Exploring 3rd-Grade Student Model-Based Explanations about Plant Growth and Development

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Abstract

To develop scientific literacy, elementary students should engage in knowledge-building of core concepts through scientific practice (Duschl, Schweingruber, & Schouse, 2007). A core scientific practice is engagement in scientific modeling to build conceptual understanding about discipline-specific concepts. Yet scientific modeling remains underemphasized in elementary science learning environments and little past research has explored early learners' engagement in domain-specific modeling practices. Here we report on a design-based study to investigate the ways in which 3rd-grade students' generate model-based explanations about two core plant growth and development processes: plant structure/function and plant life cycles. First, using design-based research, we developed and empirically tested a learning performance framework that integrates discipline-specific content with scientific practice to examine 3rd-grade students' engagement in epistemic features of model-based explanations about the plant growth and development. Next, we used the learning performance framework as a rubric to measure 3rd-grade students mechanism-based scientific explanations generated from the models they developed prior to and after a long-term plant curriculum enactment. Findings from the learning performance highlight that students hold conceptual knowledge about plant processes and use this knowledge to reason in sophisticated ways. However, our findings from the pre/post-models suggest that when students do not have opportunities to build conceptual knowledge, they depend on anthropomorphic analogies to reason about plant processes. Study findings imply that 3rd-grade students require more sophisticated opportunities in building knowledge about how and why plant processes occur so they can use this knowledge to scientifically reason about how and why plants grow, develop, and survive.

Introduction and Rationale

Plant growth and development is highlighted throughout K-12 science curriculum and has been identified as a core element for understanding global biological issues in the 21st Century (American Association for the Advancement of Science [AAAS], 2007; Next Generation Science Standards [NGSS] Lead States, 2013; National Research Council [NRC], 2011). Building this foundation in elementary science learning environments is especially critical as there is indication that if early learners' natural curiosity about plant life is not nurtured, it may disappear by the upper grade levels (NRC, 2011; Wandersee & Schussler, 1998). Wandersee and Schussler (1999) have identified this as *plant blindness*, or diminished awareness of, knowledge about, and interest in plants as core components of natural systems. To build on this natural curiosity and interest, elementary students require opportunities to scientifically reason about how and why plants grow, develop, and survive (NGSS Lead States, 2013). To support students in developing conceptual understanding and reasoning of this core biospheric systems, elementary students require opportunities to build and use knowledge of concepts through scientific activity (Krajcik, McNeill, & Reiser, 2007).

Core scientific activities are defined through the scientific practices articulated by the *Next Generation Science Standards* (NGSS Lead States, 2013) which include the practices of modeling and scientific explanation construction. Here, we examine the ways in which elementary students build knowledge about plant processes through both practices. Students construct models that focus on key system processes to make hidden elements explicit and visible, which include the elements necessary for a scientific explanation – the cause, effect, and underlying mechanism. In this manner, models have explanatory power as they are visual representations of the explanation for how and why the process behaves as it does (Bechtel & Abrahamsen, 2005; Gilbert, Boulter, & Rutherford, 2000). We identify scientific explanations derived through the practice of modeling as model-based explanations.

To identify the ways in which U.S. 3rd-grade students (age 8-9) build knowledge through developing model-based explanations about plant processes, we have engaged in design-based research (Shin, Stevens, & Krajcik, 2010) to ground an empirically-based, domain-specific learning performance (Krajcik et al., 2007). The learning performance integrates discipline-specific content of plant reproduction, growth and survival processes with mechanism-based epistemic features of model-based explanations (Authors, 2015; Schwarz et al., 2009). Learning performances, situated within the learning progression research, are a micro-level focus on crossing a "big" idea with a scientific practice over a single curricular unit within a single grade band (Krajcik et al., 2007). The questions guiding this study are:

1. What are identifiable and measurable features of students' model-based explanations of plant structure and function and the plant life cycle?
2. In what ways do 3rd-grade students conceptualize and formulate model-based explanations about plant structure and function and the plant life cycle?

Theoretical Framework and Background Literature

This study is framed by two bodies of theory and research. First, we draw upon theoretical and empirical research to define model-based explanations. Second, we leverage prior research on elementary students' conceptual understanding of plant process.

Model-Based Explanations

Within science learning environments, students develop, use, evaluate, and revise models for explanatory power (Bechtel & Abrahamson, 2005; Sensevy, Tiberghien, Santini, Laube, & Griggs, 2008; Sandoval & Reiser, 2004). When their expressed model includes the essential elements of the phenomenon, then the model has explanatory power and serves as a reasoning tool for students to bridge between their concrete observations and the underlying theories of how and why the phenomenon occurs (Bechtel & Abrahamson, 2005; Coll &

Lajium, 2011; Gilbert et al., 2000). Models hold explanatory power when the student both includes and identifies the cause, effect and nonvisible underlying mechanism central to the process in nature, makes these elements visible within the developed model, and understands the abstract relationship between the physical world and the developed model. The expressed model, then, becomes the student's conceptual understanding of the explanatory process they have determined through participating in the modeling activity (Coll & Lajium, 2011; Gilbert et al., 2000; Sensevy et al., 2008).

Research suggests that not only are elementary students able to develop models with explanatory power and understand the relationship between the model and the physical world, doing so is critical to their scientific learning because it lays the conceptual foundation for discipline-specific reasoning skills and builds on students' interest of how and why elements they have observed occur (Coll & Lajium, 2011; Duschl, Schweingruber, & Schouse, 2007; Manz, 2012; Metz, 2008). We examine students' model-based explanations through five epistemic features that seek to identify how students take a mechanism-based perspective of model-based explanations (Scientific Practices Group, n.d.). By epistemic features, our intent is to define "…what counts as valued and warranted scientific knowledge" (Sandoval & Reiser, 2004, p. 348). The epistemic features, defined in Table 1, are grounded in theory and research on generating explanations through the practices of modeling (e.g., Authors, 2015; Gilbert et al., 2000; Schwarz et al., 2009) and serve to examine students' conceptual and epistemic knowledge-building about plant processes within the practices of modeling.

Table 1

Mechanism-Based Perspective of Model-Based Explanations

Epistemic Feature	Description
Components	The elements represented in the model
Mapping	The relationship the modeler identifies between their representation and the physical world

Sequence	The recognition of connections and relationships between the represented elements
Explanatory Process	The causal mechanism underlying represented cause and effects
Scientific Principle	The underlying scientific law of the represented process

The *components* that students choose to include in their representations identify their conceptualizations of the process. In prediction models, this is students' prior knowledge about processes and the elements they conceive as essential for how and why the process behaves (Bechtel & Abrahamsen, 2005; Gilbert et al., 2000). Model-based explanation models are extended from evidence and based on new knowledge (NGSS Lead States, 2013; Sensevy et al., 2008). *Mapping* is the student's understandings of the relationship between the explanatory power of the model to the physical world (Coll & Lajium, 2011; Sensevy et al., 2008). The student demonstrates an understanding that the model is making the concrete abstract and that the process occurring on the model includes hidden elements that also exist in nature. This may be expressed as a verbal analogy to show how and why the represented process occurs (e.g., comparison of plant stems to straws that draw water up for the plant) or symbols they use on their models to show connection to the physical world (e.g., showing faces on seeds to indicate they are living and will germinate). In either case, it is an extrapolation from the model to the physical world (Sensevy et al., 2008). *Sequences* are the recognition of connections and relationships within a process. These may be either verbal expressions in discussions about the model or are symbols on the model that demonstrate one element produces change in another element. The connection between elements implies the presence of a mechanism that is responsible for the cause and effect (e.g., plants receive water → plants grow). In this manner, well-defined sequences provide explanatory power to the model (Bechtel & Abrahamsen, 2005).

Explanatory process is the explicit identification of the explanatory power of the model in which the student identifies causes, effects and underlying mechanism(s) that are crucial to the process under study. Students articulate what is occurring (e.g., water makes the tree grow), how it is occurring (e.g., the tree absorbs water through its roots) and why this occurs (e.g., water is food for plants so the tree can grow and survive; Gilbert et al., 2000). Finally, the *scientific principle* is the articulation of the theoretical rules underpinning the process such as the identification of the actions (e.g., photosynthesis) that the model demonstrates. Within this feature, the student connects their representation to the theoretical principle that the model serves to explain (Bechtel & Abrahamsen, 2005).

Elementary Students Biological Knowledge of Plants

Elementary students arrive to the science learning environments with conceptions about plant processes that they formed prior to formal schooling (Inagaki & Hatano, 2002; Carey, 2004; Vosniadou, 2007; Wellman & Gelman, 1992). These prior conceptions are considered naïve biological theories because they are built from every-day-experiences with visible observations such as rain falling down and plant life coming up from the ground (Barman, Stein, McNair, & Barman, 2006; Canal, 1999; Jewel, 2002). These every-day-experiences include incorporating knowledge based on what they understand about themselves so their reasoning about scientific phenomena is situated in an anthropomorphic stance.

Young children know that they need to eat, drink and breathe to stay alive, so it is a natural extrapolation that a plant also needs to eat, drink and breathe to stay alive (Inagaki & Hatano, 2002; Wellman & Gelman, 1992). Students then use these heuristics daily to problem-solve about phenomena they observe in the world around them which makes these naïve theories highly functional and quickly retrievable (Carey, 2004; Vosniadou, 2007). Therefore, when students are asked to consider cause and effect with underlying mechanisms for concepts in which they do not have prior knowledge, they will depend on these heuristics to attribute an agent or agency that is causing the complex system to function (e.g., rain comes down to the ground so plants can drink) which they have extrapolated from their naïve psychology complexes (e.g., when I get thirsty, I drink) (Inagaki & Hatano, 2002; Wellman & Gelman, 1992).

Early learners categorize these naïve theories into explanatory models (Carey, 2004; Vosniadou, 2007) in which they lump together things that are similar based on how things work in the natural world that they can then link and use to extrapolate to new objects with similar patterns. To challenge naïve theory, students require engagement in epistemic activity that make them aware of their prior knowledge and provides opportunities to observe and understand the explicit links between cause, effect, and mechanism (Vosniadou, 2007). Scientific knowledge builds when the learners' naïve theories are restructured because they have been able to make sense between their observations and the unseen underlying causal mechanism.

However, widely available elementary science curriculum materials typically do not provide opportunities for students to examine their prior knowledge in light of new knowledge (Metz, 2008). For example, within elementary science learning environments, hidden elements of the plant life cycle are not made explicit and the materials do not provide coherence between seed germination, mature plant, and seed development (Schussler, 2008). Rather plant growth and development is typically identified in stages that appear in bursts without acknowledging spatial or temporal boundaries of growth and development or abiotic factors such as water in the soil, temperature and air that are essential for the successful growth of plants (Barman et al., 2006; Canal, 1999). Yet a small research base suggests that when discipline-specific content is embedded with epistemic activity, elementary students may restructure their knowledge and build sophisticated understandings about plant growth and development (Authors, 2014; Manz, 2012; Metz, 2008). For example, they engage in design experiments to consider the connection between biotic dependency for seed dispersal and how and why seeds may arrive at their planted spot (Metz, 2008). And when asked to make sense of their data and evidence they identify connections between, water storage in the soil, root stability, and gravity to make sense of how and why roots grow down into soil (Authors, 2014). While there are very few research studies examining elementary students' scientific reasoning about plant life, these studies suggest that if content is interlaced with scientific practice such as modeling, then students are more likely to understand how and why phenomenon occur.

Learning Performance Development

This is a design-based empirical research study grounded in *construct centered design* ([CCD] Shin et al., 2010). The design is context dependent (i.e., the classroom) and evaluated and refined based on experiences occurring within the learning environment. This iterative nature of designed-based studies is crucial to translating a theory-driven learning performance into practice through the constant evaluation and refinement of the design within the classroom. In this manner, theory and practice are interwoven with each other so the final product is both based in theory but also relevant to practice.

Step 1: Select and Define Construct

From a review of available standards, we identified and defined the "big" idea as *plants are organisms that are composed of natural wholes which consist of many interacting processes that comprise a system* (AAAS, 2007; NGSS Lead States, 2013). The defining features of a system are that they maintain stasis through a cause and effect feedback loop in which there may be more than one causal mechanism underlying the loop. For example 3rd-grade students should be provided opportunities to understand that on a micro-level, water concentration in the soil determines how well the plants' root structures perform their functions. This affects the plant on the macro-level through determining whether or not it can maintain its life cycle (NGSS Lead States, 2013). Finally, students should also recognize that changes with available water supplies that occur on the macro-level, such as droughts, affect the micro-level of plant function.

To identify and measure the ways in which students engage with the "big" idea, we identified all relevant standards within the *Next Generation Science Standards* (NGSS Lead States, 2013) and the *Science Literacy Maps* for *Project 2061 Benchmarks* (AAAS, 1993, 2007). Unpacking the standards resulted in two foundational concepts about plant growth and development for 3rd-grade: (1) plant structures and functions for growth, survival, behavior, and reproduction; and (2) life cycles which include growth from seed to adult that produces seeds which are dispersed due to wind, water or animals, then death of adult and seedling growth (AAAS, 1993, 2007; NRC, 2013). We labeled these target concepts as (1) plant structure and function (PSF) and (2) plant life cycle (PLC).

Step 2: Create Claims through Development of a Theoretical Learning Performance

Target explanations that identify the grade-appropriate cause, effect and underlying mechanism for the core concepts were defined and aligned with the five features of the mechanism-based perspective of model-based explanations (see Table 2). This theoretical learning performance is a standard component in learning performance development as it provides the starting point for examining student understanding about this big idea through the use of modeling. The theoretical learning performance is situated in model-based explanations (Gilbert et al., 2000; Coll & Lajium, 2011; Schwarz et al., 2009), conceptual understanding of plant growth and development (Authors, 2014; Jewel, 2002; Manz, 2012; Metz, 2008; NGSS Lead States, 2013); practice-based learning performances and progressions (Authors, 2015; Krajcik et al., 2007) and scientific standards (AAAS, 2007; NGSS Lead States, 2013).

The target explanations for the theoretical learning performance are presented in Table 2. The theoretical learning performance was submitted for external review, comment, and evaluation by experienced researchers in learning performance development and in plant biology.

Table 2

Target Learning Performance for Plant Processes

	Concept 1: Plant structures/functions	Concept 2: Plant life cycle
Target Explanation	Structures serve specific functions in the presence of nutrients, sunlight, water, and air (oxygen) so that the plants grow, survive, and reproduce because plants are living organisms. If one of the structures is missing or does not perform its function then the plant will die because the system is not working correctly.	Plants undergo a life cycle which includes birth (seed germination), development, and death because plants are living organisms. Through offspring, the life cycle returns to a starting state so the species lives even though the individual plant may die.

Step 3: Specify Evidence and Define Student Tasks

We embedded the modeling lessons with modeling tasks within a pre-existing curricular unit, *Structures of Life* (SOL) Investigations 1 and 2 (FOSS, 2009). This unit was chosen because it addressed plant growth and development beginning at seed dispersal and growth and concluding with observations of fruit and mature plants. The curriculum focuses on hands-on activities and experiences to foster student understandings of plant structure and function and plant life cycles but does not substantially engage students in scientific explanations and/or the practices of modeling (Authors, 2014; Metz, 2008).

Embedded modeling lessons with modeling tasks. All modeling lessons were observed and recorded. They occurred towards the beginning of first investigation (pre-model), in between the first and second investigation (mid-model), and at the end of second investigation (post-model). This study focuses on the pre- and post-model data. The lessons and tasks were aligned with the FOSS lesson structure and supported teachers in engaging their students in model-based explanation construction about plant growth and development.

The lessons included background knowledge for teachers on the practices of scientific modeling and provided questioning prompts to ask students during discussions about the practices of modeling and how to support students' in model-based explanation construction. The modeling tasks were designed using the learning performance framework (Table 2) as a guide.

Each modeling lesson was identical and began with the teachers holding whole class discussions to elicit students' ideas about what might be a model. As the discussion occurred, the teachers asked their students to explain their thinking about why or why they identified models, how the students think scientists use models, and what is a model and what does a model look like. These ideas were recorded on the whiteboard and then referred to throughout the classroom discussion to support students in thinking about models as ways to simplify complex processes and that modeling is a continuous process, and that models may exist in a variety of forms.

Students were then asked to develop a 2-D model using pencils in response to the question *'how does a seed grow?'*. Once their models were drawn, they wrote responses to a series of reflective questions designed to elicit the epistemic considerations that comprise the mechanism-based explanations that accompany their models: a. *What does your model show happening to a seed?*; b. *Why do you think this happens to a seed?*; c. *What have you seen that makes you think this is what happens to a seed?*; and d. *How would you use your model to explain to others how a seed grows?* In addition, after the second and final supplemental modeling task the students were instructed to examine their prior models and evaluate their models for the ways in which their thinking changed since completion of the last modeling cycle.

SOL Curricular enactments. All SOL curricular enactments were observed and video-recorded. Investigation 1, *Origin of Seeds* took three weeks to complete across all participating classrooms. The investigation begins with students introduced to the idea that seeds are located in fruits. Students dissect a green bean to observe that the same kinds of fruit contain the same kind of seed and discuss that seeds only grow the fruit from which they originated. They then dissect a variety of fruits to compare seed size, number, and characteristics to observe and discuss why seeds from different fruits are not identical. Students then place a variety of seeds in a wet chamber and watch seeds germinate over the course of a week to support their understanding that seeds are living organisms that "undergo changes in the presence of water" (FOSS, 2009, p. 55). Last, they either search for seeds in the school yard or are provided a variety of seeds in their classroom to discuss how seed dispersal occurs with an emphasis on wind, water, and animals.

Investigation 2, *Growing Further* took 6 weeks to complete across all participating classrooms. Students compare the rate of germination and the order the structures appear from the germinating seed across four different seeds (bean, pea, sunflower, and corn). They collect data daily on germination and plant structures that are emerging from their seeds and identify that plants need "water, light, space, and nutrients" (FOSS, 2009, p. 105) to grow. They examine and discuss the seedling seed coat, embryo, and cotyledon and observe the plant grow throughout its life cycle using hydroponic chambers.

Methods

Purposeful sampling (Patton, 2001) was used to select three 3rd-grade classrooms (n = 73 students) from a Midwestern State that would be information-rich within time and resources available (Miles & Huberman, 1994). Sampling took into consideration the teachers' use of the SOL materials, their prior experience with the practices of modeling, and elementary classroom experience. All three teachers have used the SOL curriculum materials for 2 years and have between 21 - 23 years of experience in the elementary classroom. Finally, in the summer before this study, all three teachers participated in a week-long professional development workshop on the practices of modeling to build their knowledge about modeling complex systems in the elementary classroom (Authors, 2015).

Students were purposefully-sampled (Patton, 2001) from each classroom in collaboration with project teachers for clinical interviews (n = 15). The student sampling approach was an attempt to balance between maximum-variation sampling (Patton, 2001) identified here as high-achieving students and low-achieving students, as determined by the teachers, and typical case sampling (Patton, 2001) of students representative of the population as a whole. Time was allotted to interview five students from each classroom. The same students were interviewed over the course of the study for consistency.

Data Collection

Collected data includes student modeling artifacts, classroom observations, and student interviews.

Student modeling artifacts. Student packets (n = 73 per time point; n= 146 total) were collected after the pre- and post-model. All student identification was removed from the models and associated writings and unique identification numbers were assigned that link the models to the classroom and lesson.

Student interviews. Students were interviewed about their models at the pre- and post-model time points (n = 15 students per time point; n = 30 total). The clinical interviews followed best practices (e.g., Patton, 2001) and specific recommendations for developing trust and rapport with children of this age level (Westcott & Littelton, 2005). The student interview protocol was based on the students' generated models and designed to elicit, through open-ended questions, the five epistemic features of students' model-based explanations about PSF and the PLC. While the student interview protocol was semi-structured (Patton, 2001) the interviews were tailored for each student so that they were grounded in the student models (Westcott & Littelton, 2005). Interview questions included:

What do you think happens here?", "How do you think this happens?" and "Why does this happen?". All interviews were audio-recorded and transcribed verbatim. The interviews were assigned unique identification numbers that aligned with the student model so interviews and models were matched.

Qualitative analysis. The interviews were batched by time (pre- and post-model) and coded for *a priori* codes using classical content analysis (Patton, 2001) for each of the two concepts. Qualitative analysis involved an iterative process of data coding, displaying and verification (Miles & Huberman, 1994) to identify themes within the interviews that provided insight into the students' articulation of the two concepts. Reduction and isolation of text continued until all the emerging patterns were illustrated and dominant themes were refined and substantiated.

This data then went through a second coding round for the *a priori* codes of the five *mechanism-based epistemic features* (*components, mapping, sequence, explanatory process*, and *scientific principle*) within each individual concept. Analyses focused on the identification and articulation of four measureable levels (0 to 3) of students' model-based explanations. The empirical grounding of the levels was an iterative process between the empirical findings and the theoretical learning performance to fine-tune the learning performance so that it captured students learning about plant processes. Once the learning performance was grounded, further qualitative analysis occurred to identify themes within 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.

Qualitative validity occurred through data triangulation of sources and data review by independent researchers (Miles & Huberman, 1994; Patton, 2001). Multiple data sources (e.g., student interviews, student associated models, and student reflective writings) were used in the analysis to look for consistency across sources. Further, all findings were reviewed by another independent researcher who coded 13% (n = 3 interviews at each time point; n = 6 total) of the data to establish inter-coder reliability. Inter-coder reliability was calculated as 95% and reached 100% after discussion (Miles & Huberman, 1994).

Quantitative Analysis. After the hypothetical learning performance was grounded through the qualitative analysis, it was used as a rubric for quantitative analysis to score all models. The rubric was situated in the analytical framework of the five mechanism-based epistemic features in which each feature became a "scoring tools for quantitative rating of authentic or complex student work" (Jonsson & Svingby, 2007, p. 131). As such they provided a scaled measure of students' engagement in the mechanism-based features within the three identified concepts. This rubric allowed for examination of the learning performances for all students' modeling and associated written work at four levels of sophistication (Levels: 0 – 3).

At the zero level, the dimension is not exhibited in students' ideas about the concept; at level one the students understanding of the process is simple and may only be a description of visible elements; level two identifies a higher level of complexity within their understanding of the process; and level three is the full articulation of the complexity including cause and effect of both hidden and visible elements with underlying mechanism. The levels are not hierarchical *per se*; but rather the lower levels are simpler parts of the higher levels. The rubric was evaluated prior to use for interrater reliability (Jonsson & Svingby, 2007) to determine the reliability and consistency. Inter-rater reliability was completed by having two researchers score 10% (n = 15) of the total number of models (n = 146) using the rubric. Cronbach's alpha was calculated at 0.819. A reported alpha value of 0.7 is considered sufficient for quantitative inter-rater reliability (Jonsson & Svingby, 2007).

All scores were imported into SPSS for statistical analysis. The statistical analysis was a multi-level mixed model ANOVA (Littell, Milliken, Stroup, Wollonger & Schabenger, 2006). The levels included time (pre- and post-model), student, and teacher. Pre- and post-models were nested per student and students were then nested within their teachers. Since there is nesting for each teacher, teacher differences such as school location, experience, and enactment differences are accounted for through identifying the different teachers within the data display in SPSS.

Findings

Below we present our findings in two groups. First, we use examples from the *components* and *mapping* features to provide evidence of the complexity of the levels of sophistication present in the students' model-based explanations. Second, we present the findings from the model scoring and qualitative themes to address the research questions.

Empirical Grounding of the Learning Performance

The identified levels for all five epistemic features are presented in Table 4. Below are examples of the empirical grounding for each concept.

***Component* Examples for PSF.** At level one the students only considered visible components, such as plant structures. As seen in Katherine's description of her model where she identified the elements on her representation as: "This is the seed and it has roots" (Ka.AmM1). This was identified as level 1 because both elements are visible and are easily observed with the naked eye. When students whose models scored a one for components were asked why they choose their elements to represent, they identified that these elements were necessary for growth but not how or why they were necessary. Their discussions about their models only described the items present on their drawing and did not indicate that this was a process or relationship for growth or survival.

At level two, students included observable components, the necessity of these components, and also incorporated one non-visible component. Non-visible components include those which require activity to become visible such as: "around the seed is a….seed cover. Just to keep it safe…it can protect it" (Ka.AmM1). The student is discussing a non-visible element of a seed (the seed coat) as it only becomes visible after germination with its associated function. Non-visible components also included those below ground such as roots and non-visible elements around the plant such as oxygen.

At level three, the components students represented were the upper anchor for the learning performance as they included visible and non-visible essential components essential to PSF. As Lexi stated using her model:

> [the seed] gets roots first is so it can get water to grow all the other parts. The roots are to get the water to the plant…once they [the germinating seed] grow leaves the leaves help them get sunlight, to make food. The stem like [sic] helps support it, and it brings the water up to the leaves to make the food." (Le.HiM3).

Lexi identified structures (roots, leaves, and stem) with associated functions (germination, energy manufacture, and water distribution). In addition, the identification of multiple structures with functions resulted in a model-based explanation that included a cause: roots distribute water; effect: plant grows other parts including leaves and stem; with mechanism: energy (food) production for survival.

***Mapping* examples for the PLC.** The mapping feature identified the ways in which students connected their models as representations to the physical world. At level one mapping, students identified their models as mimics of the observable world and did not engage in model-based explanations. For example, when Ginny was asked to talk about her model, she identified that "The dots in the banana equal seeds." (Ev.TM1) but did not further identify that this occurred in nature nor discussed the banana or seeds any further. Results indicated that even when students included non-visible elements that were critical to reasoning about the process such as roots or seeds below ground, if they did not identify how their representation represented plants in the physical world, they did not use their models for explanatory power. Identified relationships were only in relation to their drawing such as "This is a seed. This is a plant" (Ev.EM1).

Mapping at level two occurred as students extrapolated from their representations to express the larger process. For example, Vivian drew only the stages of a tree growing from seed to adult (Figure 2). When she discussed her model she stated "My model shows a little plant going through the whole [life] cycle and will become a seed again" (Vi.HM1). While she did not include seed propagation on her model, she extrapolated from her model the causal mechanism for why plant processes occur in a specific manner. Students also used symbols on their models that identified activity that they understood occurred in nature. For example, Zack identified that lines on his model represented activity such as "all these lines stand for absorbing. Like these lines like tell you that it's [roots] absorbing water" (Z.NM1). He included that the activity on his model was also occurring with the large trees in the school yard. He stated that the tree on his model was absorbing water so that "it can grow like that tree [outside]. Like if we go over here by the door [door with a window to the front of the school yard]…the trees get all of this stuff [indicated on his model]" (Z.NM3). Zack engaged in mapping through identifying the activity represented on his model connected to the activity occurring with the trees in the school yard.

Figure 2. Vivian's model.

At the third level, students identified that their models were representations that connected how and why plant processes supported the plant for growth and survival. For example this occurred through Alyssa's discussion that her model represented more than just the stages a plant goes through for the life cycle:

I: What does your model show?

S: The flower that had this seed dies and then this seed starts the whole cycle over again… A seed needs a cycle just like we need a cycle…We start off as a baby and then we get older and then we uh um…we have babies if we want then and then the babies have babies and so-on and so-on (Aa.WM2)

Alyssa used an analogy to articulate that her model represented a plant life cycle that occurred in nature (the "seed starts the whole cycle over again") and she also generated a model-based explanation through how this occurred (reproduction) and why this occurred (so the species survives).

Table 4
Learning Performance

Feature	Level	Plant Structure and Function (PSF)	Plant Life Cycle (PLC)
Component	0	No plant life is represented	No plant life is represented
	1	Structures are represented. Functions are not represented	Visible plant life is represented. Seeds are present but their origin is unknown and/or not represented
	2	Structure(s) with at least one function is represented	Germination through adult plant life is represented. Seed origin is represented as coming from plants
	3	More than one structure with its associated function is represented. The multiple functions can be with the same structure or different structures with their function(s)	All components to represent the life cycle of a plant are represented above and below the ground. Includes seed, sprouting seed, adult plant, seed pods coming from plant, and sprouting seed falling from plant
Sequence	0	No sequences are considered	No sequences are considered
	1	Sequence describes a simple relationship between visible plant structures	Sequence describes a simple relationship of visible elements of the plant cycle that occurs in a prescriptive order
	2	Sequence describes an associative relationship chain between plant structures and their functions that is associative and includes visible and non-visible elements	Sequence is an associate relationship chain within the plant cycle so that one part of the cycle is related to another part of the cycle and includes visible and non-visible elements
	3	Sequence is a causal relationship chain between visible and non-visible PSF that occurs within a cycle.	Sequence is a causal relationship chain that exhibits a full plant cycle with visible and non-visible elements from seed growth to adult to seed production and dissemination.
Explanatory Process	0	No causal mechanism is indicated	No causal mechanism is indicated
	1	Student links a causal mechanism for structure and function but does not include an understanding of how or why the causal mechanism occurs.	Student links a causal mechanism for the plant life cycle but does not include an understanding of how or why the causal mechanism occurs.
	2	Student links a causal mechanism for structure and function and includes how this causal mechanism occurs	Student links a causal mechanism for the plant life cycle and includes how this causal mechanism occurs
	3	Student links a causal mechanism for structure and function and how and why causal mechanism occurs	Student links a causal mechanism for plant life cycle and includes how and why this causal mechanism occurs
Mapping	0	No relationship is identified	No relationship is identified

	1	Student identifies structures present on the model	Student identifies stages of a plant life cycle present on the model
	2	Student identifies structures with associated functions that provide a rationale for how the function is occurring. The relationships between the model and the physical world is not fully realized	Student identifies a plant life cycle with a rationale for how the life cycle occurs. The relationships between the model and the physical world is not fully realized
	3	Student identifies and provides an evidence-based rational for the represented structure(s) and function(s) that identifies a relationship to the physical world	Student identifies and provides an evidence-based rationale for the plant life cycle that identifies a relationship to the physical world
Scientific Principle	0	No scientific principle is considered	No scientific principle is considered
	1	Student may name a scientific principle associated with PSF but does not have an understanding of how the scientific principle applies	Student may name a scientific principle associated with the plant life cycle but does not have an understanding of how the scientific principle applies
	2	Student includes part of a scientific principle for PSF but it does not completely address the phenomenon	Student includes part of a scientific principle for plant life cycle but it does not completely address the phenomenon
	3	Students includes all components of the scientific principle that address PSF	Students includes all components of the scientific principle that address the plant life cycle

Identifiable and Measurable Features of Model-Based Explanations

In research question one we asked '*What are identifiable and measurable features of students' model-based explanations of plant structure and function and plant life cycle*? This research question is examined through the scoring and statistical analysis of the models.

Identifiable and Measurable Features. There was statistically significant growth within students' engagement in the epistemic features within the pre- and post-models.

PSF. Results show statistically significant differences between pre- and post-models, $F(1, 140) = 6.243$, $p = 0.000$ (Figure 3) suggesting that the students overall engagement with model-based explanations increased from the beginning to the end of the unit. However, the analysis of the individual epistemic features identified that this growth is attributed to the *components* feature (see Table 5). While *scientific principle* also measured as statistically significant (see Table 5), the averages in the pre- and post-model scores are so small, minor growth within the post-model appeared as statistically significant.

PLC. There was also statistically significant growth from the pre- to post-unit models, $F(1, 140) = 24.621$, $p = 0.000$. Results indicate statistically significant growth in all five features from pre- to post- models with the exception of *scientific principle* (Table 5). The growth indicates that students' post-models included more *components*, connected the components in meaningful ways (*sequences*), included cause and effect reasoning about their representations (*explanatory process*) and indicated the relationship between their models and the physical world (*mapping*).

Table 5

Data Summary by Mechanism-Based Epistemic Feature for PSF and PLC

	PSF				Mean PLC			
	Pre-Model	Post-Model	*F*	*P*	Pre-Model	Post-Model	*F*	*p*
Components	1.16 (0.37)	1.41 (0.68)	7.31	0.008*	1.63 (0.82)	2.23 (0.73)	29.98	0.000*
Sequence	0.60 (0.70)	0.90 (0.50)	1.73	0.190	1.29 (0.61)	2.00 (0.92)	9.076	0.003*
Mapping	0.90 (0.81)	1.01 (0.85)	0.62	0.431	0.85 (0.75)	1.22 (0.88)	4.435	0.037*
Explanatory Process	0.38 (0.56)	0.55 (0.70)	2.39	0.124	0.42 (0.62)	0.65 (0.70)	21.68	0.000*
Scientific Principle	0.01 (0.12)	0.21 (0.50)	10.2	0.002*	0.16 (0.37)	0.21 (0.49)	0.998	0.320

Note. Within each column, average is presented on top with the standard deviation underneath in parenthesis.
*Significant at $p = 0.05$

Model-Based Explanations about Plant Processes

In research question two we asked '*In what ways do 3rd-grade students conceptualize and formulate model-based explanations about plant structure and function and the plant life cycle?*' Analysis and findings are organized by PSF and PLC.

PSF. While students included essential plant structures such as flowers, leaves, stems, thorns, and roots they did not include how and why these structures occurred or if they performed functions. For example, in Arianna's representation (Figure 3), she has included plant structures above and below the ground and abiotic elements such as rain and rays from the sun. Arianna has shown all the elements necessary to give her model explanatory power about structures and functions. However, in her discussion about her representation, she does not include how or why these identified elements were essential to the growing plant or identify any association between the structures and the abiotic elements. For example, when asked what was occurring on her drawing, Arianna stated it "shows how they [the plant] grow" (An.NM1). When asked if the sun or water does anything to the specific parts she represented she replied, "Um, I don't know. I just know it [sunlight and water] gives it [the plant] food." (An.NM1). She recognized these elements as necessary for plant growth but did not know how or why.

Within this theme students frequently identified *sequences*, but they were prescriptive (i.e., one thing happens and then another thing happens). Yet they did not identify that one thing was dependent on or connected in some way to the other things in which they prescribed. This is seen in Amy's discussion of her model where she describes the emergence of structures during a plant life cycle:

> "First it starts with a seed and then the seed grows roots and then the seed with roots grows a stem and then the seed with roots grows a stem and buds and the seed with roots to the stem grows a flower. And then the flower grows seed pods. And then it goes Rest in Peace [indicates plant death] and then starts from the beginning again." (Av.WM1)

Amy identifies multiple structures within her stated sequence (first this grows, then this grows, and so on) that she has represented. However, within her discussions about her representation, she does not connect how or why the structures are necessary at each stage nor does she identify functions of these structures. Overall, results suggest that the students identified that plant structures were important, but they did not know how why they were important.

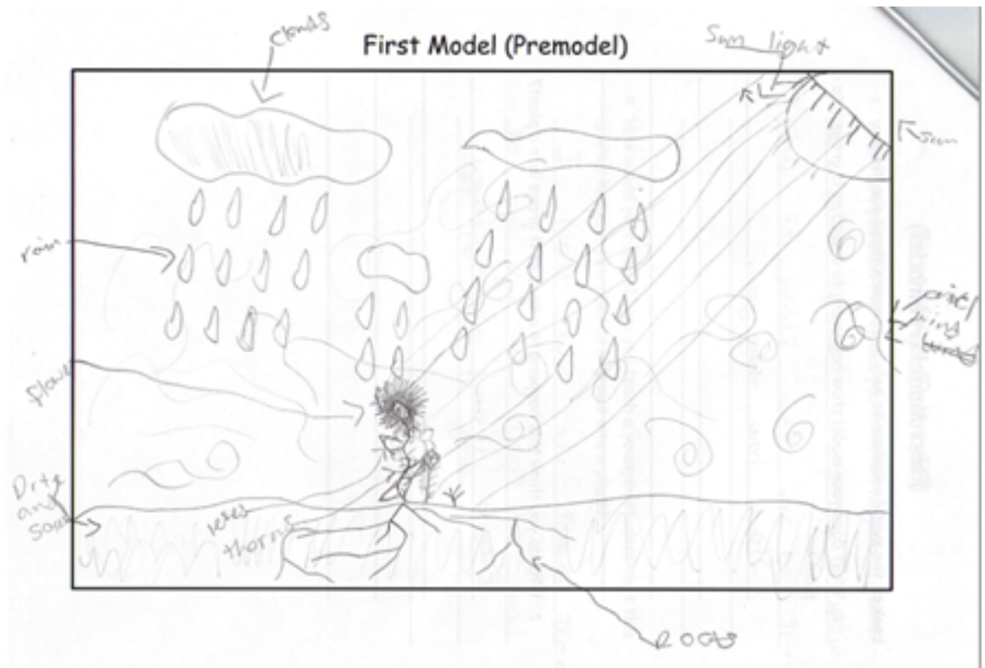

Figure 3. Arianna's model of how a seed grows.

A subgroup within this theme did engage in anthropomorphic reasoning to identify functions as they tried to figure out how water and sunlight enters the plant. To determine how this might occur, they depended on *mapping* statements analogous to themselves:

> The roots try to get to water. I think they try and soak it, like get it, and it's like we take drinks. The roots are kind of like its hands, and the leaves are kind of like its hands to get the sunlight, and to get the water (Le.HM3).

While we found evidence that they relied on anthropomorphic reasoning to understand plant functions, the students also identified within their discussions that they recognized this reasoning was not correct. They would end their discussion by telling us that they knew the plant "doesn't have a mouth" (T.WM3) and "doesn't have hands" (H.HM3) but they also identified they did not know how else these structures might work.

PLC. Overall, students typically articulated the target explanations about PLC. For example, in Alicia's model and her discussion about her model (Figure 4):

Alicia: On my…model I put I colored the seed to make it look like a black watermelon seed.

I: What have you noticed about seeds?

Alicia: Seeds are different because some have like an oval shape and some have like a circle shape and some have different colors, some are hard and some are squishy.

I: Why do you think seeds are different?

Alicia: If they all looked the same we might only have one apple…like only one apple plant in our whole world and that wouldn't be enough to keep us full with food. (A.WM2)

Between Alicia's model and her discussion using her model, she has engaged in all five epistemic features: seed, sprouting plant, and adult plant with seed production (*components*), identifying that plant stages are linked (*sequences*), identifies a relationship between her model and the physical world through her example of a "watermelon seed" (*mapping*), an *explanatory process* cause and effect (seeds look different because they come from different kinds of fruits) with an underlying mechanism (fruits grow from seeds), and the *scientific principle* that different seeds grow different fruits.

However, within the sophistication of the model-based explanations about the PLC, we also found that students encountered difficulties when determining seed origination. When Alicia was asked (Figure 4) where the seed she drew in her first column on the left came from, she stated "No idea" (A.WM2). Other students relied on anthropomorphic reasoning to identify where seeds initially originate before entering into the plant life cycle. For example when Tony was asked where his seed came from, he responded "[The seed] came from a maybe a store…people bury them." (Le.HM3). This response was common across the interviews.

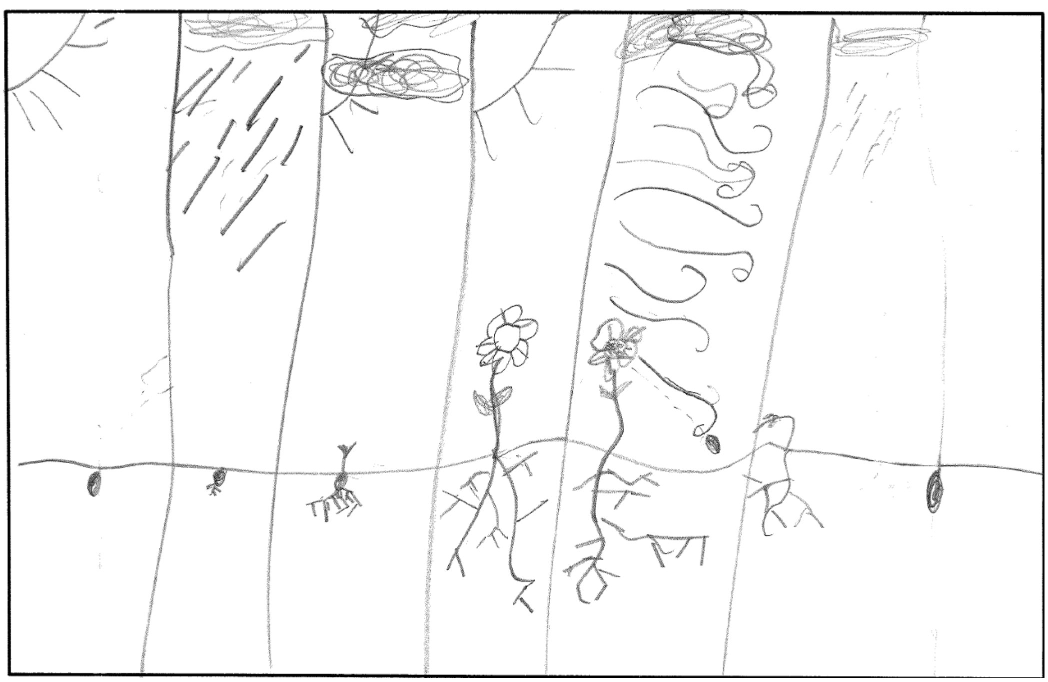

Figure 4. Alicia's model of the plant life cycle

Students also represented and discussed that humans were responsible for caring for the seeds once they planted them (Figure 5). They identified that humans must water seeds so they are no longer dormant and humans must choose sunny spots to place the seeds so when the seed sprouts, it would have adequate access to water, sunlight, and air. However, students also recognized that once the seeds began to sprout then the life cycle begins without further human intervention. Overall, students did not hold conceptual understanding that the initial seed they drew on their model also came from a plant. They understood that the plant cycle was a continuing process, but they conceptualized that it began when a human started it.

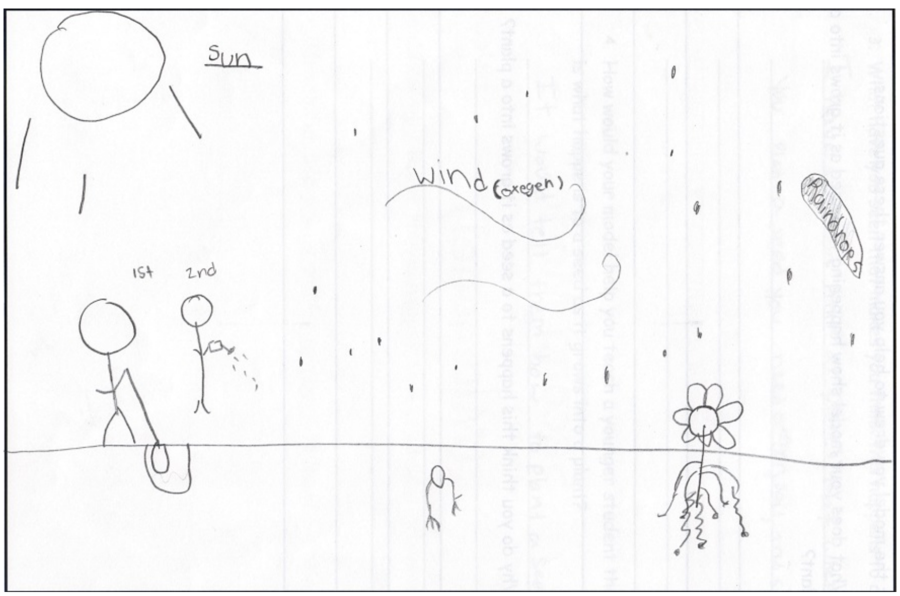

Figure 5. Tatum's model of seed origin.

Summary

The learning performance for PLC and PSF were empirically grounded across all identified levels (0, 1, 2, and 3) for each epistemic feature through student clinical interviews situated in their developed models. We found a wide range of sophistication and complexity in students' articulation of model-based explanations. Once the learning performance was empirically grounded, it was used as a scoring rubric for the students' models. The results from model scoring show 3rd-grade students engaged in the features of model-based explanations about the PLC more so than PSF. With the exception of *components*, students engagement with the epistemic features of PSF in either pre- or post-models did not typically identify how or why structures and functions were necessary for plant life. The qualitative analysis provided insight into the quantitative findings. Students did not hold conceptual knowledge about the functions that plant structures perform but did hold conceptual knowledge about how and why plants require a life cycle. Yet, while students engaged with sophisticated reasoning about PLC, they depended on anthropomorphic reasoning to identify how seeds began growing (humans plant and water them) so the seed could enter its life cycle.

Synthesis and Discussion

Both discipline specific knowledge of plant growth and development and the scientific practice of model-based explanations are highlighted for K-12 learning across the U.S. science standards (AAAS, 2007; NGSS Lead States, 2013). While there is a substantial alternate conception research base about plant growth and development (Barman et al., 2006; Canal, 1999; Jewel, 2002; Wandersee & Schussler, 1999), this research was frequently performed using pencil and paper tests on content knowledge separate from scientific (NRC, 2011). While this research built an important foundation within student conceptual understanding, the field now requires research engaging students in building knowledge through activity to understand *how* they use the scientific practices to build upon their knowledge and support their developing conceptual understanding of scientific phenomena (Duschl et al., 2007;Krajcik et al., 2007; Vosniadou, 2007).

Students' Conceptions of PSF and PLC

First, students' demonstrated a wide range of conceptual understanding about plant processes. The study results indicate that, overall, 3rd-grade students represented and articulated scientifically acceptable understandings intertwined with naïve biological theory about how and why plants grow, develop, and survive. This mixture was most prevalent in PSF. While the curricular materials were explicit in plant structures, plant functions were implicit through identifying that plants need water and sunlight.

As the cognitive development literature has suggested (e.g., Carey, 2004; Vosniadou, 2007), and as evidenced here, in the absence of knowledge about how and why plant functions occur, the 3rd-grade students' depended on prior knowledge to reason about how and why plants "eat" and "drink". Within the elementary grades, prior knowledge is situated in an anthropomorphic stance, since early learners have a wide knowledge base of themselves on which to draw (Inagaki & Hatano, 2002; Wellman & Gelman, 1992). The overall findings suggest that since the 3rd-grade students did not have conceptual knowledge of how and why structures functioned, they applied anthropomorphic characteristics gathered from their prior knowledge of themselves to understand plant functions.

However, in the post-models, students also acknowledged that they knew this comparison to themselves was not correct, but identified that they did not have knowledge about plant function with which to fill in the missing information. Recognition that their reasoning was not correct indicates a "metaconceptual awareness"

(Vosniadou, 2007, p. 55) where conceptual understanding has opened to include recognition that there are other ways, than the one they had previously known, for how and why plant processes occur. This finding highlights both the complex conceptual understanding and reasoning that elementary students are capable of and adds emphasis to the criticality that science learning environments include how and why scientific phenomena occur (Carey, 2004; Metz, 2008). Our results suggest that to support 3rd-grade students in developing conceptual foundations for plant growth and development, they require developmentally appropriate knowledge about what functions plant structures are performing and why they are performing these functions.

Students' Engagement in the *Mechanism-Based Epistemic Framework*

Second, empirical grounding of the learning performance provided evidence that students engage in all five epistemic features of mechanism-based model-based explanations. Further, while engagement at the highest level (level 3) was rare, it was present at least once within each of the individual features for both PSF and PLC. However, there were several key differences within the ways in which students engaged in model-based explanations between PSF and PLC.

As their conceptual knowledge about the PLC developed within the investigations, so did their engagement in the mechanism-based epistemic features of model-based explanations. By the end of the study, findings suggest that students were using their models for explanatory power about the PLC. However, within PSF, we found something different occur. While their understanding of plant structures increased across the investigations, so did their representations for visible and non-visible *components* they identified as necessary for plant growth. Yet while representing these essential components, we did not find they increased their engagement in the other features nor did they identify the explanatory power within their models. Taken together, our results identify that there is a critical relationship between content and process; as knowledge of one builds, so does the other (Manz, 2012; Metz, 2008). When students had to depend on their prior knowledge situated in anthropomorphic reasoning about plant functions, they did not engage in the other mechanism-based features of model-based explanations. This highlights the importance of making hidden elements, processes, and mechanisms explicit and visible otherwise students make intuitive leaps between, for example the connections between structures acting as "human-like" using prior naïve understandings. While this demonstrates their ability to scientifically reason, this also leaves their naïve conceptual understanding unchallenged and thwarts their growth in understanding the utility of scientific practice.

Implications and Conclusion

Prior research suggests that elementary students build epistemic knowledge to support their engagement in critical scientific practices such as model-based explanations (Schwarz et al., 2009); however, the field is just beginning to examine how elementary students engage with this knowledge to reason about scientific content (Authors, 2015, 2014; Manz, 2012; Metz, 2008). Model-based reasoning in the elementary grades builds critical foundations for students' science learning (Coll & Lajium, 2011; Duschl et al., 2007;Manz, 2012; Metz, 2008). Students' developed models serve as a conceptual window into the knowledge they hold and use to reason. In this manner, practices of modeling provide visible evidence of learning and help identify where students' conceptual knowledge may be leveraged or require bolstering (Glennan 2002; Halloun, 2007; NGSS Lead States, 2013). This study extends and builds-upon prior research on model-based science teaching and learning (Authors, 2015; Manz, 2012) and learning-performance-based learning progressions (Krajcik et al., 2007) to provide critical insight into fostering and promoting elementary students' model-based explanations about plant processes.

First, our results suggest that even a small modeling intervention with pre-existing curricular materials about plant growth and development demonstrates growth in conceptual understanding and model-based explanations. Elementary students may enter into the lesson with naïve biological conceptual understanding, but if provided opportunities to make their thinking visible, such as through the practices of modeling, their scientific reasoning becomes sophisticated. They begin to move beyond their naïve biological theory and consider how and why plant functions occur and also come to understand their own knowledge gaps. We suggest that model-centered curriculum materials would provide multiple opportunities for students to engage in sense-making throughout their investigations (Authors, 2015; Schwarz et al., 2009). Engagement in the practices of modeling provides students opportunities to examine their conceptual understanding, use this knowledge to make predictions about how and why processes work, test those predictions, and generate explanations. In this manner they are engaging in sense-making throughout their investigations and opportunities to generate explanations occur throughout the learning environment, rather than at the beginning and end of the curricular unit

Second, the models we collected here show that for 3rd-grade students to successfully understand how and why plants mature through these processes, they require hidden elements of plant growth and development to be explicit and visible throughout their lessons. Students had difficulties in making connections between what plants look like and how and why they function. Implications for this finding include providing students opportunities to examine how and why plant structures are important for plant growth, development, and survival. Plant curriculum materials across K-12 education typically focus on structure rather than function (Barman et al., 2006; Canal, 1999; Schussler, 2008) and key processes are left implicit rather than explicit (Jewel, 2002; Vosniadou, 2007). For example, drawings of plant growth within curriculum materials are frequently identified in unidirectional stages that appear in bursts without acknowledging spatial or temporal boundaries of growth and development or abiotic factors such as water in the soil, temperature and air that are essential for the successful growth of plants (Canal, 1999; Schussler, 2008). As we saw here, when key mechanisms are implicit rather than explicit, it becomes challenging for students to build knowledge of how and why plant structures work and where seeds originate. The employment of the learning performances developed here supported our identification of where curriculum and instruction requires bolstering and hidden mechanisms that need to be made explicit and visible in order to support our future work in plant growth and development model-centered curriculum.

The field has much to learn about how to optimally support early learners to use the scientific practice of modeling to build scientifically acceptable conceptions of and to reason scientifically about biospheric systems. Learning performance development is an emergent research area, so studies are just beginning to describe how they might inform curriculum development or the ways in which teachers might use these pedagogical maps to guide their instruction and practice (Authors, 2015). However, the impact of this line of research is promising. Learning performances provide a means to study the ways in which elementary students engage in scientific activity to build content knowledge. This research provides important insights into future work in how to support 3rd-grade students in model-based explanations about plant processes and where changes and scaffolds to curriculum and instruction might be most effective

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