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Exploring Third-Grade Student Model-Based Explanations about Plant Relationships within an Ecosystem[1]

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Elementary students should have opportunities to develop scientific models to reason and build understanding about how and why plants depend on relationships within an ecosystem for growth and survival. However, scientific modeling practices are rarely included within elementary science learning environments and disciplinary content is often treated as discrete pieces separate from scientific practice. Elementary students have few, if any, opportunities to reason about how individual organisms, such as plants, hold critical relationships with their surrounding environment. The purpose of this design-based research study is to build a learning performance to identify and explore the third-grade students' baseline understanding of and their reasoning about plant–ecosystem relationships when engaged in the practices of modeling. The developed learning performance integrated scientific content and core scientific activity to identify and measure how students build knowledge about the role of plants in ecosystems through the practices of modeling. Our findings indicate that the third-grade students' ideas about plant growth include abiotic and biotic relationships. Further, they used their models to reason about how and why these relationships were necessary to maintain plant stasis. However, while the majority of the third-grade students were able to identify and reason about plant–abiotic relationships, a much smaller group reasoned about plant–abiotic–animal relationships. Implications from the study suggest that modeling serves as a tool to support elementary students in reasoning about system relationships,

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Portions of this paper are based on that work.

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but they require greater curricular and instructional support in conceptualizing how and why ecosystem relationships are necessary for plant growth and development.

Keywords: *Elementary science; Modeling; Explanations; Systems thinking*

Introduction

Plant growth and development is foundational content throughout K-5 grade science curriculum (American Association for the Advancement of Science [AAAS], 2007; Next Generation Science Standards [NGSS] Lead States, 2013). Building a robust conceptual understanding of plant life in the elementary grades is necessary to anchor more complex understanding that students need in later grades to reason about the twenty-first century global biological issues (National Research Council [NRC], 2011). Further, elementary students hold a natural curiosity about plant life that, if not nurtured within the early grade levels, may disappear by the upper grade levels (NRC, 2011). To build on this natural curiosity and interest, as well as lay important foundational knowledge about the influence and dependency plant life maintains within an ecosystem, elementary students require opportunities to scientifically reason and propose scientific explanations that link cause and effect (e.g. plants require abiotic and biotic elements to grow and survive) to the non-visible mechanism (e.g. plants are living organisms interdependent with their ecosystem) (Coll & Lajium, 2011; Gilbert, 2004).

The practice of scientific modeling supports elementary students in engaging in systems thinking through conceptualizing and generating scientific explanations about a system, such as an ecosystem, and the interactions other systems, such as organisms living within the ecosystem, have on the ecosystem as a whole (AAAS, 2007; NGSS Lead States, 2013). Within the practices of modeling, students develop models representing *what* they know about the elements and relationships within the system and then use their representation to scientifically reason and propose model-based explanations for *how* and *why* the system works (Forbes, Zangori, & Schwarz, 2015; Gilbert, 2004; Schwarz et al., 2009; Verhoeff, Waarlo, & Boersma, 2008). Even though some evidence suggests that elementary students can productively employ scientific modeling to reason about biological systems (e.g. Manz, 2012), this scientific practice is underemphasized in elementary science learning environments (Forbes et al., 2015; Manz, 2012; Schwarz et al., 2009). The field knows little of the ways in which elementary students develop models to understand and reason about biological systems, use their models to scientifically reason about how and why biological systems work, and the ways in which these reasoning structures may change through curriculum and instruction (Evagorou, Korfiatis, Nicolaou, & Constantinou, 2009; Grotzer & Bell Basca, 2004; Verhoeff et al., 2008).

Within this design-based empirical study, we defined a learning performance (Krajcik, McNeill, & Reiser, 2007) to identify and measure the ways in which US third-grade students (ages 8–9) engage with elements of systems thinking to generate model-based explanations about plant relationships within an ecosystem. The learning performance, once empirically grounded, was then used as a rubric to score the students' constructed models to identify the ways in which they represent and reason about ecological relationships, both biotic and abiotic, that plants require to grow, develop, and survive. The questions guiding this study are:

(1) How do third-grade students' models of plant processes include relationships within an ecosystem?
(2) In what ways do third-grade students formulate model-based explanations about plant relationships within an ecosystem?

Background Literature and Theoretical Framework

Plant Systems in the Elementary Classroom

Third through fifth-grade students should develop conceptual understanding that plants are a system consisting of many interacting processes which are interdependent with the surrounding ecosystem for growth and survival (NGSS Lead States, 2013). The defining features of an organismal system, such as a plant, are that they maintain stasis through a cause and effect feedback loop occurring at both micro- and macro-levels (AAAS, 2007; Booth Sweeney & Sterman, 2007; Eilam, 2012; Evagorou et al., 2009; Hogan, 2000). For example, within the elementary grades, a plant feedback loop includes at the micro-level the abiotic components of water in the soil, water vapor, sunlight, and temperature in the air around the leaves which determine water uptake through the roots and transpiration. This affects plant survival on the macro-level through providing the plant with sufficient growth and turbidity to develop, attract pollinators, and disperse seeds (NGSS Lead States, 2013).

However, in elementary science curriculum, systems are typically broken down by subject matter and taught in discrete pieces (Ben-Zvi Assaraf & Orion, 2010; Booth Sweeney & Sterman, 2007; Metz, 2008). Plant growth and development is separated from ecosystem content and the relationships that plants require within an ecosystem are not a curricular focus (Eilam, 2012; Manz, 2012). Causal mechanisms applicable in one system, such plant roots growing down into the soil in response to gravity (i.e. gravitropism), are not connected to other systems, such as water moving down into the ground due to gravity. Since knowledge building in elementary science learning environments provides an anchor for future science learning (Hammer, Russ, Mikeska, & Scherr, 2008), fragmenting elementary science content may cause difficulties when asking middle school and high school students to reason about systems because they have not had prior opportunities to build this understanding (Ben-Zvi Assaraf & Orion, 2010; Booth Sweeney & Sterman, 2007; Eilam, 2012).

Some evidence suggests that naïve systems thinking and mechanistic reasoning abilities about biological phenomena develop in early childhood (Inagaki & Hatano, 2013). This knowledge serves as foundational conceptual 'resources' (Hammer et al., 2008, p. 152) that children use daily to make sense of and problem-solve their experiences and observations (Inagaki & Hatano, 2013). While their conceptual resources contain many gaps in understanding about non-observable processes and mechanisms, such as seed development, their naïve biological theories also contain many scientifically correct ideas, such as the relationships between soil, water, and plant growth (Leach, Driver, Scott, & Wood-Robinson, 1996). Initially, when these conceptual resources were articulated and used for mechanistic reasoning by early learners, they were seen as misconceptions that should be shifted from 'wrong' to 'right' (Hammer et al., 2008). Yet, more recently, their conceptual resources are viewed as essential and baseline understandings that are dynamic and context dependent. Elementary students may leverage and build upon these resources when engaged in discipline-specific content using core scientific practices (Manz, 2012; Metz, 2008; Zangori & Forbes, 2014).

Within the plant sciences, there is a small body of work that has examined how elementary students engage in scientific activity to leverage and build upon their baseline understanding of plant processes (Manz, 2012; Metz, 2008; Zangori & Forbes, 2014). For example, Manz (2012) found that third-grade students held baseline conceptual resources on plant reproduction, but when these ideas were situated in the practices of modeling, the students began to refine the applicability of their ideas and build on their knowledge to understand the mechanisms of seed production and dispersal. Other works (Metz, 2008; Zangori & Forbes, 2014) have also found similar results thus providing evidence that when discipline-specific content is interlaced with scientific practice, elementary students refine their ideas to understand what plants require from their environment to grow and develop. These findings suggest that elementary students' conceptual resources may hold elements of systems thinking that can be leveraged within curriculum and instruction to support them in building understanding about how and why plant life is critical to ecosystem function and vice versa.

Theorizing and Operationalizing Model-Based Explanations and Systems Thinking

Model-based explanations and systems thinking are overlapping scientific practices that go hand-in-hand to support students in building conceptual understanding (Grotzer & Bell Basca, 2004). For students to develop models of biological systems, they need to employ systems thinking to develop their representation (Verhoeff et al., 2008). Conversely, to scientifically reason and generate scientific explanations about systems, students require opportunities to develop models of biological systems. In this manner, systems become simplified, may be manipulated, and hidden key processes and mechanisms can be made visible. Within the biological sciences, engagement in the scientific modeling practices are 'essential' (Verhoeff et al., 2008, p. 544) to engagement in systems thinking.

To identify model-based explanations and systems thinking within the third-grade classroom, we draw upon two closely aligned frameworks: (a) Forbes et al.'s (2015, p. 900, see Table 1) *mechanism-based epistemic perspectives on model-based explanations* and (b) Ben-Zvi Assaraf and Orion's (2010) *System thinking hierarchical model* (p. 541, see Table 1). The two frameworks are unique in their conceptual and

Table 1. Core elements of mechanism-based epistemic (Forbes et al., 2015, p. 900) and systems thinking features (Ben-Zvi Assaraf & Orion, 2010, p. 541)

	Mechanism-based epistemic features	Systems Thinking Hierarchical features
Components	The hidden and visible essential elements of a process included in the representation	(1) The ability to identify the components of a system and processes within the system (6) The ability to recognize hidden dimensions of the system—to understand natural phenomena through patterns and interrelationships not seen on the surface
Sequences	Recognizing cause and effect connections with underlying mechanism(s) and cyclic relationships within a process that work together to form a system	(2) The ability to identify simple relationships between or among the systems' components (3) The ability to identify dynamic relationships within the system (4) The ability to organize the systems' components, processes, and their interactions within a framework of relationships (5) The ability to identify cycles of matter and energy within the system—the cyclic nature of systems

analytical approach, but are complementary so that the ways in which students use model-based explanations and systems thinking can be identified and measured. Both these frameworks align through the components that students recognize as essential to system function and the sequential cause and effect relationships and causal mechanisms they identify that connect to form dynamic processes.

Models serve as sense-making tools to provide bridges for students between their conceptual understanding, what they have observed, and underlying scientific theory so that students may use the models to make sense of phenomena and generate a scientific explanation about the phenomena (Coll & Lajium, 2011; Gilbert, 2004). We refer to scientific explanations generated from constructed models as model-based explanations. Students' initial construction of their model is in response to a driving question so that a scientific explanation can be generated about the phenomena that identify cause and effect with the underlying mechanism (Gilbert, 2004). We operationalize how elementary students develop models and propose model-based explanations through a mechanism-based epistemic perspective (Forbes et al., 2015; Schwarz et al., 2009). Core perspectives within this framework are the visible and non-visible *components* connected through *sequences* within developed representations. When students represent both visible and non-visible *components*, models can be used as explanatory tools identifying underlying cause and effects connected through *sequences* that occur through an underlying mechanism. The *sequences* are identified relationships between both visible and non-visible cause and effect processes that produce change. When students represent all essential visible and non-visible elements and activities, their models have explanatory power and can be used to generate model-based explanation connecting what happened with how and why it occurred (Gilbert, 2004).

Systems thinking is understanding the system boundaries through identifying the essential hidden and visible elements essential to system function and the relationships among the multiple processes that comprise the system (Booth Sweeney & Sterman, 2007; Evagorou et al., 2009). Ben-Zvi Assaraf and Orion's (2010) proposed *Systems thinking hierarchical model* that identifies eight characteristics of building understanding about systems; however, only the first six of these characteristics apply within the elementary classroom (see Table 1). At the first level, students identify the essential components and processes necessary to understand the system as a dynamic whole such as whole plants (e.g. leaves, stem, roots, and petals), their abiotic needs, and relationships with animals. Next, they synthesize how these elements are connected through identifying simple relationships between the systems components such as rain falling on plants. As their systems thinking becomes more robust, students include non-visible components essential to process and/or system function and link the non-visible and visible components in dynamic processes that indicate transformation through cause and effect relationships. Finally, at the highest level within the elementary classroom, they indicate that these individual relationships work together to compose the system framework and that system function is cyclic and maintained through a cause and effect feedback loop with an underlying causal mechanism that maintains system stasis.

Methods

This is a design-based empirical research study grounded in *construct centered design* (CCD; Shin, Stevens, & Krajcik, 2010) to build a learning performance examining third-grade students' model-based explanations and system thinking about plant relationships within an ecosystem. To build the learning performance, two modeling tasks were embedded within the first and second investigations of a pre-existing curricular unit on plant growth and development, *Structures of life* (SOL; full option science system [FOSS], 2009). The modeling tasks served to explore and examine the ways in which they engaged in systems thinking and model-based explanations about plant relationships within an ecosystem towards the beginning and completion of the curricular unit.

Participants

This study takes place in three third-grade classrooms (age: 8–9 years; $n = 73$) across two schools in a US Midwestern state. The elementary teachers in this study were also participants in a multi-year project (see Forbes et al., 2015) designed to support elementary teachers and their students in model-based teaching and learning about water. This study was developed from emergent findings within the larger project that suggested third-grade students may articulate elements of systems thinking to propose model-based explanations about the water cycle through leveraging prior knowledge about relationships between plants, animals, and water (see Forbes et al., 2015). Here, we explore this emergent finding using model-based teaching and learning about plant growth and development in three third-grade classrooms.

The three teachers volunteered to participate in this study and teach supplemental lessons embedded within their FOSS (2009) SOL Investigations 1 and 2. The teachers were purposefully sampled (Miles & Huberman, 1994) for this study because each (a) was a third-grade teacher; (b) taught the SOL unit during the same three-month period of the school year (c) was in the post-induction phase of her career, and (d) had previously participated in the larger model-based teaching and learning project. In addition, each teacher participated in the same mandatory 1-day training workshop on the SOL module provided by a FOSS curriculum trainer from the state's regional educational agency.

Curriculum Materials

This study took place within Investigations 1 and 2 of the SOL unit because they include hands-on activities about plant processes, although they do not explicitly identify necessary ecosystem relationships for plant growth and survival. Since the lessons were not specific to plant–ecosystem relationships, this allowed us to identify and measure students' initial ideas about this relationship and how they use their conceptual resources about plant–ecosystem relationships throughout the unit to further reason about these connections as their knowledge about plant processes grows. Investigation 1, *Origin of seeds* contains four parts that take approximately four weeks to complete. Each part of the investigation provides opportunities for students to explore through hands-on activities and experiences to foster understandings of seed structure and function and seed dispersal including abiotic and animal requirements. During the investigations, students collected data that included examining the properties of seeds, the effect of water on seeds, and investigating how seeds disperse.

Investigation 2, *Growing further* contains three parts but takes approximately six weeks to complete due to waiting for plants to grow to maturity. The investigation includes hands-on activities about plant external structures such as leaves, stem, petals, and roots with associated functions; the plant cycle that includes seed to mature plant and seed production; and plant abiotic and animal requirements that include the necessity and effect of water, sunlight for plant survival and animals required for seed dispersal.

Supplemental Modeling Lessons

The SOL curriculum does not provide student opportunities to employ the practices of modeling or scientific explanation construction (Forbes et al., 2015; FOSS, 2009; Metz, 2008). Therefore, two identical supplemental modeling lessons (SML) designed by the authors were embedded within SOL Investigations 1 and 2. The SMLs aligned with the FOSS lesson structure and were enacted by the teachers immediately after introducing the curriculum ideas in Investigation 1 and immediately following completion of Investigation 2. Throughout the study, the first author worked one-on-one with the teachers to support their practice of the SML. The teachers were provided the SML materials at least two months in advance and, even though they all had prior experience with similar lessons, the SML materials were reviewed with each teacher prior to each enactment. The lessons provided background information on the practices of scientific modeling, model-based explanations, and instructions specific to creating 2-D diagrammatic process models. All SMLs were observed by the author.

Student modeling tasks were completed after the teacher-led SML discussions. Each student constructed three 2-D diagrammatic process models over the course of the study using pencils in response to the question 'how does a seed grow?' They then used their models to write responses to a series of reflective questions to support their use of the modeling practices: (a) *What does your model show happening to a seed as it grows into a plant*?, (b) *Why do you think this happens to a seed as it grows into a plant*?, (c) *What have you seen that makes you think this happens to a seed*?, and (d) *How would you use your model to teach a younger student that this is what happens to a seed as it grows into a plant*? The models were completed within the beginning of SOL Investigation 1 (pre-model) and at the conclusion of Investigation 2 (post-model).

Data Collection

Student interviews. Five students from each classroom, for a total of 15 students, were purposefully sampled (Miles & Huberman, 1994) in collaboration with project teachers to represent a range of academic performance for clinical interviews grounded in their constructed models and writings. The student sampling approach was an attempt to balance between maximum-variation sampling (Miles & Huberman, 1994) identified here as high-achieving students and low-achieving students, as determined by the teachers, and typical sampling of students representative of the population as a whole.

The clinical interviews were conducted immediately following completion of the student modeling task. The interviews followed best practices (e.g. Miles & Huberman, 1994) and specific recommendations for developing trust and rapport with children of this age level (Westcott & Littleton, 2005). The student interview protocol was based on the students' generated models and was designed to elicit, through open-ended questions, their model-based explanations. While the student interview protocol was semi-structured (Miles & Huberman, 1994), the interviews were tailored for each child so that they were grounded in the student models (Westcott & Littleton, 2005). The semi-structured interview protocol provided questions for each interview that included: 'What do you think happens here?', 'How do you think this happens?', and 'Why does this happen?' the interviews were also based on the elements included in their constructed models and why they chose to include those elements. The interviews were audio-recorded, transcribed, and assigned unique identification numbers that aligned with the student model so interviews and models were matched.

Modeling tasks. All student pre- and post-models ($n_{pre} = 73$, $n_{post} = 73$) were collected at the conclusion of the final SML. All student identification was removed from the models and associated writings and unique identification numbers were assigned that linked each student model to the classroom and lesson.

Data Analysis

Qualitative analysis. The learning performance was developed per *construct centered design* (Shin et al., 2010). First, US science standards (AAAS, 2007; NGSS Lead States, 2013) were reviewed to determine what plant and ecosystem relationships third-grade students should understand. From the standards review, the target concept was defined as:

> The plant is dependent on its environment through both abiotic (e.g. water, sunlight, temperature, and air) and biotic elements (e.g. bees, furry animals for hitchhiker seeds, earthworms, and other animals that scatter seeds). If any of the necessary abiotic and biotic elements are missing from the system, then the plant will not grow or survive.

Next, a hypothetical learning performance for the target concept was developed for the components and sequences features of the underlying theoretical framework. It details four levels that range from zero (lowest level) to three (highest level) of characteristics for students' understanding about the target concept. We included detailed characteristics at each level that included, for example, if they viewed the represented components as a simple linear chain (level one) or if they viewed connections as a dynamic chain with activities that supported sequential actions (level three). Prior to empirical grounding, the hypothetical learning performance was submitted for external review, comment, and evaluation by experienced researchers in learning performance development and plant biology.

The student interview data were used to empirically ground the hypothetical learning performance. The first author and another researcher qualitatively (Miles & Huberman, 1994) co-coded six interviews to establish the levels of the learning performance. Iterative changes and details were added to the learning performance as findings emerged during coding (Shin et al., 2010). For example, at level 2 components, the coding scheme was modified to consider whether non-visible elements were also present at this level and to add clarity to differentiate between each level (see Table 2). After completion of coding and final discussion between the coders, 100% agreement was reached on empirical grounding of the levels for components and sequences. The final coding scheme with identifiable characteristics is presented in Table 2. Once the scheme was in place, the remaining interviews were coded ($n_{pre\text{-}models} = 15$; $n_{post\text{-}models} = 15$). Evidence of the three levels was found in pre- and post-models. Further qualitative analysis occurred to identify themes within

Table 2. Levels of empirically grounded learning performance for target explanations

Level	Component description
0	No abiotic or biotic elements represented
1	Visible plant, abiotic and/or biotic components
2	Visible plant, abiotic and/or biotic; non-visible plant and abiotic or biotic components
3	Visible and non-visible plant, biotic and abiotic elements
Level	Sequence description
0	No relationships between abiotic or biotic elements
1	Sequence describes a simple relationship chain between plants and abiotic or biotic systems that only occurs in one direction and does not include a causal story for how and why things are occurring
2	Sequence describes more than one relationship chain between plants and abiotic and/or biotic systems. The relationships only occur in one direction but is dynamic and includes associative elements such as how the relationship occurs, but is not causal
3	Sequence describes a relationship chain between plants and ecosystems that demonstrates cyclic elements. There is evidence of a causal relationship for how and why the process is occurring. There is also recognition if one element is missing, then the cycle will not occur (i.e. feedback system)

the interviews, models, and writing samples that provided insight into the students' articulation of model-based explanations. Reduction and isolation of text continued until all the emerging patterns were illustrated and dominant themes were refined and substantiated (Miles & Huberman, 1994).

Quantitative analysis. The empirically grounded learning performance was used as a rubric to score all models. The unit of analysis was the model with the associated responses to the reflective questions. Prior to use, two models were scored jointly to ensure that the rubric was appropriate. Next, 10% of the models ($n = 21$) were scored by two independent researchers to determine the reliability and consistency of the rubric. Cronbach's alpha was calculated as 0.816. A reported alpha value of 0.7 is considered sufficient for quantitative inter-rater reliability (Jonsson & Svingby, 2007). After scoring, a mixed model repeated measures ANOVA was used to see if there were statistical differences between teachers. Differences between classrooms was not statistically significant, $F(1, 74) = 0.475$, $p = .493$. Further analysis involved paired sample t-tests and Pearson correlation coefficient to examine differences and relationships within and across pre- and post-models. A Chi-square analysis was also used to identify student growth over the study in representations of plant–ecosystem relationships.

Results

Below the findings are presented in two groups. First, we present evidence of the empirical grounding of the learning performance. Second, findings from the model scoring and the qualitative themes found within the scored models and interviews are used to answer each research question.

Empirical Grounding of the Learning Performance

The empirical grounding of the learning performance with examples of interview samples used for establishing the levels are presented in Table 3. The analysis of the student interviews situated in their constructed 2-D models yielded three definitive levels for *components* and *sequences*. Results indicate that the third-grade students' understanding of plant relationships within an ecosystem occurred at all levels within their discussions about their models.

At level 1 *components* level, students' expressed understanding through simple descriptions with visible elements (Table 3). The *components* represented are those that third-grade students can immediately observe such as whole plants above the ground, falling rain, and/or bees. At level 2, students began to consider non-visible *components* between abiotic or biotic elements for plant growth and/or survival. As

Table 3. Example of analysis for learning performance levels

Level	Evidence	Analysis: Components	Analysis: Sequence
1	Rain falling from the clouds [on the plant] (T3.1)	Visible: plant water, fall (action)	Simple relationship between abiotic and plant: Water → falls on plant
2	… bees pollinate so that the flowers can grow or so the leaves and stuff can grow (A2.1)	Visible: bee, flower, leaves Non-visible: pollinate (action), grow (action)	Single direction multi-relationship chain between plants and animal systems: Bees pollinate → flowers grow
3	Seed pods fall and then it um [*sic*] the water … it gets water and then it cracks open because the seed wouldn't open if it's still dormant! It'd still be dormant if the water didn't wake it up. And then the roots come out and then the roots go down in the ground and the stem goes up and then it gets leaves and it gets blossoms and then the flower turns into the seed pods if the bee cross-pollinates (K. WM3)	Visible: seed pods, water, stem, leaves, blossoms, bee Non-visible: seed pods crack (action), roots, cross-pollinates (action)	Sequence describes a relationship chain between plants and ecosystem that demonstrates cyclic elements: Seed pods fall → water cracks seed pod → seed pod germinates → adult plant grows → bee pollinates →seed pods grow

Note: Even though a single quote was used to demonstrate all levels, it is possible for a model to score at different levels for each feature.

seen in Table 3, the student identified the non-visible actions of pollination and growth. Non-visible also includes biotic and abiotic *components* such as those underground which include earthworms, nutrients in soil, roots, and those above ground such as air, bees with pollen and/or nectar, and seed dispersal through wind, water, or animal. At level 3, students include the hidden *components* and activities such as plant roots, water, and nutrients in the soil as well as sunlight, and seed dispersal by animals.

At level 1 *sequences*, students described single relationships that were not causal; they were a description of one thing happening to another thing. At level two, *sequences* were still linear but had some elements of an explanatory process such as how the elements are related. For example, as shown at level 2 in Table 3, the student includes that bees pollinate so flowers can grow. The relationship is associative between bees pollinating and flowers growing. However, it is not causal as the example does not include *why* pollination is necessary for continued growth. At level 3, the *sequences* identify a relationship that is dynamic because one thing is a causal agent for something else. The relationship sequence includes both how and why the seed reproduces and grows (Table 3).

Model Analysis

Research question 1. Research question one asks 'How do third-grade students' models of plant processes include relationships within an ecosystem?' Paired sample t-tests were used to identify if increases in scores from pre- to post-model were statistically significant (Figure 1). The two features, *component* and *sequence*, were summed to give one score for each student's pre-model and post-model. The results show a statistical difference between the overall pre-model and post-model scores, $t(72) = 4.556$, $p = .000$, $d = 0.5$. This suggests that over the course of the study, the students' illustrations and writings formed to the question 'how does a seed grow' increased in representing relationships with abiotic and animals as necessary for seed and plant growth.

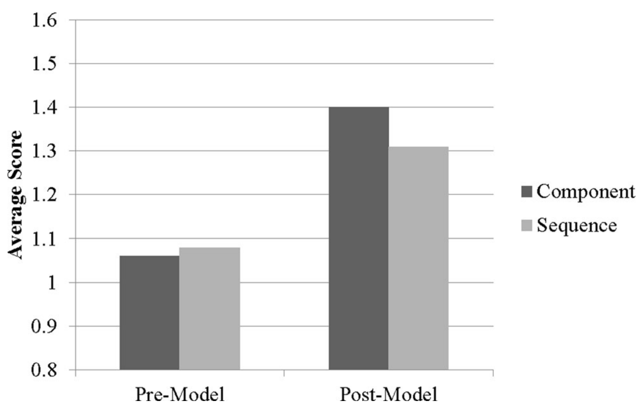

Figure 1. Pre- to post-model scores

A Pearson correlation was used to examine if there were feature score relationships between the *components* represented and the sequential connections. The correlation between *components* and *sequences* for the pre-model was statistically significant, $r = 0.714$, $p < .001$ and increased in the post-models, $r = 0.855$, $p < .001$, suggesting that as students representations increased in learning performance levels, such as representing non-visible elements like air, so did the relationships they formed between the components, such as the necessity of air for plant survival. Finally, a Chi-square analysis was used to examine what elements students were using to form relationships (plants with abiotic elements and/or biotic elements) and if the presence of plant–ecosystem relationships included in the pre-and post-models were significant as determined from the difference between observed and expected outcomes. The Chi-square analysis was significant overall, $\chi^2 = 12.3$, $p = .04$ (see Table 4). The observed versus expected differences are greatest within the plant life with abiotic and animal relationships group. While in the pre-models fewer than expected students represented these relationships, within the post-models, the number of observed significantly exceeded the expected results.

Research question 2. In research question 2, we asked 'In what ways do third-grade students' formulate model-based explanations about plant relationships within an ecosystem?' To answer this question, we examined the ways in which the students formed model-based explanations about plant–abiotic relationships and plant–abiotic–animal relationships.

Plant–abiotic relationships. Overall, across the modeling time points, as shown in Table 4, the largest percentage were representations that only included plant and abiotic *components*, such as rain, sun light, and a flower growing out of the ground and/or a seed in the ground. Within this group, 40% scored a level 2 for *components* in which they considered visible and non-visible water forms and air, temperature, and nutrients in the soil as necessary relationships for plant growth. We also found

Table 4. Pre- and post-model chi-square analysis of observed and expected

	Pre-model			Post-model		
	Observed	Expected	Difference	Observed	Expected	Difference
Plant life only with no relationships	8	6.04	1.96	4	5.96	–1.96
Plant life with only abiotic element relationships	58	54.4	3.6	50	53.6	–3.6
Plant life with only animal element relationships	3	2.52	0.48	1	2.48	–1.48
Plant life with abiotic and animal relationships	5	12.1	–7.1	18	11.9	6.1

that they proposed causal mechanisms within their identified *sequences*; however, their causal mechanisms were specific to plant–abiotic relationships. Further, their proposed mechanisms went beyond the content within their curriculum materials. For example, Violet identified that roots growing down in the soil because 'It (gravity) like um [sic] pulls the root down' (A2_3) and was necessary to hold seeds and plants in place so they could grow (Figure 2).

Students also reasoned from their models to propose how non-visible sunlight might enter the plant. For example, in our discussion with Charlie about the relationship between sunlight and plants, he indicated on his model:

Interviewer:	Why do you suppose it [the plant] needs sunlight?
Charlie:	Um [*sic*] to make food, I think. I forgot what's it's called but when sunlight comes down it makes these little food things and that's why they are hollow. It goes to the stem and it … and uh [*sic*] to the roots and goes to plant like spreading food around it and giving it to the seed which makes the plant bigger.
Interviewer:	So the sun goes into the holes in the leaves, is that what you described?
Charlie:	Yeah. It's the leaves are like solar panels kind'of [*sic*]. And instead of making electricity they make food (H3_1).

As Charlie's quote illustrates, he has considered components that are non-visible within third-grade science lessons and were not explicit within the curriculum materials such as 'holes' in the leaves as an entry point for sunlight. Further, he has expressed a dynamic sequence that includes a causal mechanism that sunlight entering the plant makes the 'plant bigger'. He also addressed the relationship between sunlight and the plant, the specific structure and function of leaves as related to sunlight, *how* sunlight enters the leaves, and *why* this relationship is necessary.

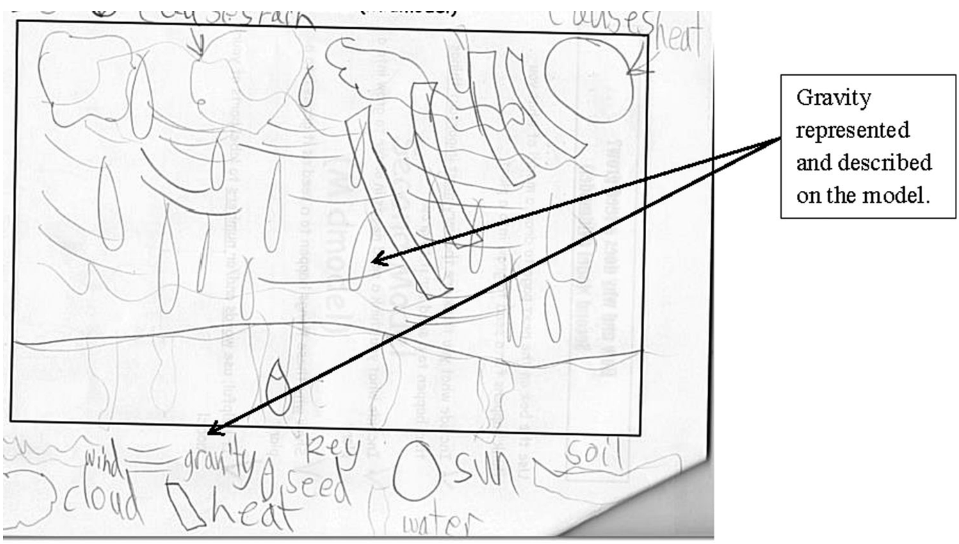

Figure 2. Violet's model (A8)

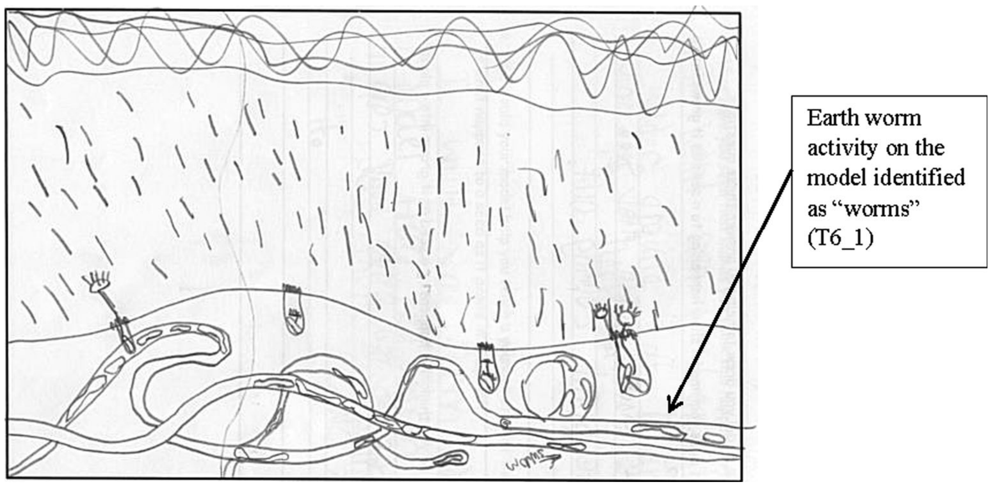

Figure 3. Mike's model (T6_1)

As well, 17% of the models that fell within this group scored a level 3 for *components* in which they represented both abiotic and animals; however, within their identified sequences they only discussed abiotic elements and causal mechanisms related to abiotic animals. Their model-based explanations did not include their represented animals. For example in the lower half of Mike's model, shown in Figure 3, he has included a great deal of earthworm activity under the surface. When asked specifically about the worms during his interview, he did not connect them to plant life:

Interviewer:	Let's go back to the worms, then. You drew them. Tell me how you think they help seeds.
Mike:	No idea.
Interviewer:	But you included them? Why do you think [you included them]?
Mike:	I just heard that they're important. (T6_1).

Yet when Mike was asked why he represented the rain, he responded 'Because if there's too much heat [from the sun] and there's no rain, it will stay warm and it [the plant] won't come out' (T6_1). He further clarified within his interview that rain is necessary to cool the seed after the sun heats the seed and both heating and cooling where necessary so that seeds remain at the correct temperature to grow. While Mike has devoted a large portion of his representation for 'how does a seed grow' to animal activity, his reasoning focused on the non-visible abiotic elements such as temperature as necessary for plant growth. Other students also represented birds, squirrels, and butterflies on their models but did not include these organisms in their writings or discussions about how or why these organisms may be necessary for plant growth and survival.

Plant–abiotic–animal relationships. The number of students' models that included abiotic, biotic, and plant life increased over the course of the study and, within the post-models, was the second largest percentage of scores (Table 4). The models that fell into this group illustrated plant structures both above and below ground, visible and non-visible abiotic elements and organisms such as bees and butterflies carrying pollen, and birds and furry animals transporting seeds. Across the pre- and post-models within this group, we found that students reasoned about both direct and indirect animal–plant relationships; however, they also identified that these relationships were 'guesses' within their models. Overall, their identified 'guesses' were scientifically accurate.

The SOL curriculum materials explicitly identified plant and animal relationships only when discussing seed dispersal. The seed dispersal lesson focused on furry animals in which seeds stick and fall-off the animal at difference locations. While the third-grade students included the animal–seed dispersal mechanism within their models and discussions, they also proposed other ways that animals have a relationship with seeds and plants. They discussed the direct effect that bees had on plants identifying that bees caused seed growth through forming seed pods. They expressed elements of pollination, such as a cause and effect between bees visiting flowers and seed pods forming, yet were unable to identify further elements of this relationship. For example, Matilda states about her model (Figure 4):

Interviewer:	So animals are necessary for plants to grow?
Matilda:	Ummm [*sic*] … I think the flower turns into the seed pods sometimes if the bee cross-pollinates. (W3_3)

Matilda identifies a direct cause and effect relationship (bees cross-pollinate which causes seed pods) which she referred back to several times during her

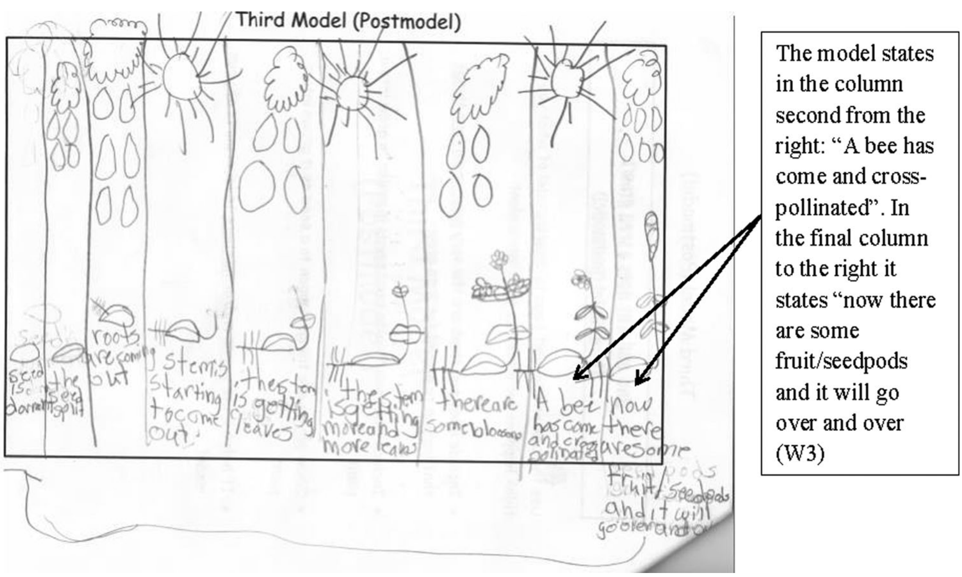

Figure 4. Matilda's model

interview about her model. While she recognized this critical relationship, she never articulated what ‘cross-pollinates’ means or how and why bees may support seed pod development.

The third-grade students also identified that animals have a direct effect on plant growth through burying seeds, either purposefully such as Sam identifies: ‘Some animals might pick them [seeds] up like squirrels and then bury them in the ground and then they might forget where they are and then [the seed] starts to grow’ (A3.1). Or burying seeds accidently such as Martha states: ‘They [seeds] probably went in the ground by animal stomping on it or animals kicked it or something like that’ (A1.2). Both these identified mechanisms occur within natural ecosystems but were not present in the curriculum materials.

They also discussed indirect relationship between plants and animals. While they were unclear on how or why this relationship occurred, they articulated that animals ‘gave’ something to the soil that in turn was able to ‘give’ something to plants to support growth. For example:

Interviewer:	What do animals do?
Serena:	Like [*sic*] the animals are like fertilizer for it and all that stuff … I wrote right here [on her model] they [animals] give the soil nutrients (N1.3).

Serena has included this relationship between animals, nutrients in the soil, and plants on her model through bird waste (Figure 5). While this relationship does not appear as a fully understood mechanism by Serena, or with other students about how or why animals give the soil nutrients, they do identify that there is a necessary indirect

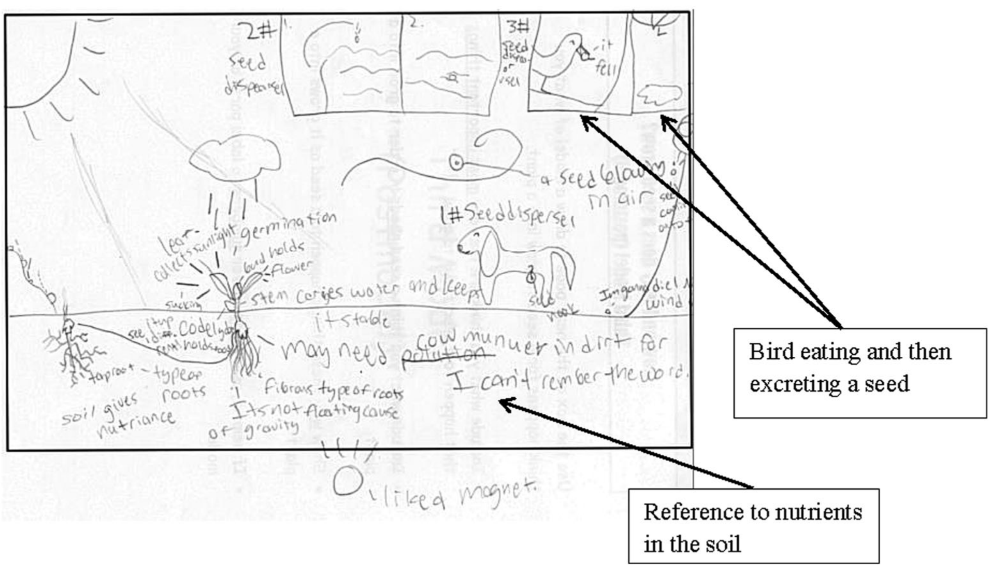

Figure 5. Serena’s model

relationship that is present. Others expressed this relationship through identifying that 'worms produce fertilizer in the ground' (A5.1) or that 'worms make the soil' (A4.1) so that the plants get 'nutrients'. While they did not express understanding how this relationship works, they are identifying elements of the nitrogen cycle through recognizing that animals 'give' something to soil that supports plant growth. Again, this relationship was not present within the curriculum materials.

Summary of Findings

Analysis of student interviews distinguished four learning performance levels (0–3), each articulating successive levels of complexity in students' model-based explanations about plant–ecosystem relationships. The learning performance was then used as a rubric to score all students' pre- and post-models. This quantitative analysis suggests growth in students' consideration of plant–ecosystem relationships from the beginning to the end of the curricular unit. However, this is predominately due to students' consideration of plant–abiotic relationships over plant–ecosystem relationships. Yet we also found that over the course of the curricular unit, a significant percentage of students' ideas shifted to consider not only abiotic elements, but also the importance of animals within plant growth and development.

Synthesis and Discussion

Engaging with the practices of modeling to understand systems and propose scientific explanations are cross-cutting concepts within the NGSS framework (NGSS Lead States, 2013). These practices are included in the elementary grades in developmentally appropriate yet critical ways to serve as foundational anchors for future science learning (Hammer et al., 2008). Thus far, there is little research on how to foster system thinking and model-based reasoning within the elementary classroom (Ben-Zvi Assaraf & Orion, 2010; Booth Sweeney & Sterman, 2007; Forbes et al., 2015; Manz, 2012). Our results from the development of a learning performance and its use to analyze third-grade students' engagement in these cross-cutting concepts about seed and plant growth indicate that they engage in elements of systems thinking to propose model-based explanations about how and why plants grow, develop, and survive.

First, our results suggest that plants may serve as entry points for elementary students to scientifically reason about how biological systems (micro- and macro-) are connected and interact. Plants are a unique biological system because they are interdependent with and a critical element of all other biological, chemical, and physical systems (hydrosphere, atmosphere, geosphere, and biosphere; NGSS Lead States, 2013). Further, young children build conceptual resources of plant life in very early childhood (Inagaki & Hatano, 2013; Leach et al., 1996). Prior studies that have specifically examined systems thinking in the elementary classroom focused on the ways in which elementary students understand and reason about food webs and predator/prey relationships within ecosystems and have noted systems thinking as challenging within elementary science learning environments (e.g. Evagorou et al., 2009; Grotzer & Bell Basca, 2004; Hogan, 2000). Yet there are multiple levels of complexity inherent in food webs and predator/prey relationships. To understand how disturbances within the web affect the larger ecosystem requires early learners to conceptualize and abstract processes with multiple visible and non-visible components and underlying mechanisms occurring simultaneously at different levels within the system (Evagorou et al., 2009; Grotzer & Bell Basca, 2004; Hogan, 2000). This is a challenging endeavor in the elementary grades because early learners have typically not had prior exposure engaging with core scientific activities to reason about causal mechanisms, the ways in which mechanisms underlie system function, or consider system functions occurring at multiple levels (Ben-Zvi Assaraf & Orion, 2010; Grotzer & Bell Basca, 2004; Metz, 2008).

The third-grade students studied here demonstrated a wealth of pre-existing conceptual resources (Hammer et al., 2008) about plant–ecosystem relationships within their pre-models that including considerations of relationships between plants and the hydrosphere, atmosphere, geosphere, and biosphere. Their baseline model-based explanations, as identified in their pre-models, included relationships between plants and visible and non-visible abiotic and biotic requirements both above and below ground as well as necessary elements within the soil to support plant growth. The systems thinking literature has suggested that educators should 'look closely at current curricular materials to identify existing topics that may act as building blocks for learning systems concepts' (Booth Sweeney & Sterman, 2007, p. 306). It is possible that plant life may serve as a building block for early learners to begin to develop their naïve systems thinking since elements of this understanding are already present within their conceptual framework.

Second, over the course of the curricular unit, our results suggest that there was an increase in students' consideration of plant–ecosystem relationships, even though this was not curricular focus. Their post-model representations included components in causal sequences to form, in some instances, a full cycle of causal relationships that included both hidden and visible plant, abiotic, and animal elements. Students articulated within their post-models that if the relationships were not present (i.e. micro-level), then the plant would not maintain stasis (i.e. macro-level). While not all students' models exhibited all of these elements, the majority of their representations exhibited more than one of these elements and connected the elements in more than simple relationships.

When early learners develop scientific models their conceptual understanding becomes visible. They can then use their representation as a reasoning tool to propose how and why the phenomenon occurs (Coll & Lajium, 2011; Gilbert, 2004; Verhoeff et al., 2008). If students are not provided the 'how' and 'why' during the lesson, they fill in those gaps using reasoning from their own observations and experiences of the physical world (Inagaki & Hatano, 2013). While the SOL curricular materials include hands-on opportunities for students to collect data on seed and plant structure and function, the materials do not include opportunities for students to generate evidence-based scientific explanations about how and why plant structures perform functions (Zangori & Forbes, 2014). Our results here suggest that students filled in these gaps with their ideas about the surrounding ecosystem. While their ideas about plant–ecosystem relationships were also in the pre-models, they became more robust in the post-models in which students considered more complex causal relationships.

Third, these findings build upon prior work examining model-based teaching and learning in the elementary grades (Forbes et al., 2015; Manz, 2012; Schwarz et al., 2009) and highlight the ways in which elementary students engage in the practices of modeling to articulate and further their understanding of how and why plant growth and development occurs. Even though both model-based reasoning and systems thinking are included in the *Next Generation Science Standards* (NGSS Lead States, 2013), opportunities to engage in these practices are rare within science learning environments (Ben-Zvi Assaraf & Orion, 2010; Forbes et al., 2015; Gilbert, 2004; Manz, 2012; Schwarz et al., 2009; Verhoeff et al., 2008). Within the elementary classroom, this underemphasis has been attributed to prevailing notions about early learners' scientific reasoning abilities which articulate that elementary students' are not yet at a cognitive stage to successfully scientifically reason and engage in the practices of modeling (Manz, 2012; Metz, 2008; Zangori & Forbes, 2014). Yet our results indicate that when third-grade students are provided space and opportunity, they engage in sophisticated scientific reasoning through the practices of modeling to provide model-based explanations that identify how essential hidden and visible elements and mechanisms connect in cause and effect occurrences. Further, asking the students to develop and use models provided a conceptual 'window' into their understanding of how and why the world works (Coll & Lajium, 2011). As the third-grade students developed models of their ideas about plant growth and used their models to articulate model-based explanations, their thinking became visible and provided evidence of the ways that their conceptual understanding and reasoning went beyond the curriculum in scientifically accurate ways.

Implications and Conclusions

Systems thinking and scientific reasoning do not develop without curricular and instructional support (Ben-Zvi Assaraf & Orion, 2010; Booth Sweeney & Sterman, 2007; Eilam, 2012). While the two modeling lessons incorporated here sought to support elementary students' engagement in the practices of modeling and consider how and why systems function, this represents that a modest intervention is a limitation of this study. Students require more sustained engagement for modeling to become a purposeful sense-making tool for their scientific reasoning and systems thinking development (Eilam, 2012; Verhoeff et al., 2008). Our implications propose areas of future work for the development of elementary curriculum materials that support third-grade students to generate model-based explanation construction about plant growth and development.

For elementary students to build robust knowledge of both modeling practice and discipline-specific content, they require iterative opportunities to engage in scientific modeling at both the process level and system levels to see how processes are connected (Ben-Zvi Assaraf & Orion, 2010; Manz, 2012). Therefore, curriculum designed from the learning performance developed here should include opportunities in grade appropriate ways for third-grade students to model processes such as, for example, the relationships between pollinators, pollen, nectar, and seed production to build understanding about seed origination, or between plant and animal death and decay into the soil to understand where the nutrients in the soil come from. They should then develop models identifying these processes within the larger ecosystem to generate model-based explanations about how these individual processes are connected within the plant–ecosystem framework. Anchoring these ideas and scientific practices in elementary school may support older students in understanding how, for example, the carbon and nitrogen cycles fits within the larger ecosystem, which has been identified as a challenging concept for the upper grade levels (NRC, 2011).

The empirically grounded learning performance identified four levels of complexity for how third-grade students understand and reason about plant–ecosystem relationships when engaging in the practices of modeling. The advantage of designing curriculum from an empirically grounded learning performance is that the curriculum is determined from the performance to facilitate multiple learning paths (Krajcik et al., 2007). The paths attempt to capture students at all levels of the performance and support their understanding of plant–ecosystem relationships within the practices of modeling. In essence, the learning performance provides a map of the possible ways in which students engage with the practices of modeling to build conceptual understanding. While this study focuses on understanding the baseline ways in which early learners engage in discipline-specific scientific activity, next steps require examining how the learning performance can provide curricular and instructional support within the elementary classroom to support students in leveraging and building upon their conceptual resources over time to understand how and why plants grow, develop, and survive.

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