

Fall 2014

Connections between Student Explanations and Arguments from Evidence about Plant Growth

Jenny Dauer

University of Nebraska-Lincoln, jenny.dauer@unl.edu

Jennifer H. Doherty

Michigan State University

Allison L. Freed

Michigan State University

Charles W. Anderson

Michigan State University, andy@msu.edu

Follow this and additional works at: <http://digitalcommons.unl.edu/natrespapers>

 Part of the [Natural Resources and Conservation Commons](#), [Natural Resources Management and Policy Commons](#), and the [Other Environmental Sciences Commons](#)

Dauer, Jenny; Doherty, Jennifer H.; Freed, Allison L.; and Anderson, Charles W., "Connections between Student Explanations and Arguments from Evidence about Plant Growth" (2014). *Papers in Natural Resources*. 646.
<http://digitalcommons.unl.edu/natrespapers/646>

This Article is brought to you for free and open access by the Natural Resources, School of at DigitalCommons@University of Nebraska - Lincoln. It has been accepted for inclusion in Papers in Natural Resources by an authorized administrator of DigitalCommons@University of Nebraska - Lincoln.

Article

Connections between Student Explanations and Arguments from Evidence about Plant Growth

Jenny M. Dauer,^{*†} Jennifer H. Doherty,[†] Allison L. Freed,[†]
and Charles W. Anderson[†]

^{*}School of Natural Resources, University of Nebraska–Lincoln, Lincoln, NE 68503; [†]Department of Teacher Education, Michigan State University, East Lansing, MI 48824

Submitted February 14, 2014; Revised June 22, 2014; Accepted June 22, 2014
Monitoring Editor: Emily A. Holt

We investigate how students connect explanations and arguments from evidence about plant growth and metabolism—two key practices described by the *Next Generation Science Standards*. This study reports analyses of interviews with 22 middle and high school students postinstruction, focusing on how their sense-making strategies led them to interpret—or misinterpret—scientific explanations and arguments from evidence. The principles of conservation of matter and energy can provide a framework for making sense of phenomena, but our results show that some students reasoned about plant growth as an action enabled by water, air, sunlight, and soil rather than a process of matter and energy transformation. These students reinterpreted the hypotheses and results of standard investigations of plant growth, such as van Helmont’s experiment, to match their own understanding of how plants grow. Only the more advanced students consistently interpreted mass changes in plants or soil as evidence of movement of matter. We also observed that a higher degree of scaffolding during some of the interview questions allowed mid-level students to improve their responses. We describe our progress and challenges developing teaching materials with scaffolding to improve students’ understanding of plant growth and metabolism.

INTRODUCTION

The principles of conservation of matter and energy provide a framework for making sense of phenomena such as plant growth by helping students to identify movements and transformations of matter and energy and to account for all of the atoms and energy in a system (Richmond *et al.*, 2010). The *Next Generation Science Standards* (NGSS Lead States, 2013) identified “energy and matter: flows, cycles, and conserva-

tion” as one of seven crosscutting concepts that students can use as organizational tools as they develop and check their growing understanding. Similarly, *Vision and Change in Undergraduate Biology Education* (American Association for the Advancement of Science [AAAS], 2011) identified “pathways and transformations of energy and matter” as one of five core concepts of a 21st-century biology curriculum.

However, student reasoning about plant growth varies in several ways from this accepted scientific framework based on principles of conservation of matter and energy. It is well documented that students from K–12 to college struggle to explain where the matter comes from that makes up plants. Most students do not understand that the dry mass of plants comes mostly from carbon dioxide and instead consistently indicate that soil or water is the source of matter for plant growth (Driver *et al.*, 1994; Canal, 1999; Wilson *et al.*, 2006; O’Connell, 2008). Students generally give little attention to where matter comes from and where it goes, other than stating carbon dioxide comes from humans and animals and is used by plants that, in turn, produce oxygen to be used by humans and animals (Driver *et al.*, 1994; Wilson *et al.*, 2006; Brown and Schwartz, 2009). These naive conceptions persist in students who have studied photosynthesis and

DOI: 10.1187/cbe.14-02-0028

Address correspondence to: Jenny M. Dauer (jenny.dauer@unl.edu).
Disclaimer: J.M.D, A.L.F., and C.W.A. are authors of the *Carbon TIME* curriculum. The curriculum is freely available to the public, and neither the authors nor the National Geographic Society profit from its distribution.

© 2014 J. M. Dauer *et al.* CBE—Life Sciences Education © 2014 The American Society for Cell Biology. This article is distributed by The American Society for Cell Biology under license from the author(s). It is available to the public under an Attribution–Noncommercial–Share Alike 3.0 Unported Creative Commons License (<http://creativecommons.org/licenses/by-nc-sa/3.0>).

“ASCB®” and “The American Society for Cell Biology®” are registered trademarks of The American Society for Cell Biology.

Supplemental Material can be found at:
<http://www.lifescied.org/content/suppl/2014/08/29/13.3.397.DC1>

cellular respiration and who have conducted matter-tracing investigations that show that growing plants gain far more mass than the soil loses, similar to van Helmont's famous experiment (Hershey, 1991; O'Connell, 2008). Even after taking an undergraduate biology course, students still struggled to conceptualize the process of photosynthesis in terms of matter tracing and matter conservation (Brown and Schwartz, 2009; Hartley *et al.*, 2011; Parker *et al.*, 2012). The core of the problem is that students lack a systems view of the natural world that incorporates a model of matter and energy at the atomic-molecular scale. Instead students tell simplified stories that help them make sense of their world (Driver *et al.*, 1994; Wilson *et al.*, 2006; Mohan *et al.*, 2009).

Current national recommendations advocate that learning involves an integration of science content and science skills or "practices." The *Next Generation Science Standards* (NGSS Lead States, 2013) integrate science and engineering practices with disciplinary core ideas and crosscutting concepts. Likewise, *Vision and Change in Undergraduate Biology Education* (AAAS, 2011) outlines core competencies and disciplinary practices as well as core concepts. Both of these standards-setting documents send the message that knowledge and practice are inherently interconnected and, to truly build science understanding, students need to practice producing model-based explanations and to support these explanations with arguments from evidence. Therefore, the van Helmont experiment, used as a classroom activity, should lead students to improved understanding of science content through multiple practices—specifically model-based explanations supported with arguments from evidence about how plants grow. In this study, we focused on both of these key practices, constructing explanations and engaging in argument from evidence during investigations.

We define an explanation as an attempt to provide a causal mechanism for phenomena by reasoning, either from scientific models or theory or, for less-sophisticated students, from everyday ideas about how the world works (Osborne and Patterson, 2011; Kang *et al.*, 2014). For example, "tree takes in air, water, sunlight and nutrients. It then converts the air and water into food, which gives it mass," is a student's explanation about how a tree gains mass as it grows. Arguments from evidence are defined as attempts to justify claims using both evidence and reasoning connected to a scientific model or theory (Krajcik and McNeill, 2009) or from everyday ideas about how the world works for less-sophisticated students. Arguments from evidence differ from explanations in that they stem from uncertainty about possible competing explanations of a phenomenon (Osborne and Patterson, 2011). The two practices are similar in that they require students to connect a model or theory with natural phenomena but differ in the use of evidence.

Using evidence from an investigation to make an argument about a phenomenon is an important component of scientific literacy, as well as a primary practice of scientists. In classrooms, educators often advocate that students engage in investigations to connect explanations about "how plants grow" with arguments from evidence during experiments of plant growth, hence using both practices to build their understanding. For example, here is a student's statement about van Helmont's investigation: "A tree's mass comes from the air, not the soil, because van Helmont's evidence showed that the plant gained more mass than the soil lost."

In our previous research into students' understanding of plant growth, we focused on matter and energy content and the practice of explanations (Mohan *et al.*, 2009; Jin and Anderson, 2012). Our research generally involves developing empirically based learning-progression frameworks, which are descriptions of increasingly sophisticated knowledge and practice (National Research Council, 2007). Each learning-progression framework has a content domain and a practice domain (Gotwals *et al.*, 2012). While our learning-progression framework for student explanations (or accounts) of matter and energy in biological processes is well developed, we are just beginning to investigate students' arguments from evidence about matter and energy in biological processes (Dauer *et al.*, 2013b). This paper builds on our previous work by describing the connections between students' explanations and arguments from evidence practices when reasoning about plant growth.

Our learning-progression framework for students' evolving explanations about matter and energy in carbon-transforming processes includes four levels of achievement, or stages, in the transition from informal or force-dynamic explanations (Talmy, 1988; Pinker, 2007) to scientific reasoning:

- Level 1. Pure force-dynamic explanations: Students' explanations focus on actors and enablers, using relatively short time frames and macroscopic-scale phenomena. Events are connected by cause and effect rather than by tracing matter and energy.
- Level 2. Elaborated force-dynamic explanations: Students' explanations continue to focus on actors and enablers, but they add detail and complexity, especially at larger and smaller scales. They include ideas about what is happening inside plants and animals when they grow and respond, for example, and they show awareness of larger-scale connections among phenomena such as food chains. Level 1 explanations are most common in elementary school students (Mohan *et al.*, 2009), so for this paper, we combine level 1 and level 2 explanations into a single category; level 2 force-dynamic reasoning.
- Level 3. Incomplete or confused scientific explanations: Students show awareness of important scientific principles and of models at smaller and larger scales, such as atoms and molecules and relationships among populations in ecosystems. They have difficulty, though, connecting accounts at different scales and applying principles consistently.
- Level 4. Coherent scientific explanations: Students successfully apply fundamental principles such as conservation of matter and energy to phenomena at multiple scales in space and time. They give complete and accurate accounts of all of the matter and energy in a system before and after an event and constrain their explanations by laws of conservation of matter and energy.

Students from middle school through college provide explanations in a range of learning-progression levels, even within the same classroom. For example, Mohan *et al.* (2009) found that only 10% of explanations given by high school students were level 4 responses, while ~35% were level 3, and 52% were level 1 or 2 explanations. In a study at the

college level that used three levels adapted from the learning progression, even after instruction in introductory biology or upper-division ecology courses, only 27% of the explanations were level 4-type responses, while 50% were level 3-type, and 16% of student responses were level 2-type (Hartley *et al.*, 2011). For the purpose of this paper, we examine middle and high school students after introductory biology instruction, a group who may display qualities that are very similar to beginning students in an introductory biology course in college in that many use informal rather than scientific ways of reasoning about carbon-transforming processes.

Even when they are scientifically incorrect, students' everyday ideas and conceptions can be used to establish a foundation to build new knowledge (Howe, 1996; Murphy, 2012). A student's everyday understandings are often cogent stories about the world that *make sense* to the student and are embedded in everyday experience and discourse (Gee, 1996; Pozo and Gómez Crespo, 2005). These initial intuitive ideas can be used as starting points for constructing more complete and complex scientific understandings. This assumption follows the constructivist theory that students build sophistication in their knowledge by integrating new ideas into their "conceptual ecologies" (Posner *et al.*, 1982) rather than simply replacing old ideas with new ones (Smith *et al.*, 1994; Maskiewicz and Lineback, 2013). In this paper, we explore how students' stories and interpretations of the world are reflected in their explanations of the process of plants growing, and their reasoning about investigations of plant growth.

The reasoning that connects investigations to scientific explanations is obvious to scientists. Scientists interpret the purpose of investigations as a way to test a claim that relates to a model, and data as evidence to support or refute a claim or model. But students do not always interpret a classroom investigation as a scientist would; students often have different purposes for their investigations, for example, to explore, to make something happen by manipulating variables, or to solicit attention (Schauble *et al.*, 1991; Rath and Brown, 1996; Windschitl *et al.*, 2008). In addition, for students, explanations have lots of different purposes, such as citing a law or a simple cause-and-effect relationship, that do not include an explanation using scientific models (Braaten and Windschitl, 2011). This disconnect between students' interpretations of investigations in the classroom and the scientific practice of investigation for the purpose of theory building can result in classroom inquiry activities that do not serve to build students' understanding of plant growth and metabolism.

In this study, we investigate the relationship between students' explanations and arguments from evidence practices in the context of plants growing. In an interview setting, we asked students to explain how plants grow in two scenarios and to reason through two claims and sets of evidence about the source of matter for plant growth. In our analysis, we focused on the consistency between students' explanations and interpretations of arguments from evidence. We discuss how students' sense-making strategies and level of understanding of chemical change lead them to correctly or incorrectly interpret investigations and arguments from evidence.

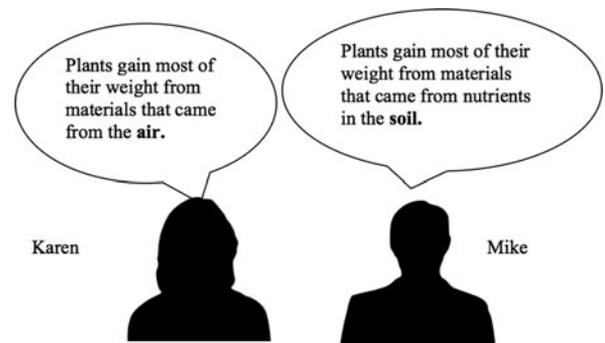


Figure 1. Initial claim card used in the Karen and Mike argumentation question. The card was presented, and the student was asked to indicate which of the two claims they agree with.

METHODS

Data Collection

To study the relationship between students' explanations and arguments from evidence practices, we coded and analyzed postinstruction interviews of middle ($n = 4$) and high school ($n = 18$) students from states including Michigan, Washington, California, Maryland, Colorado, and Pennsylvania who had completed at least three out of six curricular units about matter and energy (at least 6 wk of instruction) from pilot versions of the *Carbon TIME* (Transformations in Matter and Energy) curriculum (Anderson *et al.*, available in 2015 on the National Geographic Society website). The purpose of these curricular units was to help students learn to trace matter and energy through carbon-transforming processes (photosynthesis, cellular respiration, biosynthesis, and combustion) that are responsible for the structure and function of all living systems. The students' biology teachers conducted the postinstruction face-to-face interviews during the 2012–2013 school year. The teachers were instructed to choose two students who represented the range in academic success of the typical students in their classroom.

Teachers were provided with semistructured interview protocols (Supplemental Material). In the interviews, students were asked about plant growth in three contexts, in this order:

1. The Oak Tree questions: students were asked what an oak tree needs in order to grow and how the tree uses those things to grow.
2. The Karen and Mike questions: students were asked to critique a claim and set of evidence about plant growth provided by two different fictional "students," Karen and Mike. First, students were presented with both Karen's and Mike's claims (Figure 1) and were asked with which student they agreed. Second, students were presented with one of two follow-up cards describing an investigation (Figure 2). Students were presented with the card of the "person" whose claim they agreed with and were asked to explain: the investigation and evidence presented on the card; how the evidence supports the claim; and any weaknesses in the evidence that would strengthen the argument. Then the second card, of the "person" with whom they did not agree, was presented, and the same questions

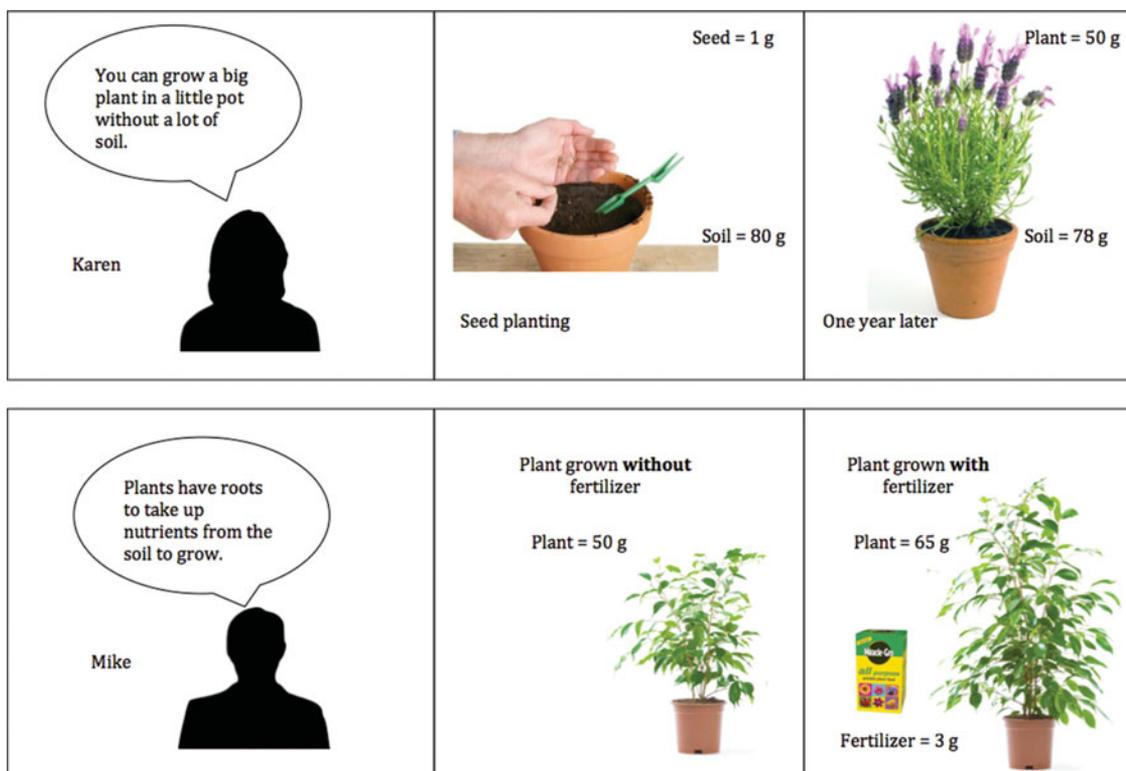


Figure 2. Two follow-up cards used in the Karen and Mike argumentation interview question that were presented one at a time to a student. Students were presented with either Karen’s or Mike’s card first, starting with the person whose claim the student thought was correct. Students then were asked to explain: the investigation presented on the card, how the evidence supports the claim, the weaknesses in the investigation, and what evidence would strengthen the argument. Then the second card was presented and the same questions were asked about either Karen’s or Mike’s investigation.

were asked. Notice, both Karen and Mike cards provided claims about matter tracing (not cause and effect), with Mike claiming that the weight of growing plants comes mostly from the soil, while Karen claims that the weight comes mostly from the air. The evidence provided by both Karen’s and Mike’s investigations is deliberately inconclusive. Karen’s investigation provides evidence that essentially replicates van Helmont’s experiment (and resembles an investigation the students did in class). The evidence from her investigation contradicts Mike’s claim but does not account for other possible sources of mass such as water. The evidence from Mike’s investigation actually contradicts his claim, since only 3 g of added fertilizer cannot account for 15 g of plant growth. The reasoning for both investigations was deliberately missing. We wanted to see what kinds of reasoning students would propose to connect claims and evidence, both for claims that they agreed with and claims with which they disagreed.

3. The Pound of Wood questions: students were asked where the matter in a pound of wood comes from when a tree grows.

Data Analysis

The interviews were video recorded and transcribed for analysis. The explanation interview tasks (Oak Tree and Pound of Wood) were coded based on a framework following two

dimensions of explanations about carbon-transforming processes (Dauer *et al.*, 2013a):

1. Movement of matter: Where does a student think that matter is moving at a macroscopic scale? Does the student recognize that gains or losses of mass from one part of a system have a reciprocal loss or gain of mass in another part of the system? Does the student connect the amount of matter or mass of a system with the number of atoms or molecules?
2. Chemical change: What does a student think is happening to atoms on an atomic–molecular scale? Does the student recognize that plant growth is a set of chemical changes involving rearrangement of atoms into new molecules?

We used these dimensions to analyze students’ explanations of growing plants. (A third dimension, transformations of energy, is not reported in this article, because students were not asked to trace energy during the van Helmont experiment.) For the two interview questions prompting for student explanations (Oak Tree and Pound of Wood), the learning-progression levels were used to describe levels of sophistication in student explanation practices including tracing materials to and from the plant (coded as the “movement of matter” explanation dimension) and describing chemical change at the atomic–molecular level (coded as the “chemical change” explanation dimension). We indicate in Table 1

Table 1. The explanation (or accounts) learning-progression levels and their relationship to the coding dimensions for explanations about carbon-transforming processes: chemical change and movement of matter

Coding dimensions ^a	Explanations learning-progression level ^b		
	2	3	4
Movement of matter	Traces cause and effect	Traces using atoms and molecule language but with mistakes or inconsistency at the atomic-molecular level	Traces atoms and molecules even when prompted at the macroscopic level
Chemical change	Hidden mechanisms, does not describe chemical change	Describes transformation of matter but with inconsistencies including matter-energy conflation or otherwise breaks the law of conservation of matter	Describes transformation of matter at the atomic-molecular level including specifically the breaking and rearrangement of molecules

^aCodes were applied to the Oak Tree and Pound of Wood interview questions.

^bMohan *et al.*, 2009.

how the explanation learning-progression levels relate to movement of matter and chemical change dimensions of understandings.

Table 2 presents our framework for coding students' responses to interview questions prompting for interpretations of arguments from evidence (Karen and Mike). We coded all of the transcripts with two coding dimensions for arguments from evidence: 1) purpose of the investigation and 2) use of evidence. These dimensions emerged after multiple rounds of coding and based on previous analyses on the Mike and Karen questions (Dauer *et al.*, 2013b). We also noted whether the students chose Karen's or Mike's explanation as being more correct.

We coded the "purpose of the investigation" based on how students' described Karen's and Mike's purposes and conclusions in doing their investigations. We found that students' views of the purpose of the experiment influenced how they interpreted claims and evidence (Dauer *et al.*, 2013b). For example, instead of tracing matter using the mass data as evidence, some students were trying to find the cause of an event by reasoning about multiple enablers that are important for plants to grow or were trying to find the winner or best strategy for plant growth by focusing on a comparison of

experimental factors (sunlight, water, soil, air) that influence plant growth. Students' views of the purpose of the investigation may influence what data are valid in the argument, leading to our second dimension for coding students' arguments from evidence.

The second arguments dimension "use of evidence" describes the students' use of observations or data in their interpretations of the argument from evidence from Karen or Mike, and the role of the observations or data in the students' reasoning. Observations include the mass data provided by the interview cards (Figure 2) or the students' reference to or implicit use of the images provided or prior personal experience.

Each transcript was coded by at least two of the authors. If there was a discrepancy in our coding, we discussed the transcript at length, resulting in reconciliation in codes and/or refinement of our coding scheme. After coding the transcripts, we compared individual students' explanation codes (i.e., movement of matter and chemical change in Oak Tree and Pound of Wood questions) with arguments of evidence codes (i.e., purpose of investigation and use of evidence in Karen and Mike questions) to identify a possible relationship between the two practices.

Table 2. Arguments from evidence levels of sophistication and their relationship to the coding dimensions for arguments from evidence: purpose of the investigation and use of evidence^a

Coding dimensions	Level of sophistication		
	Low	Medium	High
Purpose of the investigation	Identifies needs/enablers (no experiment is needed to answer the question)	Identifies strategies for plant growth without tracing matter (although an experiment or comparison is needed to answer the question)	Traces matter by applying principles of conservation of matter to constrain the argument
Use of evidence	Uses personal experience preferentially or in addition to data	Notifies the provided mass data and interprets the purpose of the data as to show successful growth	Notifies the provided mass data and interprets the purpose of the data as for tracing
	OR Does not use evidence	OR Notifies the provided plant images and interprets the purpose of the images as to show successful growth	

^aArguments from evidence codes were applied only to the Karen and Mike interview questions.

RESULTS

We begin our *Results* by describing three students who illustrate patterns of varying sophistication that we saw across the full set of interviews. In particular, we analyze how these students' explanation and argumentation practices compare across interview questions. Then we discuss how these patterns were observed across the remaining transcripts by comparing learning-progression level codes for student explanations in Oak Tree and Pound of Wood with students' interpretations of the purpose Mike's and Karen's experiments.

Three Exemplar Students

The three students we describe below represent a range of responses and trends we saw among the student interviews. All three students were interviewed at the end of a ninth-grade biology class that included instruction on matter and energy in plant growth. The three students, Olivia, Spencer, and Erika (pseudonyms), were at different schools with different teachers. All three students had instruction on photosynthesis, cellular respiration, and biosynthesis in plants and had performed experiments with growing plants in the classroom that resembled van Helmont's experiment.

Olivia: Explanations of Chemical Change and Using Mass Data as Evidence of Movement of Materials

Explanations. Olivia was able to give level 4 explanations across all interview questions. During the Oak Tree interview question Olivia quickly moved into descriptions at an atomic-molecular scale (Table 3). For example, when asked what a tree needs in order to grow, Olivia stated that a tree "needs sunlight and then necessary building blocks for the molecules in there." Olivia's descriptions of transformations of matter during chemical change revealed her understanding of the chemical change explanation dimension and of underlying mechanisms. She described chemical change by explaining the rearrangement of molecules stating that the tree "uses the carbon dioxide to grow because through photosynthesis it takes the carbon dioxide and water and the sunlight in order to create glucose. And then in the glucose it has energy stored in there." In the Oak Tree question, Olivia identified nearly all of the reactants and products in the processes of both photosynthesis and cellular respiration in plants (Table 3).

Olivia consistently included air or carbon dioxide as the primary source for materials for plant growth across all interview questions, correctly addressing the movement of matter explanation dimension in a way that was connected to her understanding of the chemical processes of photosynthesis and biosynthesis. For example, in the Pound of Wood question, when asked where a pound of wood comes from, Olivia claimed "The air around it will lose weight and also the soil could lose some weight but it won't lose, like, a ton; the air will lose most of the weight." She speculated that the air contributed either 50% or 75% of the weight that made up one pound of wood, with the remaining coming from materials in the soil. She explained her reasoning by saying that "the main thing that it gained mass in was carbon dioxide and water, that's where they came from, in the cellulose of the wood. But it could also be from the soil . . . for the other

components contained in the wood." While some of her understanding of what the soil contributes to tree materials in terms of micronutrients was missing, in this interview question, she consistently explained how matter from the air and soil could be transformed into wood.

Interpretations of Arguments from Evidence. Olivia agreed with Karen: "Karen [is right] because a lot of the carbon and stuff, it comes from the air" (Table 4). Olivia implicitly interpreted the purpose of each of the investigations to be about tracing materials, and she used mass data and the principle of conservation of matter to constrain the arguments. For example, she stated that Karen's argument supports the claim that materials for plant growth come from the air because "forty-seven of the grams that the plant's mass increased had to come somewhere else besides the soil." Olivia successfully used the mass data provided in the interview to trace matter through the plant and soil system.

Olivia also noticed that the connection between the claim and evidence in both Karen and Mike's arguments were flawed. Olivia said that Karen's argument would be strengthened "if she said what from the air helped it increase in mass," highlighting that Karen only showed that soil did not provide the majority of plant mass but did not show that carbon dioxide from the air is what contributed to the mass rather than water or some other source. However, Olivia did not directly critique the data by stating that the evidence did not eliminate alternative hypotheses such as water, which would have improved her answer. Olivia also correctly pointed out that Mike's evidence actually contradicted his claim that materials for plant mass come from the soil because "only three grams were added from the soil so that means not all of its mass came from the soil" (Table 4).

Spencer: Disconnected Reasoning between Movement of Matter and Chemical Change

Explanations. Spencer was an example of a student who was early in his understanding that atoms and molecules are necessary for scientific explanations of phenomena. He understood that materials are made of atoms and molecules, but he was unable to use this idea with consistency and detail. Therefore, we classified Spencer's explanations at a level 3 in the learning progression. In the Oak Tree question, Spencer described molecules that make up air, namely oxygen and carbon dioxide, being used to "create photosynthesis," a response focused on cause and effect more often found in level 2-type explanations. As the interviewer continued to prompt Spencer to talk about each enabler, Spencer improved in his explanation. Spencer eventually became more specific, talking about how molecules of carbon dioxide and "hydrogen" or water "create . . . glucose," but he did not give complete reactants and products (Table 3).

Spencer did not convincingly trace materials by linking locations in the environment to processes in terms of atoms and molecules. He addressed the movement of matter explanation dimension by tracing at a macroscopic level, including soil, air, and water as places that contribute materials to plant growth, without clearly describing which molecules from those locations are the materials that contribute to plant mass. Therefore, his understanding of movement of materials

Table 3. Student responses to Oak Tree

Interviewer prompts in Oak Tree	Olivia explanations at a level 4	Spencer explanations at a level 3	Erika explanations at a level 2
What does the tree need in order to grow?	<i>It needs sunlight and then necessary building blocks for the molecules in there... Like carbon dioxide, water and then like certain nitrogen and then those P's, S's and O's.</i>	<i>It needs sunlight and water and soil.</i>	<i>Sunlight, water and air... Maybe soil</i>
How does a tree use soil (or nutrients) to grow?	Not asked by interviewer.	<i>I'm not sure.</i>	<i>I think there are special nutrients that the soil has to help the tree get bigger... I think the roots take in the nutrients from the soil to help it grow.</i>
How does a tree use air to grow?	<i>It uses the carbon dioxide to grow because through photosynthesis it takes the carbon dioxide and water and the sunlight in order to create glucose. And then in the glucose it has energy stored in there.</i>	<i>Yeah, it needs oxygen to create photosynthesis I think. You have to have sunlight and water and oxygen to make that... Oh no—carbon dioxide, sorry. That's what... we use oxygen, trees use carbon dioxide, sorry.</i>	<i>There's carbon in the air, which the plant needs to create photosynthesis along with the sunlight.</i>
How does a tree use water to grow?	<i>Yeah, it uses that in the same process [photosynthesis].</i>	<i>I think, doesn't it use hydrogen and carbon dioxide to create, doesn't it like turn it into glucose somehow?</i>	<i>It uses water I guess to help the roots.</i>
How does a tree use sunlight to grow?	<i>Sunlight provides the energy that goes into the molecules, it like, provides energy for photosynthesis to happen... like all the energy for the tree basically.</i>	<i>I don't remember, but it uses something from the sunlight to help turn to glucose. Interviewer: What would the sunlight provide that might help in that process? Spencer: Oh, energy.</i>	<i>It uses sunlight to create energy for it to live because the energy is sugar for the tree... The tree uses carbon dioxide and the sunlight to make sugar for the tree, which is also energy, and it helps the tree live.</i>
Does the tree do anything with the air that surrounds it?	<i>Yeah, that's where it gets the carbon dioxide from.</i>	<i>Yeah, it takes in carbon dioxide and then it gives off oxygen.</i>	<i>It takes in the oxygen in the air and it makes more, I mean it takes in carbon and makes more oxygen.</i>
Is there a connection between exchanging gases and growing for the tree?	<i>That's how all the carbon dioxide gets into the tree to build the glucose and then also how the oxygen gets in to perform cellular respiration in order to, like, give the tree energy... then since oxygen is a byproduct of photosynthesis too it releases both oxygen and CO₂.</i>	<i>Yeah, because parts of the carbon dioxide, like, once it's broken down, it's used with the hydrogen to make glucose, which helps it grow.</i>	<i>The more oxygen it breathes out, I mean the more carbon... the trees take in the carbon and makes more oxygen.</i>

was somewhat disconnected from his ideas about chemical change (i.e., the process of photosynthesis).

When asked where one pound of wood comes from, Spencer initially included a list of multiple sources of material, including water, nutrients from the soil, and carbon dioxide from the air. When prompted further to explain what in the environment would lose weight when that tree gains weight, Spencer became more thoughtful, initially focused on soil as the source of materials of plant growth: "Possibly the soil, because I feel like the soil is holding water that the tree takes up and it's holding nutrients that the tree takes up so it's going to lose mass when the tree takes up those things." When asked about any other places that might lose weight, Spencer speculated about air as a source of matter: "The air probably would, well actually no, I don't think it would because when it takes in carbon dioxide it puts out oxygen so it probably would go full circle, but maybe at the time it would."

Spencer correctly traced materials from air to the plant but did not account for all atoms during chemical change, resulting in an interesting, but incorrect, idea: chemical change

processes release other kinds of molecules into the air that balance each other out. Because of his reasoning along these lines, he said that "probably the soil would lose like about two-thirds of the weight because it would have the nutrients and water and then the air would probably lose about one-third of the weight." Thus, we conclude that Spencer did not fully understand chemical change, particularly how carbon dioxide sequestered as glucose goes through biosynthetic processes to become the matter of the tree.

Interpretations of Arguments from Evidence. Spencer was unsure whether Karen or Mike had the better claim. He deliberated between soil and air as the source of materials for plant growth: "I think maybe soil because I don't know that the stuff from the air would give it much mass. But then I also know that it takes the carbon dioxide from the air to make glucose... Probably Karen because I'm not really sure what nutrients they would use from the soil" (Table 4). After consideration, Spencer chose Karen, relying on his understanding of photosynthesis. However, Spencer displayed uncertainty or lack of confidence about the air providing enough mass for plant

Table 4. Student responses to the Karen and Mike question

Interviewer prompts in Karen and Mike	Olivia	Spencer	Erika
Who do you think is right?	<i>Karen because a lot of the carbon and stuff, it comes from the air, and also the plant could get water from the air too.</i>	<i>I think maybe soil because I don't know that the stuff from the air would give it much mass. But then I also know that it takes the carbon dioxide from the air to make glucose . . . Probably Karen because I'm not really sure what nutrients they would use from the soil.</i>	<i>I think that Karen is right because without the air the plant wouldn't be able to make food, energy for itself for it to grow . . . Mike is kind of right too, he says that the materials, I mean the nutrients in the soil help it grow. I don't know if there is anything special in the soil that it makes it grow.</i>
How does Karen's argument support her idea that the plant gains weight from materials that came from the air?	<i>Because the soil only, like, its mass only decreased by two grams while the plant's mass increased by forty-nine grams so forty-seven of those grams had to come from some place. Forty-seven of the grams that the plant's mass increased had to come somewhere else besides the soil.</i>	<i>There's only a little bit of soil and her plant still gained a lot of mass. The soil isn't what gives it most of its mass. It's the air.</i>	<i>That the plant got bigger . . . and the soil amount got smaller. If there wasn't any air that the plant wouldn't have gotten as big as it did.</i>
Are there some weaknesses in Karen's argument? Explain what they are.	<i>She doesn't say was anything added to the soil or no? . . . That's really the only thing I could think of.</i>	<i>Yeah, because she hasn't accounted for the fact that she watered it, or if she were to add anything to the soil that would change the mass of the plant.</i>	<i>Because of [sic] the soil amount went down it's possible that the plant could have used it to grow too.</i>
What evidence would strengthen Karen's argument?	<i>If she said what from the air helped it increase in mass.</i>	<i>If she had a pot . . . one with less soil and one with more soil, and then maybe one that she fertilized and didn't, or one that she watered, one she didn't, and then she could see which changing factor made it get biggest.</i>	<i>The amount of grams the plant grew which is a lot bigger.</i>
How does Mike's argument support his idea that the plant gains weight from materials that came from the soil?	<i>Because when something new is added to the soil the plant gained more mass.</i>	<i>That most of the weight comes from the nutrients in the soil, because when he had less nutrients in the soil the plant was smaller and then when he added nutrients to the soil the plant got bigger.</i>	<i>The amount that the plant grew with the fertilizer was a lot bigger than the one without.</i>
Are there some weaknesses in Mike's argument? Explain what they are.	<i>Yeah, well the plant only gained three more grams. . . the plant gained fifteen more grams when only three grams were added from the soil so that means not all of its mass came from the soil it just helped it grow more.</i>	<i>I guess the same as with Karen's [investigation], he didn't test any other factors other than just with and without fertilizer.</i>	<i>That the plant can't just grow with fertilizer it needs other things too.</i>
What evidence would strengthen Mike's argument?	<i>Showing . . . where the plant was at, at the beginning and the end of the experiment. And to show that the plants were grown over the same amount of time.</i>	<i>Probably if he like if he . . . watered one, didn't water one, like he changed more factors, like, he hadn't changed, added or tested more factors besides just the one.</i>	Not asked by interviewer.

growth and also what kinds of molecules in the soil might be used for plant growth.

Rather than interpreting the claims in both the Karen and Mike interview questions to be about tracing matter, Spencer interpreted the claims to be about factors in creating big plant growth. Spencer was able to use the mass data provided in the interview, but only as evidence in terms of "What are the best strategies for plant growth?," rather than evidence that atoms have moved from one location to another. Therefore, Spencer did not use Karen's data to constrain her argument and did not recognize that Mike's data were actually contrary to his claim (Table 4).

During the Karen question, Spencer described Karen as making an accurate claim because "there's only a little bit

of soil and her plant still gained a lot of mass. The soil isn't what gives it most of its mass. It's the air." While Spencer's conceptual interpretation of the experiment was correct, he did not discuss how the 2 g loss in weight of the soil could not account for the 49 g of plant growth. The weaknesses Spencer pointed out concern missing information about accounting for water or adding anything to soil. Spencer went on to say that a better test of his interpretation of Karen's claim regarding "which factors add to the weight of the plant" would be to alter the amounts of each factor (Table 4).

During the Mike question, Spencer traced matter only at a macroscopic level, disconnected from chemical change. So, the weight data were less important to Spencer as evidence compared with the overall macroscopic result of a larger

plant (i.e. “when he had less nutrients in the soil the plant was smaller and then when he added nutrients to the soil the plant got bigger”), resulting in Spencer not noticing that Mike’s evidence was actually counter to his claim. The only weaknesses that Spencer pointed out in the experiment is about testing *all* of the factors for plant growth: “I guess the same as with Karen’s he didn’t test any other factors other than just with and without fertilizer.”

Erika: Force-Dynamic Reasoning throughout Explanations and Interpretations of Arguments from Evidence

Explanations. Erika gave level 2–type explanations, reasoning that trees grow based on force-dynamic explanations that involved actors (the oak tree) and enablers (sunlight, water, air, and soil) that help the tree to grow. Across all interview questions, Erika consistently gave explanations of the role of each of the “enablers” without addressing the chemical change explanation dimension by reasoning about processes involved in chemical change at the atomic–molecular level.

In the Oak Tree question, although Erika could name “photosynthesis,” she described carbon and sunlight as *creating* photosynthesis. So to Erika, carbon and sunlight are the causes in a simple story about a phenomenon called photosynthesis, rather than reactants in a chemical processes. When asked whether a plant needs “air” to grow or when asked about gas exchange, Erika frequently responded by talking about “carbon” (three times during Oak Tree and twice during Pound of Wood) when referring to a “carbon dioxide” molecule (a phrase she used only once during Oak Tree; Table 3). We interpret her use of the word “carbon” as a description of a quality or property of air, rather than as the molecules that make up air. This lack of precision in language is evidence that Erika did not have a strong explanation about what materials are made of at an atomic–molecular level, which is knowledge necessary for understanding chemical change. She described soil as important for a tree to “get bigger” rather than tracing materials (Table 3). Therefore, Erika consistently explained cause and effect rather than tracing matter (movement of matter explanation dimension).

Erika continued to provide general answers about how plants use enablers to grow, rather than tracing matter, during the Pound of Wood question. When asked where a pound of wood comes from, Erika responded, “I would assume the roots getting bigger and coming out of the ground.” She identified air as a place that would lose mass but was unable to articulate why or to speculate how much how much mass the air would lose for a tree to gain a pound of wood.

Interpretations of Arguments from Evidence. When evaluating Karen’s and Mike’s investigations, Erika interpreted the investigations to be about “what causes a plant to grow” rather than tasks requiring tracing of matter using evidence. Throughout both the Karen and Mike segments of the interview, Erika continued to account for plant growth by using force-dynamic explanations instead of addressing movement of matter.

Erika was not easily able to decide whether Karen or Mike had a more correct claim. This is consistent with her force-dynamic reasoning that multiple enablers (sunlight, soil, water, and air) all cause a plant to grow. To Erika, both were correct, since both soil and air were needed for plant growth. “I think that Karen is right because without the air the plant

wouldn’t be able to make food, energy for itself for it to grow. . . . Mike is kind of right too, he says that the materials, I mean the nutrients in the soil help it grow” (Table 4). Erika significantly changed the meaning of the original question of Karen and Mike: “How do plants gain weight as they grow?” (Supplemental Material). To Erika, the question is “What does a plant need to grow bigger?” So the answer is that both Karen and Mike had good ideas about what helps a plant to grow.

Erika did not cite the mass data provided in the interview. When asked about Karen’s argument, Erika explained that Karen’s argument showed “that the plant got bigger . . . and the soil amount got smaller,” and that “if there wasn’t any air that the plant wouldn’t have gotten as big as it did.” In fact, to Erika, the idea that the mass of soil decreased in Karen’s experiment was a weakness, because it showed that the soil probably contributed some to growing a bigger plant. She said, “Because of the soil amount went down it’s possible that the plant could have used it to grow too.” Likewise, Erika did not refer to the mass data in her discussion of Mike’s investigation. Erika explained that Mike’s experiment supported the idea that plants gained weight from materials that came from the soil because “the amount that the plant grew with the fertilizer was a lot bigger than the one without.” To Erika, the weakness in Mike’s argument was that “that the plant can’t just grow with fertilizer it needs other things too,” including “air and the sun and water,” essentially naming all the enablers of plant growth.

Overall Trends in the Data. Eight out of 22 students (36%), responded to the Oak Tree interview question with level 3 explanations (Table 5). These students provided incomplete or confused accounts of movement of matter and chemical change, vaguely explaining chemical transformation and tracing materials only in terms of macroscopic location instead of at the atomic–molecular level. Of the remaining students, three students (14%) achieved only level 2 explanations, describing plants growing in terms of actors and enablers and simplified cause and effect; and 11 students (50%) achieved level 4 explanations, describing chemical change during photosynthesis or biosynthesis and describing the origin of atomic–molecular level materials for plant. Generally, students gave explanations at the same level of sophistication for both the Oak Tree and Pound of Wood questions. No differences between middle school and high school students were detected because of our small sample size.

We used the “purpose of the investigation” arguments from the evidence coding dimension to compare with explanation learning–progression level (Table 5), because it best described the level of sophistication in the students’ arguments from evidence. We found that the students who interpreted the purpose of the investigation as about tracing matter during either the Karen or Mike interview question (high level of sophistication for “purpose of the investigation”) also noticed the mass data and interpreted the purpose of the data as being for tracing (high level of sophistication for “use of evidence”). The students who interpreted the purpose of the investigation as strategies for plant growth or to identify needs of the plant did not attempt to reason using the mass data (medium and low levels of sophistication). Overall, those who traced materials in the Karen or Mike interview question were more

Table 5. Total student count ($n = 22$) in a comparison of learning-progression level for explanations based level of achievement during the Oak Tree interview question and student’s interpretation of the purpose of the investigation during the Karen and Mike interview questions^a

Type of explanations given	Count at each explanation level (n)	Type of arguments from evidence given						
		Karen arguments from evidence				Mike arguments from evidence		
		Tracing materials	Strategies for plant growth	Identifying enablers	Uncodable	Tracing materials	Strategies for plant growth	Identifying enablers
Level 4	11	11	0	0	0	7	4	0
Level 3	8	5	3	0	0	2	4	2
Level 2	3	0	1	1	1	0	1	2
Total count	22	16	4	1	1	9	9	4

^aStudent counts are redundant between the Karen and Mike columns because each student answered both questions.

likely to choose Karen as overall being more correct in their claims.

We found that none of the students who gave level 2 explanations during either (or both) of the Oak Tree and Pound of Wood questions correctly interpreted the purpose of either Karen’s or Mike’s experiment to be about tracing materials (Table 5). Instead, all three described Karen’s and Mike’s experiments to be about “What do plants need?” Although they ultimately chose between Mike (two students) or Karen (one student) as correct, the level 2 students agreed that both soil nutrients and air are important to plant growth.

The 11 students who gave level 4 explanations during either (or both) of the Oak Tree and Pound of Wood questions primarily chose Karen (10 students) as being more correct, consistent with their explanations of the movement of matter in Oak Tree and Pound of Wood questions and interpreting both Karen’s and Mike’s claims to be about tracing matter (Table 5). One student who gave level 4 explanations chose Mike as being more correct. This student had a strong level 4 explanation of chemical change, but a weaker understanding of the movement of matter, and interpreted Mike’s claim to be an argument about strategies for plant growth rather than about tracing matter.

Table 5 shows that students who achieved a level 3 in their explanations had a range in their performance on arguments from evidence, and some performed better than Spencer, achieving a “high” level of sophistication for purpose of the investigation by tracing matter for either the Karen or the Mike interview question. Students at a level 3 are inherently varied in their explanations of carbon transforming (Miller *et al.*, 2013), and many attempted to trace matter and energy without complete success. Most of the students chose Karen as being more correct (seven out of eight students), although the reason for choosing one claim over another varied. We interpret these students who gave level 3 explanations to be “in transition,” in Vygotsky’s zone of proximal development (ZPD; Vygotsky, 1978; Howe, 1996; Murphy, 2012). Students in the ZPD tend to be sensitive to the kinds of support or scaffolding available for their responses. For instance, if a teacher offers leading questions and shows students different ways to solve problems, it may help students in the ZPD to solve new, more difficult problems that they could not have solved individually.

The students who gave level 3 explanations also interpreted Karen’s versus Mike’s evidence differently, with five of the

eight interpreting Karen’s investigation as about tracing materials, but only two interpreting Mike’s investigation using this frame (Table 5). The difference, we hypothesize, lies in the kinds of responses scaffolded by the evidence inherent in the Karen or Mike interview question. Mike’s experimental comparison of “with” and “without” fertilizer encourages a “horse race” interpretation, with students often interpreting the purpose of the experiment as figuring out what factors cause a plant to grow “the best.” Karen’s mass evidence without a comparison, on the other hand, encourages students to focus more on her matter-tracing claim. Overall, students performed better on the Karen interview question, with the majority of students recognizing that the purpose of the experiment is to trace the source of mass for growing plants.

Additionally, while all of our interview questions asked students to trace matter, the Oak Tree question in particular is less scaffolded for tracing, simply asking students to explain what a tree needs in order to grow and how it uses those things to grow. Some of the students who did not successfully trace matter during this open-ended question were more likely to trace in the Karen interview question when explicitly asked to compare changes in mass data between plants and soil. This explains how some students who gave level 3 explanations in Oak Tree were able to trace during the Karen or Mike arguments from evidence interview questions. The high sensitivity to scaffolding that we observed in our data, especially in students who are learning, emphasizes the importance of thoughtful scaffolding during classroom activities. In the *Discussion*, we outline the ideas for scaffolding that we have developed in teaching materials for explanations and arguments from evidence about carbon-transforming processes that could be useful for transitioning students.

DISCUSSION

We have good reasons for advocating that empirical investigations should play an important role in teaching about plants and that students should build explanations based on arguments from evidence. We want students to understand that the ultimate source of all scientific knowledge lies in our observations of phenomena in the material world, and we want them to gain knowledge through their own investigations not simply by accepting textbook knowledge as

authoritative. So when students like Erika and Spencer—the vast majority of high school and college students—incorrectly believe that “when *plants grow*, their added weight *comes from* nutrients in the soil,” it seems obvious that van Helmont-type investigations could be useful in a classroom to serve as a discrepant event. In these investigations, the difference between the mass that the plants gain and the mass that the soil loses make it obvious that the mass must be coming from somewhere else.

And yet—we saw that most students do not view a van Helmont-like experiment as discrepant with their own beliefs. To see how this happened, we can consider what our data reveal about the three exemplar students, Erika, Spencer, and Olivia:

- For students like Erika, “plant growth” was an *action* rather than a process involving movement and transformation of matter, and “comes from” implied causality rather than movement of matter (as when we say “his brown eyes come from his mother”). So for Erika the statement above simply meant that soil nutrients cause or help plants to grow. Mike’s investigation supports this claim, and Karen’s investigation seems pointless: of course plants need air to grow, besides, how can you learn about *air* by weighing the *soil*?
- Students like Spencer recognized that plants are somehow transforming matter as they grow, but it seemed obvious that plants turn “like into like.” In other words, plants transform carbon dioxide into oxygen (both colorless, odorless gases) and soil nutrients into the materials that they are made of (both solids). So the investigation became either a comparison of whether air or soil is slightly more important, or confirmed that both air and soil are important factors for plant growth.
- For Olivia, Karen’s and Mike’s investigations simply confirmed what she already understood about plant growth—that plants transform carbon dioxide from the air and water into glucose through the process of photosynthesis and use glucose and soil minerals through the processes of biosynthesis to create the materials from which plants are made.

This study shows that students like our exemplars do not clearly connect investigations with explanations of carbon-transforming processes, because they reinterpret results and conclusions to fit their understanding of scientific principles and the purposes of investigations. Even after instruction, many students in our study with level 2- and level 3-type explanations understood conservation of mass and atomic-molecular theory as *facts* but not as *rules that govern practices*. That is, students can often correctly state the law of conservation of mass, some molecular formulas, and some chemical equations but, at the same time, cannot use these ideas consistently or effectively in their explanations or arguments from evidence. However, we also observed that a minority of our students, those with level 3-type explanations who were more sophisticated than Spencer, were able to apply the rules of conservation of mass and atomic-molecular theory when investigations provided scaffolding that allowed them to trace matter more successfully. Thus, scaffolding is likewise important in classroom investigations of plant growth like van Helmont’s experiment to

support a strong sense of necessity about conservation of matter applied to matter tracing. Our data support the idea that, for some students, this scaffolding is required for students to see the scientific implications of investigations in the classroom.

So how could students like Erika and Spencer actually *learn* from van Helmont-like investigations and use the investigations to develop new and deeper understandings of plant growth? Our results suggest that, in order to investigate how matter and energy are transformed in plant growth and metabolism, students need some foundational understandings about matter and energy but not the contents of the typical “molecules of life” chapter in a biology textbook.

We have been working toward instructional designs that address these challenges, both at the college level (Rice *et al.*, 2014) and in our continued development of the *Carbon TIME* curriculum (Anderson *et al.*, available in 2015 on the National Geographic Society website) at the middle and high school level. Despite a small sample size, this analysis of *Carbon TIME* students postinstruction indicates that the curriculum has promise; half of the students interviewed achieved level 4 explanations, which is higher than previously observed for high school or college (Mohan *et al.*, 2009; Hartley *et al.*, 2011). In *Carbon TIME*, we focus on three core challenges to instruction in enabling students to learn more effectively from investigations focusing on plant growth and metabolism. Some key strategies are summarized in the following sections.

Challenge 1: Understanding the Nature of Scientific Explanations

Students need to value and engage in reductionist explanations of plant growth and metabolism as visible manifestations of underlying chemical changes. There are multiple scientific ways to explain plant growth—evolutionary, genetic, developmental, and so forth. So students need to understand that in some circumstances tracing matter and energy provides a powerful approach to explaining biological phenomena. In our instructional design work, we seek both to recognize the legitimacy of alternate forms of explanations and to provide consistent scaffolding (see *The Importance of Scaffolding*) for scientific explanations. In *Carbon TIME* we use the *Powers of Ten* video (Eames *et al.*, 1989) and a “Powers of Ten” benchmark heuristic to introduce students to the invisible world of atoms and molecules inside every organism. We also use PowerPoint animations to link visible processes such as plant growth to invisible movements and changes in molecules.

Challenge 2: Using Conservation Laws and Atomic-Molecular Theory as Rules

Students need to “follow the rules” of conservation of matter and energy whenever they engage in explanations and arguments from evidence. We have worked to support students’ conservation-based reasoning with both explicit scaffolding and physical models. In the *Carbon TIME* units, the “Three Questions” (Table 6) both structure student explanations and provide explicit guidance focused on conservation reasoning. The “Rules to Follow” help remind students to follow the laws of conservation of matter and energy. Finally,

Table 6. The “Three Questions”

Question	“Rules to Follow”	“Connecting Atoms with Evidence”
The location and movement question: Where are atoms moving? • Where are atoms moving from? • Where are atoms going to?	Atoms last forever in combustion and living systems. All materials (solids, liquids, and gases) are made of atoms.	When materials change mass, atoms are moving. When materials move, atoms are moving.
The carbon question: What is happening to carbon atoms? • What molecules are carbon atoms in before the process? • How are the atoms rearranged into new molecules?	Carbon atoms are bound to other atoms in molecules Atoms can be rearranged to make new molecules.	The air has carbon atoms in carbon dioxide. Organic materials are made of molecules with carbon atoms. • Foods • Fuels • Living and dead plants and animals
The energy question: What is happening to chemical energy? • What forms of energy are involved? • How is energy changing from one form to another?	Energy lasts forever in combustion and living systems. C-C and C-H bonds have more stored chemical energy than C-O and H-O bonds.	We can observe indicators of different forms of energy. • Organic materials with chemical energy • Light • Heat energy • Motion

“Connecting Atoms with Evidence” allows students to link mass data to the question “Where are atoms moving?” So, if a plant gains weight, that means atoms *must* have moved into the plant from somewhere. We also use physical models to help students trace matter and energy through processes. In her college-level course, Jane Rice uses “clips and strips”—paper clips to represent atoms and paper strips to represent energy units (Rice *et al.*, 2014). In *Carbon TIME*, we rely on molecular modeling kits, using twist ties to identify high-energy bonds in molecules (Dauer *et al.*, 2013b), and on animations showing how atoms are rearranged into new molecules.

Challenge 3: Understanding Purposes of Investigations

Students need to interpret the hypotheses, procedures, and results of investigations in ways consistent with their scientific purpose and design. We found that both teachers and students often misunderstood the purposes of investigations in the *Carbon TIME* curricular units, either using them to confirm what they had already been told or misinterpreting the results in ways similar to Erika and Spencer. Therefore, we have made the “Three Questions” framework (Table 6) central to investigations: The investigations are designed to produce arguments from evidence that will answer the “Three Questions.” The evidence produced by the investigations themselves is incomplete to answer all of the “Three Questions” (e.g., we do not quantify chemical energy gained by the plant while it grows), so additional teaching to answer the questions more completely is necessary. Thus, students use the framework of the “Three Questions” to explore both the nature and the limits of scientific investigations and arguments from evidence.

The Importance of Scaffolding

Teachers who are strategic with a variety of scaffolding types can prompt students to a higher level of sophistication in

both explanations and arguments from evidence (Kang *et al.*, 2014). As discussed earlier, these strategies may be particularly useful for students like Spencer who are sensitive to scaffolding and are in the ZPD (Vygotsky, 1978; Howe, 1996; Murphy, 2012). With appropriate support, students can provide sufficient explanations of carbon-transforming processes, but they are also likely to revert back to their everyday or familiar understanding of a concept and disregard the new information (Howe, 1996). Therefore, they need both explicit frameworks for scientific practice and opportunities for knowledge construction that involve moving back and forth between their everyday and scientific understandings (Murphy, 2012). Eventually, with coaching and practice, students are able to internalize the use of scientific concepts as a way of thinking about and interpreting their everyday world. In turn, they will use their reorganized and re-constructed concepts to reason across multiple contexts and situations.

CONCLUSION

There are persistent problems for students from K–12 to college in explaining where the matter that makes plants comes from and in understanding investigations about plant growth. We found that these persistent problems are associated with powerful and appealing explanations that plant growth is an action and that water, air, sunlight, and soil are enablers of this action rather than sources of matter and energy that are transformed in living systems. These informal explanations for plant growth also influence how students interpret the purposes of investigations of how plants transform matter and energy. Many students reinterpret the claims provided in interview questions to be consistent with claims about the best ways to grow plants, rather than claims about tracing matter. So learning about plants through investigations requires both careful coaching about the purposes of inquiry and a fundamental understanding of the nature of matter and energy.

ACKNOWLEDGMENTS

This research is supported in part by grants from the National Science Foundation: Learning Progression on Carbon-transforming Processes in Socio-Ecological Systems (NSF 0815993); Targeted Partnership: Culturally Relevant Ecology, Learning Progressions, and Environmental Literacy (NSF-0832173); and A Learning Progression-based System for Promoting Understanding of Carbon-transforming Processes (DRL 1020187). Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation or the U.S. Department of Energy. Special thanks to Staci Sharp, Hannah Miller, and the *Carbon TIME* teachers for their contributions to this work.

REFERENCES

- American Association for the Advancement of Science (2011). *Vision and Change in Undergraduate Biology Education: A Call to Action*, Washington, DC.
- Braaten M, Windschitl M (2011). Working toward a stronger conceptualization of scientific explanation for science education. *Sci Educ* 95, 639–669.
- Brown MH, Schwartz RS (2009). Connecting photosynthesis and cellular respiration: preservice teachers' conceptions. *J Res Sci Teach* 46, 791–812.
- Canal P (1999). Photosynthesis and "inverse respiration" in plants: an inevitable misconception? *Int J Sci Educ* 21, 363–371.
- Dauer JM, Miller HK, Anderson CW (2013a). Conservation of energy: an analytical tool for student accounts of carbon-transforming processes. In: *Teaching and Learning of Energy in K–12 Education*, ed. RF Chen, A Eisenkraft, D Fortus, J Krajcik, K Neumann, JC Nordine, and A Scheff, New York: Springer, 47–61.
- Dauer JM, Miller HK, Anderson CW (2013b). Students' inquiry and argumentation about carbon transforming processes. Paper presented at the National Association for Research in Science Teaching conference, April 6–9, 2013, Rio Grande, PR.
- Driver R, Squires A, Rushworth P, Wood-Robinson V (1994). *Making Sense of Secondary Science*, New York: Routledge.
- Eames C, Peck G, Eames R, Demetrios E, Mills S (1989). *Powers of Ten*, Los Angeles, CA: Pyramid Film & Video.
- Gee JP (1996). *Social Linguistics and Literacies: Ideology in Discourses*, Bristol, PA: Taylor & Francis.
- Gotwals A, Songer N, Bullard L (2012). Assessing students' progressing abilities to construct scientific explanations. In: *Learning Progressions in Science*, ed. A Alonzo and A Gotwals, Springer, New York, 183–210.
- Hartley LM, Wilke BJ, Schramm JW, D'Avanzo C, Anderson CW (2011). College students' understanding of the carbon cycle: contrasting principle-based and informal reasoning. *BioScience* 61, 65–75.
- Hershey DR (1991). Digging deeper into Helmont's famous willow tree experiment. *Am Biol Teach* 53, 458–460.
- Howe AC (1996). Development of science concepts within a Vygotskian framework. *Sci Educ* 80, 35–51.
- Jin H, Anderson CW (2012). A learning progression for energy in socio-ecological systems. *J Res Sci Teach* 49, 1149–1180.
- Kang H, Thompson J, Windschitl M (2014). Creating opportunities for students to show what they know: the role of scaffolding in assessment tasks. *Sci Educ* 98, 674–704.
- Krajcik J, McNeill KL (2009). Designing Instructional Materials to Support Students in Writing Scientific Explanations. Paper presented at the National Association for Research in Science Teaching conference, April 17–21, 2009, Garden Grove, CA.
- Maskiewicz AC, Lineback JE (2013). Misconceptions are "So yesterday!" *CBE Life Sci Educ* 12, 352–356.
- Miller H, Webster A, Dauer J, Anderson CW (2013). Alternative learning trajectories toward understanding matter and energy in socio-ecological systems. Paper presented at the National Association for Research in Science Teaching conference, April 6–9, 2013, Rio Grande, PR.
- Mohan L, Chen J, Anderson CW (2009). Developing a multi-year learning progression for carbon cycling in socio-ecological systems. *J Res Sci Teach* 46, 675–698.
- Murphy C (2012). Vygotsky and primary science. In: *Second International Handbook of Science Education*, ed. BJ Fraser, K Tobin, and CJ McRobbie, Springer, Dordrecht, Netherlands, 177–187.
- National Research Council (2007). *Taking Science to School: Learning and Teaching Science in Grades K–8*, Washington, DC: National Academies Press.
- NGSS Lead States (2013). *Next Generation Science Standards: For States, By States*, Washington, DC: Achieve. www.nextgenscience.org/next-generation-science-standards.
- O'Connell D (2008). An inquiry-based approach to teaching photosynthesis and cellular respiration. *Am Biol Teach* 70, 350–356.
- Osborne JF, Patterson A (2011). Scientific argument and explanation: a necessary distinction? *Sci Educ* 95, 627–638.
- Parker JM, Anderson CW, Heidemann M, Merrill J, Merritt B, Richmond G, Urban-Lurain M (2012). Exploring undergraduates' understanding of photosynthesis using diagnostic question clusters. *CBE Life Sci Educ* 11, 47–57.
- Pinker S (2007). *The Stuff of Thought: Language as a Window into Human Nature*, New York: Penguin.
- Posner GJ, Strike KA, Hewson PW, Gertzog WA (1982). Accommodation of a scientific conception: toward a theory of conceptual change. *Sci Educ* 66, 211–227.
- Pozo JI, Gómez Crespo MÁ (2005). The embodied nature of implicit theories: the consistency of ideas about the nature of matter. *Cogn Instr* 23, 351–387.
- Rath A, Brown DE (1996). Modes of engagement in science inquiry: a microanalysis of elementary students' orientations toward phenomena at a summer science camp. *J Res Sci Teach* 33, 1083–1097.
- Rice J, Doherty JH, Anderson CW (2014). Principles, first and foremost: a tool for understanding biological processes. *J Coll Sci Teach* 43, 74–82.
- Richmond G, Merritt B, Urban-Lurain M, Parker J (2010). The development of a conceptual framework and tools to assess undergraduates' principled use of models in cellular biology. *CBE Life Sci Educ* 9, 441–452.
- Schauble L, Klopfer LE, Raghavan K (1991). Students' transition from an engineering model to a science model of experimentation. *J Res Sci Teach* 28, 859–882.
- Smith JP, diSessa AA, Roschelle J (1994). Misconceptions reconceived: a constructivist analysis of knowledge in transition. *J Learn Sci* 3, 115–163.
- Talmy L (1988). Force dynamics in language and cognition. *Cogn Sci* 12, 49–100.
- Vygotsky LS (1978). *Mind in Society*, Cambridge, MA: Harvard University Press.
- Wilson CD, Anderson CW, Heidemann M, Merrill JE, Merritt BW, Richmond G, Sibley DF, Parker JM (2006). Assessing students' ability to trace matter in dynamic systems in cell biology. *Cell Biol Educ* 5, 323–331.
- Windschitl M, Thompson J, Braaten M (2008). Beyond the scientific method: model-based inquiry as a new paradigm of preference for school science investigations. *Sci Educ* 92, 941–967.

Supplemental Material

Interview Script:

General Tracing Questions: Tree Growing



1. [Elicit a list of enablers: air, water, soil (nutrients), and sunlight.]
“What does the tree need in order to grow?”
2. [For enablers not listed by students ask the following until all enablers, sunlight/soil/water/nutrients, are mentioned.]
“Other students told me that the tree needs X to grow. Do you agree?”
3. [Follow up with specific probes about role of all the enablers in growing.]
“How does the tree use air to grow?”
“How does the tree use water to grow?”
“How does the tree use soil (nutrients) to grow?”
“How does the tree use sunlight to grow?”
4. “Does a tree do anything with the air that surrounds it?”
[Possible alternate wording for lower-level students: Does the tree breathe?]
“What does it do? (How does it do that?) What gases are involved?”
5. “Is there a connection between exchanging gases (breathing) and growing for the tree?” [If student says yes] “What is the connection?”

Arguments from Evidence Questions

[Show the image of Karen and Mike silhouettes.]

“We are interested in how people use evidence to support their ideas. We’re going to talk about two students who disagree with each other about how plants gain weight when they grow. One student Karen said: “The plant gains most of its weight from materials that came from the air.”

“Another student, Mike said: ‘The plant gains most of its weight from materials that came from nutrients in the soil.’

1. “Who do you think is right?”

“Now let’s talk about the quality of their arguments that support their idea.” [Start with the argument that the student agrees with; either Karen or Mike could be first. Show the card associated with Karen or Mike one at a time.]

Karen who you _____ [agree/disagree] with, explains, ‘You can grow a big plant in a little pot without a lot of soil.’ Karen adds some evidence to her argument and explains ‘A seed weighing 1 g was planted in 80 g of soil. After two years the plant weighed 50 g and the soil weighed 78 g.’

1. “Can you explain Karen’s argument?”
2. “How does Karen’s argument support her idea that the plant gains weight from materials that came from the air?”
3. “Are there some weaknesses in Karen’s argument? Explain what they are.”

4. *What evidence would strengthen Karen's argument?*

Mike who you ____ [agree/disagree] with explains, 'Plants have roots to take up nutrients from the soil to grow.' Mike adds some evidence to his argument and explains 'A plant grown with no fertilizer weighed 50 g, and a plant grown with 3 g of fertilizer weighed 65 g.'

5. *"Can you explain Mike's argument?"*
6. *"How does Mike's argument support his idea that plant gains weight from materials that came from the soil?"*
7. *"Are there some weaknesses in Mike's argument? Explain what they are."*
8. *What evidence would strengthen Mike's argument?*

Mass and Energy Tracing Questions

1. *"The tree gains weight as it grows. Suppose the tree gains exactly one pound of wood. Where does that one pound of wood come from?"*
2. *"Does something in the tree's environment have to lose weight in order for the tree to gain weight?"*
[Alternative explanation for lower level students: "When you gain weight, you use the food you eat, so it loses weight. Is there anything like that for the tree—the tree uses it so that it loses weight when the tree grows?"]

[If the student answers "yes."] *"What loses weight when the tree gains weight? If the tree gains exactly one pound, can you predict how much weight [the materials named by the student] will lose?"*
3. *"What parts of the tree's environment will lose weight? How much?"*
4. *"Do you think that the tree needs energy?"*
[If yes] *"Where does the tree get its energy? Out of the things that you named before [sunlight/soil/water/nutrients], which ones are sources of energy for the tree?"*
5. *"What is the difference between the things that give the tree energy and the things that don't?"*
6. *"Do different things give the tree different kinds of energy? Explain."*
7. *"Why does a tree need energy? Where does that energy go inside the tree? Is it still energy? Does it change into other things? How?"*