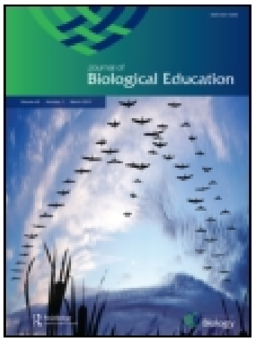

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How does grasping the underlying causal structures of ecosystems impact students' understanding?

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Students have difficulty understanding ecosystem concepts. This article argues that the difficulty stems partly from not grasping the underlying causality that structures the concepts. We report on an intervention study designed to teach eight- and nine-year-olds to reason about domino, cyclic, and mutual causality by infusing causally focused activities and explicit discussion about the nature of each type of causality into a teacher-taught unit on ecosystems. The teacher-taught unit was typical of ecosystems units taught in many elementary schools. The students were third graders from a suburban middle class community and ranged from low to high achieving students. Three conditions were contrasted: 1) activities with discussion; 2) activities only; and 3) no infused activities. Students who participated in both the activities designed to reveal the underlying causal structure and the discussion of the nature of causality showed significantly deeper understanding of the connectedness within ecosystems and demonstrated a significantly better grasp of the process of decomposition and the mechanisms that cause it. The results suggest that it is important to teach students how to structure ecosystems concepts in addition to teaching ecosystems information.

Key words: Ecosystems, Causality, Deep understanding.

Introduction

Most teachers consider ecosystems and the related concepts of food webs and food chains important topics for students to learn (Barman and Mayer, 1994). However, many teachers also consider these topics to be relatively easy for students to grasp. The wealth of research on students' misconceptions about ecosystems concepts contradicts this belief (e.g. Adeniyi, 1985; Barmen, Griffiths, and Okebukola, 1995; Gallegos *et al.*, 1994; Griffiths and Grant, 1985; Hogan and Fisherkeller, 1996; Leach *et al.*, 1996; Munson, 1994). Students hold numerous misconceptions about ecosystem concepts and the nature of the interrelatedness in ecosystems.

In this article, we explore the possibility that many of these misunderstandings have at their core a simplistic understanding of the nature of causality. As elaborated below, students' difficulties reveal an inability to reason about causality in a systemic sense as well as an inability to deal with the specific types of causal patterns embedded in ecosystems. We argue that by impacting the way students think about causality, we can change how they structure the information they receive about ecosystems and improve their understanding of ecosystem concepts.

It is well substantiated that students have difficulty reasoning about systems. They tend to reason locally and miss the larger picture. Resnick and others (e.g. Resnick, 1994; Resnick and Wilensky, 1997; Penner, 2000) have demonstrated across a number of topics that students find it difficult to reason about macro-level properties that emerge in systems as a result of micro-level interactions. Research on the understanding of ecosystems echoes this finding. Leach and colleagues (Leach *et al.*, 1996) found that students tend to reason about individuals and miss population effects. Strommen (1995) found that first graders missed the broader conceptual relationships between the different organisms of a forest habitat. They focused on the animals and neglected to include plant life, insects, and decomposers unless they were probed to do so. Grotzer (1989, 1993) found that seven- to nine-year-olds typically reasoned about immediate effects and overlooked extended, indirect effects. For instance, they did not detect ripple effects that might occur if certain plants or animals disappeared. While it is perhaps not surprising that the youngest children have such difficulties, research reveals that middle school and high school students (e.g. Barmen, *et al.*, 1995; Palmer, 1996) also miss the systems level interactions.

Understanding and reasoning effectively about ecosystems involves comprehending a variety of causal patterns, for instance, domino-like, cyclic, or reciprocal patterns. Without a grasp of how such patterns behave, students are likely to impose a simple linear pattern to organise new information they are learning about ecosystems and the embedded food web (Grotzer, 1989; 1993). In a simple linear pattern, there is typically one cause and one effect. The relationship is unidirectional and direct.

In contrast, *domino causality* describes a causal pattern in which effects propagate from causes in domino-like patterns (e.g. Grotzer, 1989; Perkins and Grotzer, 2000). The patterns tend to be linear – branching or radiating. Domino causal patterns depart from simple linear causality in that they compound simple linear patterns and therefore result in indirect effects. Effects in turn become causes. In the food web, energy flow follows a domino pattern. All energy originates with the sun's energy and propagates through the food web (with some lost to the environment during the process) until it dissipates into the atmosphere as heat energy during the process of decomposition. Recognising domino causality includes, for instance, recognising that if the green plants completely disappeared, it would affect not only the animals that eat green plants, but also the secondary consumers that eat the things that eat green plants.

While recognising domino causality might not seem particularly difficult, students typically miss the domino-type connections within ecosystems (e.g. Griffiths and Grant, 1985; Webb and Boltt, 1990). Young children tend to use simple linear causality where one population directly affects another (Leach *et al.*, 1996). Research (Barmen *et al.*, 1995; Griffiths and Grant; 1985) shows that high school students believe that a change in one population will not be passed along several different pathways of a food web and that a change in one population will only affect another population if the two are related in a predator-prey relationship. Palmer (1996) studied the concept of role/ interdependence, the notion that each species has a role to play in maintaining the balance of nature and interdependence and found that 12- and 16-year-olds applied the concept infrequently and inconsistently. Grotzer (1989, 1993) found that the tendency to ignore indirect effects was somewhat age-related with seven-year-olds less likely than nine- and 11-year-olds to detect indirect effects on their own. However, instances where indirect effects were ignored or explicitly rejected occurred with fairly high frequencies across the age groups. White (1997) found a 'dissipation effect' – the tendency to judge that effects of a perturbation at a particular locus in an ecosystem weaken or dissipate as they spread out from that locus. He argues that subjects might apply reasoning from physical systems that appear to exhibit dissipation of force or energy or momentum.

Students not only have difficulty viewing the biotic factors of an ecosystem as interconnected, they also tend to miss the abiotic components and their effects on an ecosystem. Eyster and Tashiro (1997) found that students could draw a food web when asked to do so, but when asked to include the abiotic components as limiting factors, many students were confused.

In our work with elementary teachers, they are often initially confused when we present energy transfer in an ecosystem as domino-like and matter recycling as cyclic because they believe that the energy is recycled into the food web. They are surprised to learn that the energy from the sun cannot be recycled. Understanding that the energy propagates in domino-like patterns (with much of it lost to the food web as it is transferred and the rest ultimately given off as heat in a compost bin) is an important realisation in grasping the sun's role in the ecosystem and the essential link that plants make. The contrast between energy transfer as domino-like and matter recycling as cyclic (with the sun's energy driving the cycle in the sense that it is part of the process of photosynthesis that generates the organic matter) underscores this distinction.

Local causal reasoning as opposed to extended domino-like reasoning is common in students' thinking about ecosystem relationships. Local reasoning reflects a tension between efficiency versus sensitivity to extended patterns of cause and effect. It is typically most efficient to look for local causes rather than consider temporally and spatially distant factors or systemic relationships. However, a tendency toward efficiency or seeking factors that minimally satisfy to explain an event can result in limited sensitivity to more extended and/ or complex effects. In addition to looking for causes that are local to the effect, students also tend to assume that a cause is necessary when it may only be sufficient. Sufficiency refers to the idea that while one cause can lead to the effect, so can a number of others. Or students may assume that one factor is causal when there are a number of contributing causes. In the context of ecosystems, these tendencies can lead to a shortsightedness that results in unanticipated effects.

Re-entrant causality involves recognising feedback loops and simple cyclic patterns such as in the process of decomposition. Rather than a linear relationship, the pattern is a circle in that it has a feedback loop. Causes become effects and effects become causes. Decomposition involves the process of matter recycling and the related understanding that matter is conserved. Most students do not understand the nature of decay and very few students understand the concept of decay as organic matter turning into mineral matter (e.g. Hogan and Fisherkeller, 1996; Leach *et al.*, 1992; Smith and Anderson, 1986). More common are notions of the matter disappearing, wearing out, or being eaten. Leach, Konicek, and Shapiro (1992) found that between ages seven and 10, increasing numbers of students begin to mention the fate of matter in their descriptions of the decay process, however the emphasis was mainly on the enrichment of soil. No students in their study of five- to 16-year-olds revealed a concept of a matter cycle that linked specific knowledge about photosynthesis, feeding, and respiration.

While some research suggests that an understanding of re-entrant causal models develops around nine to 12 years of age (Grotzer, 1989, 1993; Smith and Anderson, 1986), the classroom findings suggest that students do not necessarily generate models with inherent cyclic causality. Whether this pattern is due to developmental constraints or the lack of an effective pedagogy is an open question. However, even when students are developmentally able to grasp a cyclic model, they are not necessarily likely to be sensitive to the possibility that one exists.

Mutual causality involves recognising reciprocal patterns such as 'two-way' causal patterns where each element affects the other. Often such causalities involve a relationship of balance or imbalance between two or more elements that leads to a certain outcome or sets of outcomes. For instance in a 'two-way' or mutual causality such as those found in the food web, the mice cause energy to be present for owls and the owls help to maintain the size of the mouse population such that it is in greater balance with its food sources.

Students do not easily recognise mutual causalities without support. Most students break these patterns apart and miss the reciprocal aspects of them. According to Green (1997), although many systems in our world (economic, human relationships) involve complex chains of cause and effect encompassing two-way causal processes, people tend to construct one-way linear chains when explaining them. He found that only 16% of 20-year-olds gave two-way causal accounts of a predator-prey relationship in un-cued conditions. When problems increased in complexity, this number went down. Only 9.5% used two-way causal models when explaining a three-level problem involving three species in which one, two or all of the populations changed over time.

High school students believe that a change in the size of a prey population has no influence on its predator's population, and that a change in the population of a first-order consumer will not affect one or more producer populations (Barman *et al.*, 1995; Barman and Mayer, 1994). The type of relationship also matters. Students are more likely to trace effects from trophic levels up the food web, than from top predators down to trophic levels (Leach *et al.*, 1996).

A number of variables related to causality can exacerbate students' difficulty in noticing extended domino, re-entrant, and mutual causalities. One such variable is the level of contact between causes and effects. When effects are removed in time and space from their causes, students have difficulty recognising them as connected to the precipitating events. Developmental research shows that temporal and spatial gaps give young children difficulty (e.g. Michotte, 1963; Lesser, 1977; Spelke *et al.*, 1995). Spelke and colleagues have shown that action at a distance is a difficult concept to grasp and that from infancy we tend to expect contact between causes and effects, at least in the instance of physical causality (e.g. Spelke *et al.*, 1995).

Difficulty recognising effects that are removed in space and time from their causes can make it difficult to trace out extended domino-like effects. Natural systems often contain assurances or checks and balances that function to dampen effects or slow the obvious appearance of effects. This makes it less likely that we will notice effects of certain actions on the environment immediately. When interacting with complex systems, people typically 'overcorrect' or 'oversteer' because the outcome they want isn't immediate rather than waiting to let the system's dynamics play out and acting on the overall process. According to Dorner (1989), this tendency led to the infamous disaster at the Chernobyl Nuclear Power Plant.

A second such variable is non-obvious causes. Hidden agents may disguise a causal relationship or contribute to processes in unexpected ways. Most students do not understand the role of microbes as recyclers of carbon, nitrogen, water, and minerals (Brinkman and Boschhuizen, 1989). The causal actions of microorganisms are not easily available to students without special tools and there is no particular reason they would assume that there is a causal mechanism that they cannot see.

Understanding decay involves recognising a cyclic causal model that includes both of these difficulties – recognising a non-obvious causal mechanism in addition to dealing with the time delay associated with nutrient recycling. The time delay makes it difficult to observe decay without repeated observations and even then, it may be difficult for younger children to hold all of the information in their heads and to assemble and make sense of their observations.

Typical school curriculums are not equipped to help students surmount these cognitive challenges. For instance, Adeniyi (1985) studied classroom lectures, laboratories, tests, and texts, and found that student's misconceptions stemmed from previous knowledge, information from the teacher and other lesson materials. However, these are not the sole source of students' difficulties. Even when teachers had a good understanding of what they wanted students to learn and guided students to make careful observations and measurements, students typically failed to draw the correct conclusions (Smith and Anderson, 1984).

What is needed to help students surmount the challenges described above? Information alone may not be enough to help students understand ecosystem concepts (Barman *et al.*, 1995; Barman and Mayer, 1994; Griffiths and Grant, 1985). We'd like to create a distinction between teaching information about ecosystems and teaching students how to structure the information. We hypothesise that students need to learn both the information AND the modes for structuring it. The difficulties that students have with understanding and structuring causality as outlined above interact with their ability to make sense of the information they receive. Students commonly distort information that they learn to fit it into a simpler causal structure. Classroom materials do not typically offer support for learning to structure the information (Barman and Mayer, 1994).

Previous research suggests that when students' difficulties in structuring the information are addressed, students may overcome their misconceptions. Grotzer (1989, 1993) found that seven to nine-year-olds who were exposed to branching, radiating, and cyclic diagrams significantly outperformed control students in their ability to detect levels of connectedness in a food web system. Leach *et al.* (1992) found improved student reasoning about the nature of decay when they supported students' understanding of time delay by showing a time-lapse video. They also offered students ways to deduce the non-obvious causal mechanism by providing opportunities to learn about instances in which there was no obvious mechanism for decay.

The research presented here suggests the efficacy of explicitly addressing the cognitive challenges related to causal patterns in helping students develop an understanding of ecosystems. We hypothesised that introducing information about ecosystems along with support for structuring the causal concepts would help students develop a better understanding of ecosystem concepts. Specifically, we reasoned that the combination of causally focused activities, explicit discussion of the nature of domino and re-entrant causality, and support for understanding the time lapse, and non-obviousness of microbe decomposers would result in deeper understanding of the connectedness within ecosystems and patterns of matter recycling. Teachers commonly engage students in activities that embed (but do not elucidate) these difficult concepts. Rarely, if ever, do they attempt to explicitly teach the underlying causal structures. This leaves students to attempt to extract the causal structures on their own from the specific cases of causation studied. We reasoned that this approach would be less effective than explicitly focusing on the causal patterns and puzzles.

In order to test the above hypotheses, we conducted an experiment in which we probed students' initial causal conceptions about specific ecosystem relationships. Specifically, we considered, 'How do students describe the cause and effect relationships in a forest or pond food web? How do students construe the process of decay?' Then we engaged students in causally focused activities, explicit discussion of the nature of domino and re-entrant causality, and provided support for understanding the time lapse, and non-obviousness of microbe decomposers. Then we re-interviewed students to assess the impact of the intervention.

Methods

Overview of research design

Three Grade 3 classes (a total of 60 students; aged eight to nine years) participated in the following research design. 10 students from each class (n = 30) were pre- and post-interviewed using a clinical interview designed to reveal their understanding of ecosystem concepts. The interview used a scaffolded approach in which questions proceeded from open-ended towards more directed. Isomorphic versions (pond and forest) were given in a counterbalanced design. All three classes participated in an inquiry-based unit on ecosystems designed by teachers in the school district. Two intervention conditions were infused into the teacher-designed curriculum and a control group was included. For one class, the Causal Activities plus Discussion (CAD) group, information about ecosystems was introduced through activities focused on the underlying causality and through explicit discussion of the causal structure and the difficulties that students typically have in understanding causal structures in ecosystems. For a second class, the Causal Activities-Only (CAO) group, activities focused on the underlying causal patterns and puzzles, but there was no explicit discussion of them. The activities were designed to reveal the underlying causal structure (as discussed later). A third class functioned as a control group (CON). They had the same information about ecosystems available to them but received no special interventions to help them learn how to structure it.

Instructional Setting

The students were from a suburban middle class community and ranged from low to high achieving students. While a small percentage of the students were from diverse backgrounds (primarily from India and the Middle East), most of the students are Caucasian. The school district has had a tradition of supporting science education and for providing resources to teachers. However, more recently, as in surrounding communities, there has been an increased emphasis on standardised test scores, and teachers have responded by teaching more for information and less for depth of understanding.

Pre- and post-interview

The interview was designed to probe students' initial causal conceptions about specific ecosystem relationships. For instance, how do students initially describe the cause and effect relationships in a forest or pond food web? How do they construe the process of decay? Specifically, the interview investigated their understanding of 1) connectedness within ecosystems; and 2) the role of decomposers and process of nutrient recycling. The questions began open-endedly to probe students' unscaffolded understanding and were followed by more directed questions to probe students' scaffolded understanding.

Each interview version focused on either a forest or a pond ecosystem. An earlier study (Grotzer, 1989) tested students' performance on three ecosystems – forest, pond, and coral reef – and found that there were significant differences in students' ability to detect connections on the coral reef as compared to pond and forest, but no significant differences between the pond and forest. Therefore, the pond and forest were chosen for this study and were administered in a counterbalanced pre- to post-test design across groups.

The first of two interview tasks showed students a set of 10 pictures of ecosystem components (plants and animals, including fungi and dirt) and asked students to construct relationships between them. So as not to confound the students' ability to construct causal connections with information about food web members, students were given information about each component (what it ate, whether it made it's own food using energy from the sun, and so on.) The information given was ecologically valid so as not to confuse students who brought their own information to the study.

A second task asked students what happens to a tree in the forest (or plant in a pond, depending upon interview version) after it dies. Students were asked to predict what they might see if they came to the spot where a tree died in the forest after different amounts of time. The interview protocol can be found in the Appendix (see page 29).

An interview task was chosen for a number of reasons. First, it enabled us to begin in a very open-ended manner by asking students how the ecosystem members are important to each other. This gave us a sense of what types of connections students were sensitive to and how they construed the relationships. It would have been difficult to accomplish this with a written task given the age of the students. In order to do so, we would have had to include sufficient structure so it did not become a measure of how much students were willing to write and yet a more structured task from the outset risked losing the open-ended quality. Afterwards, we progressed to more targeted questions to ask about each ecosystem relationship systematically and to give students the chance to accept or decline whether a given event would impact it. This was important because some students are more reticent than others and we wanted to give all students the same opportunity to accept or reject connections. Furthermore, Grotzer (1993) found that the ways students spoke about the relationships differed at different ages. For instance, 11-year-olds tended to make statements in terms of overriding principles and then could apply those to the individual food web members while younger children tended to give concrete connections.

Intervention

The learning programme for each group (CAD, CAO, and CON) is described below. The intervention for the CAD group illuminated the underlying causal patterns and puzzles through activities and explicit discussion. The intervention for the CAO group provided opportunities to extract the underlying causal patterns and puzzles through activities but without the support of explicit discussion. The intervention activities differed from typical curriculum activities in that they were carefully designed to <u>RE</u>veal the <u>CA</u>usal <u>ST</u>ructure, or to help students RECAST the way they framed the concept. We refer to these activities as RECAST activities to differentiate them from other types of activities. The programme for the CON group offered students equivalent information about ecosystem concepts through activities and discussion. It did not attempt to illuminate the underlying causal structures beyond what the existing curriculum, as typifies ecosystems curriculum in many schools, already did.

The connectedness within ecosystems

Students in all three groups had the opportunity to learn about the connectedness and interdependence within ecosystems. The focus of the intervention groups was to help students recognise domino causal patterns inherent within ecosystems as a means of helping them understand the connectedness and interdependence.

Students in the CAO and CAD groups participated in two RECAST activities in which they created food webs. Food webs were explicitly compared to food chains. The first activity was a game. Students began with the sun and constructed the connections between different plants and animals based upon who gave energy to whom. Individual students played the role of different food web members by wearing a card depicting the diet sources of each animal. Students discussed the connections between the ecosystem members and used strings to illustrate the connections. By beginning with the sun, following with the plants, then including primary and secondary consumers, a branching visual pattern was created that fits with a domino-like pattern of events should something happen to different portions of the branch. From this, students in the CAO group could possibly surmise the domino-like causal connections that would result should something happen to portions of the branching structure. The CAO group discussed that there were a lot of strings, how web-like the resulting pattern was, and the importance of the different connections. With the CAD group, researchers led students through a number of cause and effect scenarios involving discussion of domino causal patterns, such as what would happen if all of the green plants were to disappear. (The student playing the role of the green plants would tug on the strings that he or she was holding and all of those animals depending upon that connection would sit down to show that they had been affected. Then those animals holding strings of those that sat down would sit down and so on.)

The CON group students also participated in a version of the ecosystems game as part of their regular curriculum. The version they played does illustrate the connectedness within the ecosystem. However, it is not designed to reveal the domino-type causality as above. In the CON group version, students choose to be an animal and receive information about that animal. Then they choose one other student whose animal is somehow connected to theirs and a string is passed between them. This continues until everyone has made a connection. Then the teacher plucks on different strings so that everyone feels a vibration to show that everyone is connected. Thus, the CON group students received the equivalent information about the connectedness within ecosystems. They did not, however, receive support structuring the domino-like causal pattern of events should something happen to portions of the ecosystem.

In the second activity, students in the CAO and CAD groups created their own food webs on paper using information about different animals to help them. As students created their food webs, we noted that many students depicted the active relationships or who eats whom rather than energy transfer relationships. Others (Hogan, 1994; Leach *et al.*, 1996; Senior, 1983) have found this pattern. Therefore, researchers guided students to use the arrows to show energy transfer as opposed to who eats whom. The terms 'producer,' 'primary consumer,' 'secondary consumer,' and 'decomposer' 'herbivore,' 'omnivore' and 'carnivore' were introduced in the context of creating food webs. The CON group also learned these terms. However, their lesson focused more on food chains even though the term food web was included. It emphasised how the sun provides energy for the green plants (producers) that provide energy for the herbivores (primary consumers) that provide energy for the carnivores (secondary consumers) with decomposers and green plants included at the end of the chain. Again, the information was available for students to notice the domino-like causality and perhaps even cyclic causality (with the decomposers and plants included again at the end of the chain.) However, students would need to construct the causal structures on their own.

In the context of both activities, students in the CAD group were engaged in explicit discussion of domino causal patterns. Explicit comparisons were made to actual dominoes and what happens when one is knocked over. There was also brief discussion of two-way causal patterns in an attempt to help students see that domino causality is only one type of causal pattern in play in an ecosystem. However, there were no activities focused explicitly on helping students learn two-way causality, in part because there was concern that too great an emphasis on two-way causality would confuse students' understanding of the flow of energy in a food web. The terms, 'domino cause and effect' and 'two-way cause and effect' were introduced. Arrows illustrating the cause and effect patterns were drawn on the board. Students discussed the food webs that they had created in terms of domino models.

The role of decomposers and matter recycling

Students in each group had the opportunity to learn about decomposers and the role that they play in matter recycling. The focus of the intervention groups was to support students' developing understanding by addressing the cyclic causal pattern of matter recycling. Noticing the cyclic structure can be difficult because the majority of decomposers are microscopic (and therefore, non-obvious) and because decay involves a time delay.

Students in both intervention groups participated in a RECAST activity focused on earthworms (an obvious decomposer.) They discussed, predicted, and then observed what happens in a tank of leaves (with equivalent amounts of matter) with worms as compared to a tank without worms. (It was not possible to measure this precisely, though it was possible to observe a difference between the tanks. The worm tank actually rose up as the worms made burrows in the soil. The non-worm tank sunk below the initial level but students observed that there seemed to be more dirt and fewer leaf fragments than there had been.)

Another RECAST activity involved examining rotting logs. Students took apart the logs and discovered decomposers such as insects and fungi. They also found that there was soil inside their logs. Both intervention groups discussed where the dirt came from and considered that the log was turning back into soil. They watched 'The Puzzle of the Rotting Log' (Missouri Botanical Garden, 1990), a film focused on what would happen if there were no decomposers. Thus students in both groups had the opportunity to extract information from the activities about the cyclic nature of decomposition and students in the CAD group participated in explicit discussion designed to help them do so.

Both intervention groups participated in a RECAST activity on microscopic decomposers. Students set up an experiment in which they rubbed pieces of bread in various places in the school (such as the banisters, and cafeteria floor), put them in ziplock bags, and observed them over the next few weeks. Over the course of the month and a half unit, they observed and discussed changes to the bread.

Both intervention groups had the opportunity to extract information about the nature of time in relation to decay. Students in the CAO and CAD groups observed decaying food at different stages (sealed tightly in containers) and discussed what was slowly happening to it. They watched and discussed a time-lapse video by Oxford Scientific Films (1999) that showed fruit, vegetables, bread and other organic items decaying. It was explained that the film showed time speeded-up.

Students in the CAD group were explicitly introduced to the concept of cyclic causal models and these models were used as a framework for their activities and discussion about decomposers. Cyclic causal patterns using arrows were drawn on the board to introduce and discuss what was happening in the activities above. The terms 'circle' and 'cyclic' causality were taught. Students engaged in explicit discussion of how some causes, such as the microscopic decomposers, are hard to notice and how this can complicate seeing the cyclic pattern. Students in the CAD group explicitly discussed the issue of effects that take a long time to appear and how this can make it hard to perceive cyclic causal patterns. They discussed how it would be difficult to notice the information in the time-lapse film without time-lapse because you would have to observe and remember what you had seen over a long period of time.

Students in the CON group received information about decomposers and their role in the ecosystem. They learned the terms 'bacteria,' 'fungus,' and discussed what happens to things when they die. They watched a series of eight 'Eyewitness Videos' (Kindersley, 1996) to help acquaint them with different ecosystems and then compared different ecosystems and discussed which decomposers might exist in each one. Decomposers were included in their discussion of food chains (as mentioned above). The food chains were drawn to include decomposers and then plants again at the end of the chain. The CON group students received the equivalent information about decomposers as did students in the other groups. However, they did not, through activities or explicit discussion, consider the cyclic causal pattern or the obviousness or non-obviousness of decomposers and the time delay that makes the cyclic pattern difficult to detect.

The infused activities were conducted in six sessions and took approximately six hours. The overall length of the units (teacher-designed and teacher-designed plus intervention activities) was approximately the same and involved approximately the same amount of time on task.

Scoring

The interview protocols were scored: 1) to assess the initial ideas students brought to their reasoning about ecosystem related concepts and; 2) to assess whether or not students' reasoning became more sophisticated on the measures each question set was intended to address and on ecosystem concepts in general given the targeted intervention conditions. While students' responses to the open-ended questions gave important qualitative information about patterns of what students noticed, thought about and prioritised, the unscaffolded and scaffolded responses were collapsed for the quantitative analysis so as not to handicap more reticent students.

Task 1: Detecting the connectedness in ecosystems

The first task was scored for students' understanding of the connectedness within ecosystems. Categories of connection types as outlined below were noted and weighted to generate an overall point score for connections made by the student.

Categories of connection types

The scoring scheme defined the following categories of connections. *One-step linear connections* are connections that focus only on a predator-prey relationship in a one-step, unidirectional fashion. *Multi-step linear connections* are those that involve multiple connections such as 'the insects eat the grass and the toad eats the insects'. Within this category, it was noted how many steps each connection involved, for instance, whether the connection was a two-step, three-step, four-step and so on.

Two other types of connections, cyclic and mutual, were scored even though they were not the focus of the first task. *Cyclic connections* are those that involve an iterative pattern, for instance, the process of decomposition. *Mutually causal (two-way) connections* are those where the subject noted that two components impacted each other. For example, a student may state 'the mice are important to owls because they provide energy for them, and the owls are important to mice because they keep the mouse population in balance'.

Students were credited once for each connection mentioned. Organisms mentioned that were not part of the set of ten presented to students were not counted. Inaccurate connections mentioned were not counted as a connection.

Overall point score for connectedness

An overall point score for connectedness was tallied for each student (see Table 1). Connections were weighted based upon connection type with one-step linear connections weighted the least and multi-step and two-way connections weighted the most. For example a student who made 24 one-step linear connections (24*1), four two-step connections (4*2), one three-step connection (1*3) and six two-way connections (6*3) attained an overall point score of 53 based upon Table 1. The rationale for the weighting of the relationships was that for linear, domino connections, each connection was accounted for (a two-step connection includes two connections so one two-step connection would be worth two points, one for each inherent connection. Each connection in a two-way connection was similarly counted and one additional point was assigned for detecting the mutuality. For cyclic connections, the number of connections was multiplied times two, because the cycling back resulted in additional, inherent connections.

Reliability

Two independent scorers rated the data. One scorer scored 100% of the data; the second scorer scored a subset of 25% to check for reliability. A Pearson Product-Moment Correlation was done on the overall score assigned to each subject with agreement of $r = 0.99$. Reliability was also assessed on a decision-by-decision basis (even though the exact decision did not

Table 1 Calculation of overall point score for connectedness.

Totals	Linear	Mutually causal (two-way)	Cyclic
One-Step	N*1	N*3	N*2
Two-Step	N*2	N*5	N*2
Three-Step	N*3	N*7	N*2
Four-Step	N*4	N*9	N*2
Five-Step	N*5	N*11	N*2
Six-Step	N*6	N*13	N*2
	= A	= B	= C
	Overall Point Score = A + B + C		

effect overall score) in which each step of a connection mentioned by a student was looked upon as a decision that the scorer made in terms of coding. The scorers made 226 decisions of which they agreed to 200 of them – 88% of the decisions made. Discrepancies were discussed and resolved. Most of the discrepancies involved differences in coding instances when students equated dead matter with soil as compared to treating them as two separate ecosystem components.

Task 2: Understanding the role of decomposers and matter recycling

The second task assessed students' understanding of the nature of decay and matter recycling. Responses were scored for: 1) whether changes to the plant after it died were predicted; 2) how the changes were characterised; 3) whether the changes were attributed to a causal mechanism; 4) how the mechanisms responsible for changes to the plant were characterised and 5) whether factors related to matter recycling were specifically mentioned. The scoring system was designed based upon certain patterns of responses that were expected based upon the findings of earlier research (e.g. Leach *et al.*, 1992). Points were assigned for each of the five questions as described below and then added for a global score.

Predicted change

Was there a predicted change? Responses asserting that something would happen to the dead plant, that it would change in some way over time were scored as one point. Statements asserting that nothing would happen to the plant were scored as zero points.

Characterisation of changes

How were changes characterised? Students' characterisations of what would happen to the dead plant were scored into five categories: appearance, location, existence, structural-macro, and structural-micro. Typical responses indicating a change at the level of appearance included: 'It turns brown;' 'It looks bad.' Typical responses at the level of location included: 'An animal might move it;' 'It would be gone, maybe water took it away;' 'It would blow away.' These two categories of response were all scored at level one (worth one point) because they indicated changes that were surface level. Responses were scored as structural-macro if they indicated a weakening of the structure in some way that distinguished them from appearance changes. Typical structural-macro changes included, 'It is falling apart;' 'Termites make it fall apart.' Responses such as 'It wouldn't have lots of branches;' 'It gets holes in it,' were scored at the level of appearance unless the implications of those changes were specified. Typical responses indicating a change at the level of existence included: 'It disappears;' 'It gets eaten up by tubeworms;' 'It shrinks until you can't see it;' 'It disintegrates.' These two categories of response were scored at level two (worth two points) because they indicated significant changes but did not yet address matter recycling. The 'existence' category combines appearance and location to recognise that the dead plant can no longer be recognised as it once was, but it does so at a less than superficial level. Still, it does not recognise the recycling of matter. Typical responses indicating structural change at the micro level included, 'It turns into rich soil,' 'It gets broken down into soil.' These responses were scored as level three (three points).

Existence of a causal mechanism

Were the changes attributed to a causal mechanism? Student protocols were scored for whether or not they indicated a causal mechanism. Responses indicating a causal mechanism were given one point. Responses indicating no causal mechanism (i.e. 'It just happens') were given zero points.

Characterisation of the causal mechanism

How did students characterise the causal mechanism? This scoring scheme was based, in part, upon the patterns found by Hogan (1994). Causal mechanisms were categorised as follows: 1) **Unreliable** – Animals happen to sit on it, thunderstorms, and animals passing by. (Students were likely to offer unreliable mechanisms when they focused on ecosystem members as individuals rather than as representatives of populations); 2) **Processes or conditions** – heat, wetness, rain, snow, lack of sustenance, aging, the sun or wind dries it out, and so on; 3) **Macro-decomposers** – termites, and fungi and; 4) **Micro-decomposers** – molds, bacteria, germs, etc. Unreliable causes were scored as level one (worth one point), Processes were scored as level two (two points), Macro-decomposers were scored as level three (three points), and Micro-decomposers were scored as level four (four points).

Understanding of matter recycling

Was matter recycling (in terminology appropriate to the age level of the students) mentioned? Subjects' spontaneous mention of cycles was credited at the level of one point for responses acknowledging that decay is a cyclic event (i.e. 'It's a cycle;' 'It's like the circle of life'). Two points were credited to responses that acknowledged decay as part of turning dead matter into soil ('It decomposes into soil;' 'It turns back into dirt that's what happens'). Three points were credited to responses that acknowledged that dead matter turns into soil and that this in turn helps plants grow (i.e. 'It creates rich soil which helps the plants to grow and then they die and create more soil').

Reliability

One scorer scored 100% of the data and a second scorer scored a random selection of 25% to check for reliability. A Pearson Product-Moment Correlation showed the level of agreement at r = 0.94. Discrepancies were discussed and areas of disagreement resolved until there was 100% agreement.

Results

Task 1 analysis

Pre-interview performance: How did students perform prior to the ecosystems unit in detecting connectedness within the system? The first task provided students with the opportunity to make connections between organisms within a forest or pond ecosystem. Their performance was measured in terms of overall point scores and the types of connections they detected. An analysis of variance of pre-interview scores showed no significant differences between the three groups prior to the intervention (F (2, 29) = 1.57, p = 0.23) in overall point scores for connectedness. This was expected due to the random assignment of the interventions. Despite the lack of significant differences, subsequent analysis focused on gain scores as a more accurate assessment of students' improvement from pre- to post-interview.

What was most interesting about the pre-interview data was how students spoke about connections and the types of connections they made. Not surprisingly, student responses revealed that they reasoned from salient experiences. For example, students mentioned times when they had seen one animal eating another, when rabbits or mice had eaten plants in their garden, or from movies such as, 'The Lion King' (Dewey *et al.*, 1994) in which concepts of predator and prey are introduced.

The types of connections they made fit those found by previous research (e.g. Grotzer, 1989. 1993). Most of the connections were expressed at the one-step linear level specifying predator-prey connections such as 'The raccoon eats crayfish and shrews' or 'The water insects eat green plants.' Only 13 of the 30 students made multi-step linear connections in the pre-interviews. For instance, 'The foxes eat the mice, the mice eat the insects, the insects eat the green plants, the sun provides the energy by itself' [Subject #4]. Most of the multi-step connections students made in the pre-interviews were at the two-step level (two-step = 36; three-step = 11; four-step = 1).

Only eight students in the pre-interviews explicitly expressed mutually causal connections and the type of two-way connections that they made were quite limited. A common pattern was to refer to the foxes or the raccoons, the highest order consumer in each web, and to refer first to the direct (one-step) linear connections in terms of what eats what. Then students went on to explain that if the higher-order consumer disappeared for any reason, the impact on its potential prey would be increased numbers or happiness (because they weren't being eaten) of the organisms since they would have otherwise been consumed. Thus the 'two-way' part of the relationship focused more on individual food web members rather than population issues of balance and flux. When students did note that there would be an impact on their numbers, they seldom mentioned the potential implications of increased number. This fits with previous research on children's reasoning at this age (e.g. Driver *et al.*, 1996; Marek, 1986; Wood-Robinson, 1994). The following pre-interview excerpt reveals this tendency:

Interviewer: How are the foxes important to the other things?
[Subject #1]: Not really.
Interviewer: What if the foxes disappeared? Would it affect anything?
[Subject #1]: I don't know, maybe or maybe not.
Interviewer: Okay. Can you tell me some more about that, what you think about that?
[Subject #1]: Because if like it might not matter because then there would be a lot more animals.
Interviewer: Why would there be a lot more animals?
[Subject #1]: Because if all the foxes are gone then, umm, there would be a lot more plants, because the fox eats all the mice, and toads and the spiders and the green plants, and skunks.
Interviewer: So if they disappeared, those things...
[Subject #1]: They could live more.
Interviewer: Can you think of anything else that might be affected if all the foxes disappeared?
[Subject #1]: No.

The student realised that the populations of the foxes' prey would increase, but did not mention broader implications, such as possible fluctuations within the ecosystem. Students typically failed to note any systemic implications within the food web beyond the specific two-way, predator-prey relationship.

No students stated cyclic causal connections in Task 1 on the pre-interviews, but this portion of the assessment was not designed to elicit this understanding.

Post-interview performance: How did students' performance change following the intervention?

Overall Point Scores

The analysis of students' gain scores in overall points revealed a significant main effect of intervention condition (F (2, 26) = 3.95, p = 0.03). The variable interview type was included in the model because scatter plots and subsequent analysis of variance suggested that it was a significant contributor to students' post-test (F (1,29) = 6.42, p = 0.0172), (but not pre-test scores (F (1,29) = 2.00, p = 0.17)). The overall model explained a fair amount of the variance ($R^2 = 0.47$). The difference between students who had RECAST activities without causal discussion (CAO) and students in the control group (CON) was non-significant (t (26) = 0.89, p = 0.38). However, students who had a combination of RECAST activities and causal discussion about the activities (CAD) modestly, yet significantly outperformed controls (t (26) = 2.75, p = 0.01).

Figure 1 presents the total gain prediction formula detailing the parameter estimates that were shown to be significant in the model. For intervention condition, students who participated in causal activities and causal discussion (CAD) had a base gain of 40 points. Students who participated only in the causal activities (CAO) had a base gain of 19.8 points. Control (CON) students had a base gain of 10.2 points. Table 2 details the predicted and actual gains for each group and interview condition.

On average students had a base gain of 23.3 points between the pre- and post-interviews. Students who had the pond interview first had a base gain of 40.6 points. Students who had the forest interview first had a base gain of 6.0 points. This resulted in a difference of 34.6 points depending upon the interview order. This difference may reflect a greater focus on forest relationships in the classroom activities and the extended unit (designed by the teachers) in which students participated. It seems unlikely that one version was inherently more difficult

$$\begin{array}{l} \text{Task 1: Total} \\ \text{Gain Score in} \\ \text{Overall Points} \end{array} = 23.33 + \left\{ \begin{array}{ll} \text{match} & \textit{group} \\ -13.13 & \text{when control} \\ -3.53 & \text{when RECAST Activities} \\ +16.66 & \text{when RECAST Activities plus} \\ & \text{Discussion} \end{array} \right. + \left\{ \begin{array}{ll} \text{match} & \textit{preinterview} \\ -17.26 & \text{when forest} \\ +17.26 & \text{when pond} \end{array} \right.$$

Figure 1 *Prediction formula detailing parameter estimates.*

Table 2 Predicted and actual total gains in overall points for connectedness by intervention group and interview order.

	Total gain in overall points for connectedness		
	Forest interview first	Pond interview first	Average
Intervention group	Predicted/Actual	Predicted/Actual	Predicted/Actual
CON	−7.1 / −0.2	27.5 / 20.6	10.2 / 10.2
CAO	2.5 / 6.2	37.1 / 33.4	19.8 / 19.8
CAD	22.7 / 12.2	57.3 / 67.8	40 / 40
Average	6.0 / 6.0	40.6 / 40.6	23.3 / 23.3

than the other especially given that earlier research with the pond and forest interviews revealed no significant differences between them (Grotzer, 1989; 1993), nor did the pre-interview scores in the present study. This issue is discussed further, under Task 2, below. In retrospect, we could have chosen to use just one interview version throughout, but this would have introduced possible test-retest issues. The counterbalanced design of the study (each group had five forest to pond and five pond to forest interviews) makes it possible to assess the outcome of intervention condition regardless of the significance of interview version.

These results suggest that RECAST activities alone were not enough to produce a significant difference. However, engaging students in activities that are carefully designed, plus causal discussion about the nature of the causality involved in the activity, results in a more sophisticated understanding.

Types of connectedness

While overall point totals offer a general sense of the level of sophistication of students' performance, the types of connectedness that students detected offer a finer grain analysis of how their understanding changed.

One-step connections are those that involve a direct link between two food web components. So, for instance, 'If the green plants disappeared, it would affect the mice' is a one-step direct link because mice eat green plants and parts of green plants. Students detected many one-step connections on the post-test. There was a significant main effect of intervention condition (F (2, 26) = 4.13, p = 0.02). The difference between students who participated in causal activities only (CAO) and students in the CON group was non-significant (t (26) = 1.41, p = 0.1693). However, there was a significant difference between students who had causal activities plus causal discussion and the control group (t (26) = 2.87, p = 0.007). The least squares means were 3.1, 6.1 and 9.2 (SE = 1.5) for the CON, CAO and CAD groups respectively. As a measure of noticing connectedness within ecosystems, these connections are a positive outcome. However, if students only improved in detecting one-step connections, it would signal that the result of the intervention was limited.

The number of multi-step connections that students detected offers a sense of how they reasoned about ecosystem relationships. Were they able to see domino-type relationships of cause and effects that extended beyond direct producer-consumer relationships? The main effect of intervention condition on gain in multi-step connections was non-significant (F (2, 26) = 2.37, p = 0.11). The difference between the group with causal activities only and the control group was non-significant (t (26) = 0.50, p = 0.6238), Those students who participated in causal activities plus causal discussion, however, significantly outperformed control students (t (26) = 2.08, p = .04). The least squares means were 1.2, 2.7, and 7.5 (SE = 2.13) for the CON, CAO, and CAD groups, respectively. 21 of the 30 students detected some number of multi-step connections on the post-interview (CAD = 8 students, CAO = 7 students, CON = 6 students) and the number of multi-step connections increased as well, particularly in the CAD group with counts of 106, 34, and 22 for the CAD, CAO, and CON groups, respectively. Typical responses from students included the following:

[Subject #26]: '...if the green plants disappeared, it would matter to everything because the insects would die and then whatever ate the insects, a lot of little animals eat the insects and then the bigger animals eat the little animals...so they all won't live.'

[Subject #28]: ' ...the crayfish probably wouldn't be too healthy because...the crayfish would die because the green plants are gone so the crayfish would die. Um...let's see...die who eats crayfish...the raccoon wouldn't' be too healthy.'

Table 3 shows mean gain scores broken down by two-, three- and four-step connections between intervention conditions. The CAD group had the highest gain in mean scores on two-, three-, and four-step connections. Scatter plots and tests of variance revealed that the CAD group had a greater amount of variance than the other groups on three- and four-step connections. This reflects the fact that while students across the group improved in detecting multi-step connections of two steps (which involve recognising indirect effects), the gains on three- and four-step connections were limited to a couple of students. The teacher described these students as middle level achievers but also as students with a deep interest in science. It is possible that they were especially engaged in the lesson and perhaps more likely to process the information more deeply. It also suggests that the CAD intervention helped students detect indirect two-step connections, but did less to help all of the students detect connections extending beyond that.

Table 3 Mean gain scores for each type of multi-step connection between groups.

	CON	CAO	CAD	
	M	M	M	SE
Two-Step	0.8	2.2	4.6	1.2
Three-Step	0.3	0.4	2.3	0.8
Four-Step	0.1	0.1	0.6	0.2

Mutually causal (two-way) connections

Patterns of mutually causal (two-way) connections were scored and analysed. Typical responses from students included the following:

[Subject #9]: '...if the foxes died, there'd be too much mice, toads, spiders, green plants and skunks'.

[Subject #16]: '...he (the fox) keeps everything balanced. Like if there were no foxes, there'd be too many mice, and they would eat all the green plants and then there wouldn't be any green plants left for the worms and skunks'.

[Subject #26]: '...if there were no fungi then all of the dead matter would stay there, well not all of it because there would be some earthworms, but without it a lot of dead matter would just be left there and nothing would eat it'.

It would be surprising to see real differences between intervention groups on this measure because the intervention focused so little on this particular type of causal pattern. The data bears this out. Differences between the groups were not significant at the $p \leq 0.05$ level from pre- to post-interview. Students in the CAD, CAO and CON groups detected counts of 45, 29, and 23 two-way connections, respectively, on the post-interview.

Cyclic connections

Although students in all groups discussed the food webs in terms of multi-step connections and mutually causal (two-way) connections, the CAD group was the only group to make any cyclic connections in the post-interviews (CAD = 5; CAO = 0; CON = 0). It should be noted, however, that this task was not designed to elicit this type of connection. Responses from students included the following:

[Subject #8]: 'Each one of them has something to do, so a fox eats the mice and the mice eat the insects and the insects eat the green plants and they are all connected and then the earthworms and the fungi break down when the things die. They break it down to make new soil for the green plants so everything else can eat'.

[Subject #26]: 'I think of it as a circle because when green plants die the earthworm and the fungi break it up into dead matter for more green plants to grow so it just keeps on going and going'.

Task 2 analysis

<u>Pre-interview performance: How did students perform prior to the ecosystems unit on the nature of decay and matter recycling?</u>

A one-way analysis of variance confirmed that there were no significant starting differences between the groups (F (2, 29) = 1.33, p = 0.28). Because pre-interview version was a significant covariate on Task 1, we analyzed its contribution to Task 2. Interestingly, students who had the pond version for the pre-interview did significantly better than students who had the forest version (F (1, 27) = 5.46, p = 0.02) as revealed by a one-way ANOVA (Pond – M = 5.28; Forest – M = 4.08, SD = 1.3). This was the opposite pattern than was found within Task 1. It may be due to students reasoning that plants falling into water would decay or change more easily than those falling on the forest floor. However, on the post-interview, students who had the forest version (the pond for pre-test and forest for post-test) did significantly better (F (1, 27) = 5.10, p = 0.03) gaining on average 2.4 points more than those who had the forest version first and then the pond version for their post-interview. For this reason, gain scores were used to analyse students' overall performances and pre-interview type was entered as a covariate in further analyses.

Most students on the pre-test described the changes that would occur to the dead plant at the level of appearance ('It will turn all black' [Subject #22]; 'It will look wrinkled' [Subject #26]) or at the level of location ('It will float away' [Subject #11]; 'The wind blows it away' [Subject #8]). Seven students made arguments at the structural- micro level. Two students on the pre-interview mentioned the process of the plant dying as having to do with decay ('It turns into soil' [Subject #26]) and two students mentioned it as having to do with matter recycling ('It turns into soil which is needed for new plants to grow' [Subject #16]). Most students named some type of causal mechanism as responsible for the change, although some of these reversed what would typically be considered cause and effect ('Rot makes it happen' [Subject # 24]). 25 students gave causal mechanisms that were scored as unreliable ('An animal sits on it' [Subject #20]) or process ('Water makes it soggy' [Subject #3]) explanations; three gave macro-decomposers (worms, fungi, etc); and one mentioned a micro-decomposer ('stuff you need a microscope to see' [Subject # 8]) on the pre-interview.

<u>Post-interview performance: How did students' performance change following the intervention?</u>

An analysis plotting group and pre-interview version against total gain scores revealed a significant main effect of group (F (2, 28) = 3.58, p = 0.04). Interview version was not significant (F (1, 28) = 0.37, p = 0.5464), though an interaction between group and interview type approached significance (F (5, 29) = 2.98, p = 0.0697) and was included in the model. (The overall model resulted in $R^2 = 0.40$). Students who had causal activities plus causal discussion performed significantly better (t (26) = 2.42, p = 0.0231) than control subjects. The difference between the CAO and CON group was approaching significance (t (26) = 1.90, p = 0.0690. The least squares means were -0.30, 1.90, and 2.68 (SE = 0.82) for the CON, CAO, and CAD groups, respectively.

Further analyses indicated that there were significant differences in how students in the CAO and CAD groups characterised

$$\begin{array}{l}\text{Task 2: Total Gain Score}\\ \text{on Characterization of}\\ \text{Causal Mechanism}\end{array} = 0.39 + \left\{\begin{array}{ll} \text{match} & \textit{group} \\ -0.99 & \text{when control} \\ +0.34 & \text{when RECAST Activities} \\ +0.65 & \text{when RECAST Activities plus} \\ & \text{Discussion}\end{array}\right. + \left\{\begin{array}{ll} \text{match} & \textit{preinterview} \\ -0.36 & \text{when forest} \\ +0.36 & \text{when pond} \end{array}\right.$$

***Figure 2** Prediction formula detailing parameter estimates (intervention condition and interview version) to estimate gain scores in characterisation of causal mechanism.*

the causal mechanisms associated with decay as compared to the CON group. An analysis plotting group and pre-interview version against gain scores in how students characterised the causal mechanism for decay showed the significant effects of group (F (2, 28) = 5.88, p = 0.008). Pre-interview version approached significance at (F (1, 28) = 2.96, p = 0.0981). The CAD and CAO groups were significantly different (t (26) = 3.38, p = 0.002) and (t (26) = 2.60, p = 0.0159), respectively, than that of the CON group with respective mean gains of 1.04; 0.737; and -0.60 (SE = 0.37) (see Figure 2 and Table 4). The CAD and CAO groups were not significantly different from each other. No other significant differences were found.

Structural-micro explanations increased from seven to 16 from pre- to post-interview (CAD = 9; CAO = 5; CON = 2). Explanations that focused on decay and matter recycling increased from two to six (CAD – 3; CAO – 2; CON – 1) and two to six (CAD – 3; CAO – 3; CON – 0) respectively. Unreliable causal mechanisms declined from 25 to 15 (CAD – 2; CAO – 4: CON – 9) with macro-decomposer explanations increasing from three to 12 (CAD – 6; CAO – 5; CON –1) and micro-decomposer explanations increasing from one to three, (CAD – 2; CAO – 1; CON – 0) pre- to post-interview.

The results across both tasks lend some limited support to the idea that teaching underlying causal structure can be helpful. The RECAST activities appear to have benefited the students in their understanding of the connectedness within ecosystem concepts when they were accompanied by discussion of the underlying causality. Students who experienced the RECAST activities plus discussion were better able to detect extended effects and in general, performed better at understanding decay as measured by total point scores. However, students experiencing RECAST activities alone also showed significant improvement in understanding decay. Focusing on the non-obviousness of microbe decomposers and the time lapse appear to have improved students' understanding. Previous findings by Leach et al. (1992) would support this. The results on understanding decay are less clear when one looks at particular concepts. Despite demonstrating a better understanding of the causal mechanisms involved in decay, the differences in students' ability to detect the underlying cyclic causal structure were not significant.

Table 4 Gains in characterisation of causal mechanism by intervention group and interview order.

	Gains in characterisation of causal mechanism		
	Forest interview first	Pond interview first	Average
Intervention group	Predicted/Actual	Predicted/Actual	Predicted/Actual
CON	–0.9 / –1.0	–0.24 / –0.20	–0.60 / –0.60
CAO	0.38 / 0.00	1.10 / 1.40	0.74 / 0.77
CAD	0.69 / 1.01	1.41 / 1.00	1.05 / 1.01
Average	0.03 / 0.005	0.75 / 0.71	0.39 / 0.39

Discussion

The results here offer some support for the hypothesis that it is not enough to simply introduce information about ecosystems and that students also need to learn how to structure the information. Providing information with support for structuring the causal concepts helped students develop a deeper understanding of a number of the ecosystem concepts under investigation. The significant, yet modest differences in the performance of the intervention groups signals the promise of the approach – that illuminating causal structures, along with scaffolds for understanding the time lapse and non-obviousness of decomposers, benefits students as compared to just offering information. The pedagogies used in the intervention represent a first attempt and we expect that they could be made increasingly effective in future iterations.

The findings suggest that the combination of offering carefully designed activities to reveal the underlying causal structure with explicit discussion of the nature of the causality involved offers the most promise. The activities alone were not consistently effective though they were most helpful in understanding the nature of decay. It is possible that merely knowing about the non-obviousness of the decomposers and about the time lapse involved made it possible to understand the nature of decay. In contrast, when students were evaluating connectedness within an ecosystem, actually thinking of it as domino-like might have pushed them to extend their search. We did not test the condition of causal discussion alone because we felt that it needed a meaningful context (i.e. the activities) in order for students to make sense of the nature of the causalities involved and to be able to apply them. It certainly is a possibility that could be examined given the outcomes here. The discussion components appear to have helped students make sense of the activities. It is possible that a pure causal discussion condition could be effective, particularly with older students.

We note, anecdotally, that those students in the activities plus discussion group were able to explain how certain models helped and hindered them in talking about various effects. For instance, here is a student's explanation of how the models helped her and how she used them in combination to analyse different situations:

> It's like the food web, if you set up your dominoes and you knock down the first one, then the second one will knock down as the effect to the cause of the first one, it's just gonna keep on going. But with dominoes you don't have enough unless you put it in a circle because the earthworms are the end of, they also, they're the end AND they're the beginning of the food web because they end one part with one generation of the food web and they start the new generation for the new plants to grow because that's what their job is. So they're the end and the beginning of the food web. [With dominoes] when you knock down the first one, all the other ones will knock down as the effect of the first one, so each one until the last one that you have knocks down but the last one is only an effect because it doesn't have anything to knock down, but most of them are causes and effects because it affects the one in front of it to knock it down but that was the cause of the next one to fall down. With the things that break down dead matter, then it would be a circle. [Subject #8, a third grader explaining how domino cause and effect explains some things in the food web and circle cause and effect explains others.]

A value to the discussion component that was not assessed in the current research may be in better assessing students' current understanding and suggesting areas where aspects of the curriculum should be modified or amplified. For instance, in the example above, a greater emphasis on domino models for understanding the transfer of energy from the sun and cyclic models for understanding matter recycling might be the next important teaching point to stress.

We expected that intervention students would show more improvement in understanding the underlying cyclic causal structure as compared to the control group than they did, given that they saw the time-lapse films and revealed a better grasp of the causal mechanisms involved in decomposition. It is possible that the intervention did not do enough to draw out the connections between the causal mechanism and the underlying re-entrant pattern. Further inquiry with targeted attempts to make this link explicit might illuminate why there was no discernible impact. Additionally, it makes sense to assess different ways of involving students with the causal structures in an effort to find those that most deeply engage them.

In the context of this work, we noticed other causal reasoning tendencies that would exacerbate students' difficulties in understanding ecosystem concepts. For instance, in understanding energy flow, students (and teachers) tended to focus on the active event of who eats whom rather than the relatively passive event of energy transfer. Most students positioned the arrows to show which organism would eat which organism and did not take into account the abstract idea of energy transfer through a food web. Other researchers have found this pattern (e.g. Barmen *et al.*, 1995; Gallegos *et al.*, 1994; Hogan, 1994; Senior, 1983). Barman and colleagues (Barman *et al.*, 1995; Barman and Mayer, 1994) for instance, found that students explained the feeding relationship in terms of one organism feeding on another without any mention of energy transfer, producer, or consumer. When provided with food web diagrams, the students did not question the direction of the arrows even though in most cases they conflicted with their own construction of a food chain. Energy flow is already a difficult concept to understand because it refers to an abstract, non-visible entity. It is made more difficult because it competes with an active notion of causality which teachers and students bring to their learning. Support for dealing with passive versus active causes could be built into the intervention.

Educational implications

The results of this investigation suggest that it is not enough to teach information about ecosystems. Too often, students will distort the information to fit with simple linear causal models. This finding is particularly important given teachers' concern with making sure that students gain the information that they need to perform well on standardised tests. Students also need to learn the underlying causal patterns. Our experience suggests that it is not necessarily difficult to help students learn these patterns, however, it requires a focused effort.

The results here raise the broader question of whether it is enough to teach conceptual and procedural information and whether we also ought to be teaching students structural information. Structural knowledge refers to the way that experts in a domain deal with foundational concepts, such as causality or categorisation, for instance, that impact how we frame experience or information. The ways that scientists structure knowledge is not easily available to learners. It involves abstracting patterns of reasoning from across one's science experiences. It is unlikely that most learners would be able to construct these patterns on their own and yet the results here suggest the promise of helping students to be aware of these patterns.

The goal of teaching about underlying causal structures should be to encourage students to learn a flexible repertoire of models that they understand how to map to relevant occasions. Focusing too much on any one structure might result in similar distortions to information that one sees with a heavy reliance on simple linear models. White (1997) noted this idea in reference to escalating causality in that biological systems in general tend to correct these 'perturbations' by feedback mechanisms. Although the short-term effects on a population may be severe, in the long run conditions should stabilise and return to normal. Pickett (1999) has argued that educators and scientists take the idea that 'everything is connected' too far and that often subtle fluxes and transformations play an important role in the definition of 'connectedness' in ecology yet are often overlooked. These points bear consideration when teaching particular causal structures. It underscores the importance of presenting the various causal forms as a repertoire – with enough flexibility that students see them as possible models – to be modified, combined, and discarded as the situation at hand calls for it.

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Appendix

Forest Interview Protocol

[Note: Version B focuses on a Pond Ecosystem and is structurally isomorphic to Version A.]

Task 1

Interviewer: Here I have pictures of things that live in the forest. It tells the name and some information about each thing. I'm going to ask you to read the cards for me.

Interviewer: Hand the child one card at a time in the following order: foxes; mice, insects; green plants; sun; fungi, earthworms, skunks, toads, spiders, soil. Provide help on any that they have difficulty reading. Explain that each card stands for ALL of that kind of thing. So all the foxes, all the green plants, and so on, not just the fox in the picture.

Interviewer: Ask how are these things important to each other?

Interviewer: How are the green plants important to the other things?

Interviewer: What if the green plants disappeared?

Interviewer: What would that cause to happen?

Interviewer: Why would it cause that to happen?

Interviewer: How are the mice important to the other things?

Interviewer: What if the mice disappeared?

Interviewer: What would that cause to happen?

Interviewer: Why would it cause that to happen?

Interviewer: How are the fungi important to the other things?

Interviewer: What if the fungi disappeared?

Interviewer: What would that cause to happen?

Interviewer: Why would it cause that to happen?

Interviewer: How are the earthworms important to the other things?

Interviewer: What if the earthworms disappeared?

Interviewer: What would that cause to happen?

Interviewer: Why would it cause that to happen?

Interviewer: How are the foxes important to the other things?

Interviewer: What if the foxes disappeared?

Interviewer: What would that cause to happen?

Interviewer: Why would it cause that to happen?

Interviewer: How is the soil important to the other things?

Interviewer: What if all the soil disappeared?

Interviewer: What would that cause to happen?

Interviewer: Why would it cause that to happen?

Task 2

Interviewer: Here is a picture of a tree in the forest. What happens to a tree in the forest when it dies?

Interviewer: What would happen to the tree after a long time, for instance, in a few years?

Interviewer: What causes this to happen?

Interviewer: Is there anything else? What?

Interviewer: Can you think of anything else that would make it happen?

Interviewer: Is there anything else that might make this happen that you can't see?

Interviewer: What if [the thing that they described in question #2 – Use whatever language they used] didn't happen? If none of the things that died, (trees, plants, animals or anything) [broke down, disappeared, decayed- depending upon child's explanation], can you tell me what would happen?
Tell me as many things as you can think of.

Interviewer: Would it matter to animals in the forest? If so, ask how.

Interviewer: Would it matter to plants in the forest? If so, ask how.