient. These operations require abilities for identifying cause and effect relations, linking micro processes to relevant macro ones, differentiating between matter and energy based on their characteristics, and recognizing processes as multilevel. Only some students constructed such understanding.

(6) *Hierarchical order*: this criterion may reflect students' identification of some relations in their systems. Unfortunately, the number of students who regarded components' order as determined by their size, developmental stage, or strength (instead of by long-term evolutionary processes) increased significantly after learning. Students invariably placed a small-sized component before a bigger and stronger one (e.g., "grass, eaten by an insect, eaten by a small bird, eaten by a wolf"). This may have been the result of exposure to stereotypic presentations of feeding relations in textbooks or media, and it constrained students' ability to accept relations that did not conform to rules of size and strength. It also pinpointed students' focus on systems' macro properties and rules pertaining to these properties for explaining feeding relations' sequences (e.g., strength, development). The fact that students tended to remain at the single macro level of the system, instead of interrelating between it and lower levels or looking for underlying properties (processes like respiration and photosynthesis or evolution) to explain components' interrelations, suggested deficient system thinking. Although the number of students who perceived order to be random increased significantly too, it reflected only a small portion of the students who could ignore organisms' size factor. This minority used examples like Ebola or lice ("…and the lice are a kind of parasite that lives on human beings and gets its food from them").

Interim summary: macro and micro understanding of the first six criteria

The first six criteria reported above (#1–6) reflected students' improved understanding of the concrete macro level of the feeding relations system, as a web or linear feeding organization of biotic components, arranged in a specific order according to macro properties. However, findings for these criteria also suggested some understanding of the abstract, implicit micro level, as expressed in students' improved understanding of feeding relations' order—with a plant first and with decomposers feeding on each chain element, rather than describing matter as disappearing in the soil. This improvement may promote students' understanding of matter transfer in the feeding relations and the biosphere. However, students' ability to refer to relations between system levels was found deficient.

The significant increase in the number of students who named plants as necessary and as a first element did not always reflect students' true understanding of the reasons for such facts, as found in their responses to other criteria. Naming of plants as first element in chains could reflect knowledge enrichment, rather than knowledge revision due to understanding of plants' role in ecosystems, as well as matter and energy transfers through plants, feeding relations, and the biosphere. This factual knowledge is expressed in the significant decrease in the number of students who considered the possibility of non-plant first elements, and who disqualified the chain presented in probe 6, in which a worm constituted a first element. Some of these students' reasoning exhibited rote learning ("Being in the ground, and serving as food, plants just have to be first") or did not confirm an understanding of plants' role: "green plants always have to be the first link because they carry out photosynthesis." This was also reflected in students' responses to other probes, like stating that "the number of trophic levels [elements] in chains is unlimited," thereby exhibiting deficient system thinking concerning: the plant's role (photosynthesis) in providing useable energy to organisms, energy conservation, and energy undergoing transformations.

Two interesting findings that warrant attention were revealed by the criteria of configuration and structure—the cyclic configuration and the branched structure. Both are not common, but may enlighten our understanding of students' cognitive development regarding feeding relations. The cyclic notion probably originated in the many biology cycles students recognize (e.g., life cycles, nitrogen cycle, water cycles). Other researchers also found that students and teachers alike widely use cycle-related phrases for describing feedback scenarios, repeated sequences of events, and for depicting balancing and reinforcing feedback (Booth Sweeney and Sterman 2007). These researchers claimed that cyclic descriptions confound the understanding of the systemic structure and behavior of chains. The cyclic notion may also decrease students' sharp distinction of the abiotic world from the biotic chain system, blurring their understanding of the necessary interactions of all feeding relations with the abiotic environment, which comprises part of the complex non-linear interrelations among various system levels.

Students' espousal of a branched model points to their unidirectional thinking, which may hinder their understanding of concepts necessary for comprehension of complex systems like reversibility or dynamic equilibrium.

(7) *Each element's number of functions*: the significant increase after learning in the number of students who perceived it possible for elements to hold more than a single function reflects the change from thinking dominated by linear patterns (where each element has a single function like being a consumer only) to thinking that also includes web patterns of occurrences (where an element may be both a producer and a consumer, for example), as also evidenced for the criterion of structure.

(8) *Matter characteristics*:

Significantly more students exhibited awareness of the distinction between organic and inorganic after their yearlong inquiry, whereas no significant change was evidenced regarding students' beliefs about matter conservation reflecting their prior knowledge of this issue (Hogan and Fisherkeller 1996). Their description of matter as flowing forever through the feeding relations system's biotic components, until they die and then return to the soil or are decomposed, may imply students are aware to a certain extent of matter flow through organisms as part of biosphere matter cycles. Interestingly, students' responses never mentioned gasses as returning to the biosphere (atmosphere), although gasses constituted an important topic in their model ecosystems. The findings showed a significant change regarding matter's ability to transform, but also in the number of students believing that matter does not transform. An examination of students' responses showed that their understanding of transformation coincided with the specific case discussed. Mainly they linked this process with decomposers and photosynthesis, but infrequently also with matter in the biotic cycles in general.

Matter transformation as related to plant photosynthesis is of particular interest. Several probes examined this issue. One probe dealt with spinach leaves as a first element in feeding relations. All students after learning appropriately approved this green plant element as a part of a food chain. However, in other probes, the first element constituted nectar, pollen, or humus, which are all indirect organic products of photosynthesis. As these materials departed further from the direct photosynthesis product—sugar—and from the photosynthesis location—green leaves—the number of students who accepted these variations as constituting feeding relations decreased dramatically. These erroneous responses reflect students' difficulties in conceiving notions of matter's flow within the micro levels of the system and of matter transformation in the micro-level breakup and rebuilding into various organic molecules, as expressed in the macro level of feeding relations' components, hence a deficient view of interactions among system different levels. These are also expressed in the findings concerning the criteria of matter and more so of energy.

(9) *Energy characteristics*: unsurprisingly, a significant increase emerged in students' recognition of light as a source of energy for feeding relations (due to photosynthesis). Significantly more students also recognized heat and in particular the energy contained in matter—chemical energy—indicating their understanding that feeding on materials supplies organisms with energy. However, no significant change emerged regarding metabolic energy, which may hinder students' understanding of the food pyramid idea. Students' improvement concerning chemical energy may evolve from its containment in concrete matter and the fact that it is not abstract to students because they are familiar with diets and calories. After learning, students showed a stronger inclination to regard energy as different from matter, as expressed in the significantly larger number of students perceiving energy as unconserved along system processes. This understanding was manifested in students' post-learning recognition of the limited possible number of trophic levels in a chain as stemming from loss of energy rather than from the number of available organisms or their size or strength (e.g., "There can only be a limited number of levels along the food chain, even when it is a part of a web. This is because the plant at its beginning can only produce a certain amount of energy, which is used by organisms along the chain, and part of it is lost as heat when chemical reactions occur or lost in a leaf that dries up and falls off the tree. These cannot be used anymore; therefore, after some levels no energy is left for the next organism."

(10) *Process characteristics*: the significant changes found for this criteria regarding the reversibility and direction of processes do not necessarily reflect better system understanding of all students, because the irreversible and unidirectional views still dominated. These views may hinder the understanding of dynamic equilibrium and web structure. The few examples of the branched configuration hint at the constraints that the notion of unidirectionality may impose on system thinking (e.g., "Humus is abiotic, it can be eaten but cannot eat others;" or "If a link in a chain is extinct, the whole chain after this point will be extinct too, because feeding events in the chain occur in that

direction”). Finally, and related to these characteristics, significant increases emerged in the number of students who regarded events as occurring one at a time and who perceived the possibility of simultaneously occurring events (e.g., a carnivore plant was seen as both a producer and a second consumer; a component in a web was seen as a first and a second or third consumer).

(11) *Evolution*: students’ deficient understanding of evolution’s function in shaping the structure and behavior patterns of feeding relations probably stemmed from the subject being highly difficult for students as reported by researchers and from the fact that students learned about evolution only in previous years, and it was barely mentioned in the traditional classroom during the current project. Nonetheless, some significant changes indicated an improvement after the interactions with the model system; namely, significantly fewer students showed a Lamarkian view of evolution as a temporally short-term event (e.g., “If the wolf has nothing to eat, it can feed on anything in its surroundings”), and significantly more students perceived it as a long-term event, thus revealing understanding that evolution is the result of gene frequencies in populations and that mutations are random.

(12) *Chain length*: significantly fewer students believed after learning that the length of chains is determined by organisms’ number, size, developmental stage, or strength. Some students did not change their view, suggesting they did not understand how energy passing through the chain elements determine it length (as visually described by the food pyramid). However, interacting with the live models brought about a significant increase in the number of students who did regard energy as a determining factor in chain length.

Dynamic equilibrium: as may be seen, almost all students, even after learning, explicitly expressed a deficient understanding of this system phenomenon and related feedback mechanisms. As mentioned above, an artificial ecosystem cannot reach an equilibrium state and must be constantly maintained to exist (like, for example, a public garden). During the year, students did encounter changes in populations and in chemical reactions as described above, and learned about feedback mechanisms and equilibrium. Hence this finding is disappointing.

Mostly, both pretest and posttest responses suggested a static unidirectional view of the feeding relations system. For example, students continued to predict, even after participation in the yearlong project, that all elements would remain the same after a link in a chain became extinct, except for the one organism located after it, which would need to directly feed on the one located before the extinct link.

Summary of results and their implications for system thinking

Although initial system thinking was evidenced, some students’ responses (depending on the specific criteria) still exhibited difficulties in this area despite the full academic year of student interaction with a live model. Hopefully, understanding these identified difficulties may promote the instruction of system thinking.

Specifically, students’ perception of feeding relations as a linear rather than web configuration suggests a deficient systemic view. Such compartmentalized knowledge disregards the idea that systems nest within larger systems and interact with them (Brown and Schwartz 2009; Jacobson and Wilensky 2006). Likewise, students’ understanding of webs was constrained by deficiencies in temporal and spatial thinking, which in turn affected students’ ability to identify causality and implicit interactions (Grotzer and Bell Baska

2003), strengthening notions of distinct components rather than whole systems. Web comprehension was also hindered by students' predominating views about the irreversibility and unidirectionality of processes (Leach et al. 1996; Steiff and Wilensky 2003).

These 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 (Hogan and Fisherkeller 1996). In addition, students' ontologies regarding matter and energy (Chi et al. 1994), their inability to distinguish between inorganic and organic materials (Hogan and Fisherkeller 1996), and their perception of matter as successive (Nakhleh et al. 2005) further constrained students' systemic thinking. These views diminished students' ability to regard systems as encompassing many factors interacting at all levels, especially dynamic processes like diffusion, random molecular movements, molecular interactions, transfer of matter and energy among system levels and within each level, as they are expressed in the emergence phenomenon, self-organization, and non-linearity (Jacobson and Wilensky 2006). For example, oxygen and carbon-dioxide gasses were mentioned many times as inflow in relation to photosynthesis and respiration, but no evidence was found indicating that students regarded them as matter or as related to the matter cycles (Anderson et al. 1990). Neither was there any evidence of understanding that those gasses were an outflow of the feeding system (Booth Sweeney and Sterman 2007), which would indicate students' understanding of those gasses' (i.e., matter's) interactions with the feeding web components.

Students' improvement in identifying the biotic and abiotic components of food chains (and their type and sequence) enabled students to enhance their comprehension of other dimensions of feeding relations such as the roles of bacteria and plants (Reiner and Eilam 2001), which in turn strengthened students' awareness of the web configuration on the one hand and the relations between organisms and their surrounding abiotic world on the other hand. It also enabled students to accept and recognize a large number of alternative feeding relations rather than the common "grass, cow, man" relations. However, students' identified difficulties regarding matter and molecular mobility still constrained their ability to comprehend feeding on nectar or humus. This current data concerning the learning of the topic of evolution suggest that these students' deficient understanding of evolution hindered their ability to perceive feeding relations (webs' structure, components, and their sequence) as an outcome of a long-term process of organisms' development due to mutations (Kaneko and Tsuda 2000). Understanding the evolution phenomenon would allow students to better apply temporal and spatial thinking while considering web-related problems. The data did show some ability for improvement in students' understanding that energy is not conserved and therefore energy inflow must be constantly supplied from a higher or lower level system. However, as in the case of gasses, the outflow of heat remained implicit to many students. A disregard of outflows may also hinder students' construction of knowledge regarding dynamic equilibrium (Booth Sweeney and Sterman 2007; Ossimitz 2000).

The appreciation of all components in a system, and of the system as a whole, is constructed both ways simultaneously—from concepts to systems and vice versa, and every concept is related to all others. The findings of the current study take us another step forward in helping science educators plan more effective ways to assist students in grasping this very complex set of conceptions.

Summary, limitations, and directions for future research

Meaningful acquisition of knowledge in ecology first requires the acquisition of difficult distinct core concepts in relevant disciplines (e.g., feeding, organism structures and functions, diffusion, organic and inorganic matter). At the same time as students master distinct concepts (e.g., photosynthesis, respiration, matter and energy cycles, system functions), they may begin to integrate higher constructs, and even systems. Instruction of distinct concepts, while leaving students to integrate them on their own, will likely not result in promoting their system understanding, because systems are more than the sum of their components.

This study examined ninth graders' learning about ecosystems as a whole after interaction with a live model and receipt of formal instruction and laboratory support. Students' systemic understanding was assessed by indirect questions about feeding relations as an ecosystem nested sub-system. The findings shed light on students' systemic conceptual understanding, following their full academic year of interactions with the model system and their learning about ecosystems. In this sense, the study met its goal. The fine grain analysis using criteria and descriptors and the probes—each probe revealing knowledge regarding several descriptors, thus rendered a fuller view of students constructed knowledge of the system rather than on a specific component. Although the study results do not provide a direct answer to whether students achieve an understanding of specific systemic phenomena/concepts like 'emergence', they do show that students' understanding of the feeding relations system is constructed from a complex network of understanding specific concepts, sub–sub-systems, processes, phenomena, and the way they interrelate or interact. Results emphasized how certain knowledge (revealed by specific criteria) may promote or hinder system thinking. My claim is that just as knowledge of distinct components does not ensure system understanding, neither does knowledge of system concepts like emergence ensure system thinking and system understanding. I contend that the path to acquiring system understanding and system thinking is bidirectional—from concepts to systems and from systems to concepts.

Overall, the current pretest–posttest comparisons suggested that all these ninth-grade ecology students changed at least some of their initial ideas regarding feeding relations, developing at least some initial capacity for system thinking after the long-term interaction with the live model. To different extents, after learning different students demonstrated an increased ability to: identify components and processes, construe interrelations among them and among different system levels, detect patterns and control mechanisms in their ecosystems, recognize equilibrium shifts, and/or pinpoint spatial and temporal aspects of feeding relations. The current analysis of multiple descriptors, as well as the probes, designed to reveal students' knowledge regarding several descriptors, revealed some of the students' specific areas of deficient understanding, and in particular their understanding of dynamic equilibrium, feedback mechanisms, matter, and energy, as well as process characteristics as related to feeding relations and the biosphere. Students could adopt a canonic term like "web" or "photosynthesis" but their responses to other probes showed they still hold simplistic intuitive perceptions of related issues, suggesting that the combination of top-down instruction and bottom-up knowledge construction through the live model system only partially opened up the conceptual space of naïve knowledge and beliefs to result in conceptual change. Hence, the study objectives to examine students' system thinking after their long-term interactions with the live model as well as to identify specific concepts and phenomena related to the feeding relations system that hinder their system thinking were achieved. Students' difficulties and specific constraining factors were reported (e.g., understanding evolution and its relation to feeding relations, unidirectional thinking, use of cycles).

Study limitations

The current study's main limitation is its lack of a control group (because of unexpected realities while conducting the study), which limits possible conclusions. Moreover, the specific context precludes direct generalizations until relevance is confirmed. Regarding the methodology, extensive in-depth interviews rather than use of probes only are recommended to deepen insights into students' system comprehension. Finally, a larger sample may afford a more comprehensive data analysis.

Using a combination of instructional modes

Pros and cons may be identified in the application of the live model-based instructional approach described in the present paper. First, when this approach is applied in a learning environment in which students are engaged in an open but massively supported independent inquiry, it affords students with opportunities to constantly shift between model system levels. On the one hand, students can explain observed macro-level behaviors by using constructed knowledge of various components and processes measured and observed in the system. On the other hand, students can identify implicit components, causal relations, patterns, and processes based on the observed macro level. Such shifts between the micro and macro levels are inherent to system thinking. Second, a live model affords ecology students learning about natural resources—getting to know aspects of real ecosystems and organisms living in them—while using a cost-effective, simplified method. The interrogation of live ecosystems may be too difficult due to their complexity and is frequently impossible in school conditions.

Together with computerized models, the use of live models or live systems as varied instructional modes may promote students' acquisition of system thinking. All these modes involve the visual sense, and each may contribute its advantages to learning. According to the literature regarding learning with multimedia, learners may construct a more holistic and deep understanding of the represented phenomenon if models are used in combination, due to different properties of the involved representations. Ainsworth's (1999, 2006) functional taxonomy suggested that different representation-types may complement each other, for example, by each presenting different processes or information that cannot be presented by another. However, multi-representational instruction may also hinder learning, mostly due to learners' difficulties to map analogical elements among these representations (Ainsworth 1999; Eilam and Poyas 2008; Tabachneck-Schijf and Simon 1998; Yerushalmy 1991), calling for further research to systematically examine additional ways to comprehensively promote students' understanding of feeding relations and systems.

Future research would do well to investigate the use of a combination of live models with various computer models and simulations, which may support students' back-and-forth shifts between real world phenomena and symbolic representations and their shifts within phenomena levels.

Appendix 1

Ten probes for revealing students' understanding of feeding relations

(Expected scientific responses and explanations are provided after each probe using the criteria presented in Table 1; examples are presented in the "Results and discussion" section)

1. Describe in detail what a food chain is. Explain your answer using examples.

This open question was designed to elicit students' free associations to this construct. Students' examples mainly provided evidences concerning the macro-level facet of feeding relations; its configuration, structure, components, and their hierarchical order; the number of each element's functions; and some process characteristics.

2. Can the following organisms, in this order, be considered a food chain? "Nectar, a Butterfly, and a Bird; and Decomposers on each of these links." Justify your answer in detail.

This is a food chain. Students' argumentations may provide evidences concerning their [i] perception of decomposers as living on every element in chains, [ii] ability to identify complex rather than linear patterns of matter cycles, and [iii] understanding of photosynthesis products as providing matter and energy (any organic matter rather than sugar alone, in any non-green plant part), of micro-level processes, as well as of matter and energy characteristics (molecule mobility or matter transformation).

3. Can the following organisms, in this order, be considered a food chain? "Spinach leaves, a Human being, and Lice sitting on the human skull; and Decomposers on each of these links." Justify your answer in detail.

This is a food chain. Students' explanations may provide evidences concerning their [i] perceptions of the macro-level facet (chain sequence), [ii] views of decomposers as above, and [iii] understanding matter cycle and matter transformation as occurring among organisms and within them (transfer of spinach to other organisms and its transformation in structure).

4. Can the following components, in this order, be considered a food chain? "Humus, an Earthworm, and a Bird; and Decomposers on each of these links." Justify your answer in detail.

This is a food chain. Students' explanations may provide evidences for [i] understanding at the micro-level (humus is organic matter and provides matter and energy), [ii] understanding matter and energy cycles (abiotic) as related to the biotic, [iii] ability to differentiate inorganic and organic, and [iv] understanding decomposers as above.

5. Can the following organisms, in this order, be considered a food chain? "Pollen grains, Bees, a Frog, and a Snake; and Decomposers on each of these links." Justify your answer in detail.

This is a food chain. Responses may substantiate all the above, particularly regarding matter transformation (pollen as an organic plant material but not necessarily sweet).

6. Can the following organisms, in this order, be considered a food chain? "A microscopic water Worm, a Shrimp, a Fish, and a Seagull; and Decomposers on each of these links." Justify your answer in detail.

This is not a food chain. Students' explanations may provide evidences for [i] micro-level understanding (energy source is missing).

7. Describe in detail what might happen if one link on a food chain becomes extinct. Explain and justify your answer in detail, using some examples.

Three possible occurrences may be evidenced, the first two show a simplistic local thinking: [i] the extinction of those elements that fed on the extinct element, suggesting conceptions of unidirectionality and irreversibility of feeding relations, [ii] an increase in the number of elements that served as food for the extinct ones, due to their successful reproduction, and [iii] a reliance on other food sources among those elements that fed on the extinct element, thereby allowing the elements on the brink of extinction to recover (understanding webs, population equilibrium, temporal and spatial events, reversibility, and directionality of processes). Some responses to this probe also provided evidence for students' conceptions regarding evolution and mutation.

8. Do bacteria inside the human body constitute a link in a food chain? Explain your answer in detail and justify it.

Yes, bacteria feed on organic compounds in organs or cells. This probe provided evidence for students' understanding that elements carry several roles simultaneously.

9. Assuming (hypothetically) that the bacteria inside the human body constitute a link in a food chain, what might be the first link of this chain? Explain your answer in detail and justify it.

A response indicating organic matter (or plants—a narrower response) as a first link provides evidence of students' understanding that organic matter serves as a source for matter/energy.

10. Is the length of a food chain limited in the number of links forming it? Explain your answer in detail.

Yes. Students' responses may show an understanding that energy is not conserved and is lost as heat during each transformation, or may provide additional evidences for misconceptions [i] a cyclic view (infinite chain length), [ii] matter is in-conserved (length depending on amount of matter remaining), or [iii] a macro view (length depending on number of organisms available, organisms' strength and size, etc.).

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