Students’ inquiry and argumentation about carbon transforming processes[1]

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Abstract

Inquiry and argumentation are important student practices for science learning. We define inquiry as students taking observations, pattern-finding and developing a model that explains how the world works. We define argumentation as supporting or refuting a claim using evidence connected to reasoning using scientific principles. We describe two types of scientific arguments: pattern-based arguments and model-based arguments. This paper describes our progress toward developing a learning progression for inquiry and argumentation in a specific context: transformations of matter and energy in carbon-transforming processes.

Using empirical data from student interviews and a grounded approach, we describe four different student approaches to inquiry and argumentation: Scientific Inquiry, Naïve Inquiry, Naïve Engineering and School Science Inquiry. While “Scientific Inquiry” is our goal for environmentally literate students, many of the students we interviewed had approached to inquiry and argumentation that varied from this goal. We describe ways that these alternative approaches vary from “Scientific Inquiry” due to student’s perceived purpose of the investigation. For both pattern-based arguments and model-based arguments, instead of noticing or managing uncertainty (“Scientific Inquiry”) students were trying to find the cause of an event (“Naïve Inquiry”), trying find the winner or best approach (“Naïve Engineering”) or trying to replicate the right answer (“School Science Inquiry”). When doing pattern-based arguments, students included patterns in overall experience and not just in the data provided (“Naïve Inquiry”), considered central tendency only (“Naïve Engineering”) and engaged in confirmation bias (“School Science Inquiry”). In model-based arguments, students substituted claims about tracing matter and weight data as evidence with alternative claims and evidence.

We have defined our goal for environmentally literate students and have identified three alternative student strategies, but have not yet developed a full learning progression for inquiry and argumentation about carbon-transforming processes, because as yet, we have not found these student practices to be hierarchical. We conclude with some thoughts about implications for teaching and curriculum development around the idea that these alternative conceptions of the purpose of the investigation could be related to the way that inquiry is conducted in the classroom and how our framework connects with studies of teacher practice.

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Introduction

Inquiry and *argumentation* describe complex and interconnected sets of scientific practices that are used both colloquially and in the scholarly literature. Both terms are understood differently by different scholars and take on different meanings depending on context. In this paper we describe our progress toward developing a learning progression for inquiry and argumentation in a specific context: transformations of matter and energy in carbon-transforming processes. We briefly discuss the meaning of these terms *inquiry* and *argumentation* as we are using them in this research.

Inquiry. The word "inquiry" is used in many contexts with different associated meanings. Inquiry is sometimes used with a very broad meaning, including generally *all* the practices in which scientist engage (NRC's *A Framework for K-12 Science Education*, 2012). We define inquiry more specifically as collecting observations and describing patterns in order to create models that explain natural phenomena (Figure 1).

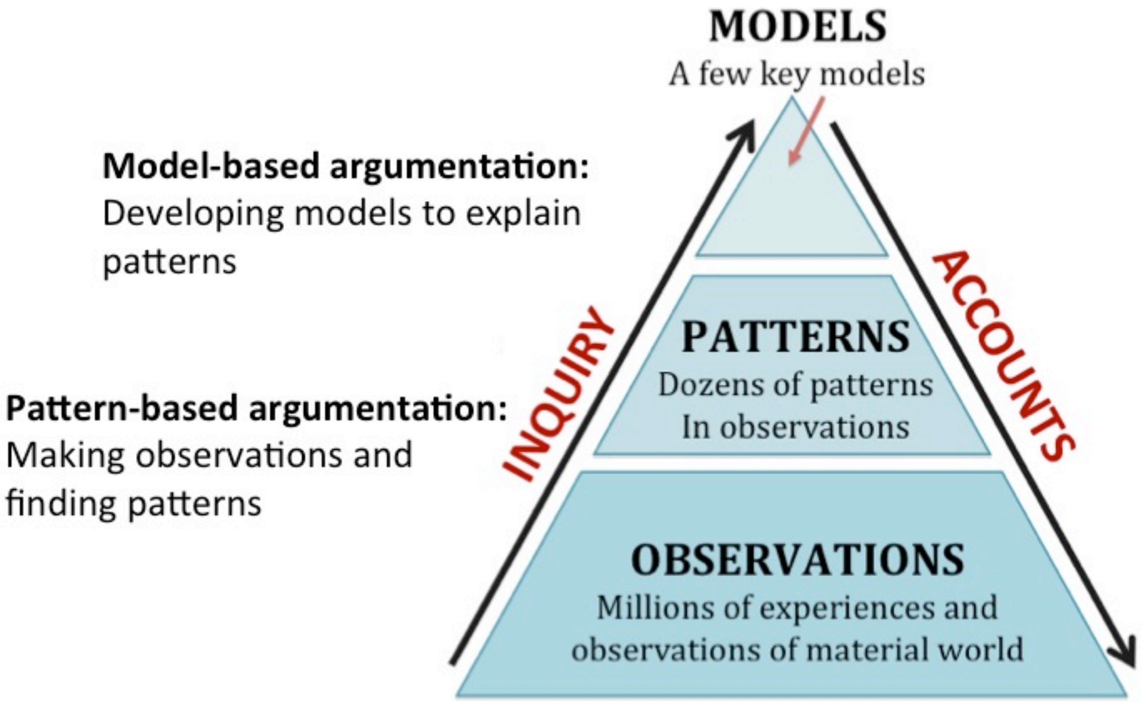

Figure 1. Observations, Patterns, Models Inquiry/Application Triangle

We concur with Windschitl (et. al. 2008) who describes model-based inquiry as a means to develop defensible explanations about the way the natural world works. An idea, represented as a system of related processes, events or structures, is tested against real-world observations and the adequacy of the idea is assessed. This differs from defining inquiry as all practices a scientist might do. For example, using a model to make a prediction can play a critical role in a scientific investigation, but we would label this practice as application of a model (accounts). Our definition also differs from those that define inquiry as consisting of a specific sequence of practices, such as the steps of the scientific method. Our definition also contrasts with the NRC's *A Framework for K-12 Science Education* (2012, Figure 3.1 p. 60) description of the practices of scientists, in that we emphasize pattern finding as an important practice that occurs between observations (data collection) and models (theories and models). In the NRC*'s Framework* the specific practice of pattern finding is somewhat hidden and probably a diffuse aspect of all three panels in Figure 3.1 ("Investigating," "Evaluating" and "Developing Explanations and Solutions"). Our emphasis reflects the idea that many scientists do spend a significant amount of time finding and evaluating patterns in data (for example, work using inferential statistics), and reflects the idea that in a classroom pattern finding is essential students to interpret the data that they collect.

We follow Metz (2004) in seeing *dealing with uncertainty* as a key issue in students' understanding of scientific inquiry. Our knowledge of the past, present and future is inevitably uncertain because of the indeterminacy of reality. For example United States Secretary of State Donald Rumsfield once said: "There are known knowns; there are things we know we know. We also know there are known unknowns; that is to say, we know there are some things we do not know. But there are also unknown unknowns – the ones we don't know we don't know." The reason we do investigations is to reduce the number of unknowns—especially unknown unknowns. Scientific inquiry requires thinking that notices and manages uncertainty, whereas, non-scientific thinking is often characterized by unwarranted certainty, found in individuals who think they understand, but really they do not (Kahneman, 2011; Covitt et al 2013).

The NRC's *A Framework for K-12 Science Education* (2012) recognizes two kinds of investigations that reduce uncertainty, but with different purposes: scientific inquiry, and engineering design. Scientific inquiry is driven by our desire to understand and explain phenomena, and is focused on predicting and explaining observable phenomena by building models and theories about the world. In scientific inquiry, a key practice of scientists who do inquiry is identifying, quantifying and managing this uncertainty in data and conclusions. For example, scientists commit to rigor in research methods during measurements, use statistical techniques to understand variation in data, and give authority to arguments from evidence rather than to individual people. The second kind of investigation recognized by The NRC's *Framework* (2012), engineering design, is aimed at designing and building systems, and comparing the benefits and/or costs of different systems or courses of action. Engineering design is driven by our desire to control systems and phenomena for our benefit. As with scientific inquiry, managing uncertainty in data and conclusions is a key practice in engineering, but in this case the uncertainty is primarily in procedural aspects like tools and methods.

Argumentation. Like inquiry, argumentation has multiple meanings in the scholarly literature and in everyday language. Argument usually connotes an attempt to persuade; we engage in many arguments that have little to do with science. In this paper we are particularly interested in what the NRC *Framework* (2012) labels "engaging in argument from evidence." We are interested in this kind of argumentation as a key student practice embedded in our definition of inquiry and inquiry practices (the up arrow in Figure 1 above). Analyses of arguments from evidence have commonly relied on Toulmin's (1958) argumentation framework or on simplifications of that framework such as the claims-evidence-reasoning framework (McNeill & Krajcik, 2008; 2011).

We refer to Figure 1 to illustrate two kinds of arguments from evidence that are commonly involved in scientific inquiry: *Pattern-based arguments*, in which the claims are about patterns in data (patterns providing evidence about tracing matter in our case), the evidence consists of individual observations or data points, and the reasoning argues that the patterns are "real." And *model-based arguments,* in which the claims are about explanatory models (atomic-molecular explanations of carbon-transforming processes in our case), the evidence consists of patterns in data, and the reasoning argues that the data support or reject a hypothesis based on scientific principles, and connects the model to more general theoretical frameworks or other models. Thus most scientific investigations involve both pattern-based arguments and model-based arguments as two different kinds of arguments from evidence (Figure 1).

Student approaches to inquiry and argumentation. Others have reported various students' approaches to investigations that represent vary from scientific approaches that are characterized by inquiry and argumentation. For example, Rath and Brown (1996) reported on how students explore natural phenomena in a summer science camp. They reported on six "modes of engagement" that students exhibited in working with systems such as siphons:

> The six frequently observed orientations toward phenomena include exploration mode (to find out about the object and study its basic properties), engineering mode (a focus on making something happen), pet care mode (a personal connection focused on nurturing), procedural mode (an imitation and step-following orientation), performance mode (soliciting attention using the phenomenon as a prop), and fantasy mode (an imaginative play activity which builds on some aspect of the phenomena). (Rath & Brown, 1996, p. 1083).

All of these modes represent different approaches that students have when approaching the problem, resulting in different goals and strategies. Likewise, Schauble, Klopfer, and Raghavan (1991) reported on a study in which they compared science and engineering models of investigation: "When children are engaged in science experiments, the goal of which is to understand relations among causes and effects, they often use the engineering model of experimentation, characterized by the more familiar goal of manipulating variables to produce a desired outcome." They reported progress in helping students adopt the science model, which was "associated with broader exploration, more selectiveness about evidence interpreted, and greater attention to establishing that some variables are not causal. The findings suggest that research on scientific inquiry processes should attend not only to the science content students are reasoning about, but also to their beliefs about the goals of inquiry." Similarly to these two studies, we investigated how students reason about claims and evidence as a way to reveal the student's approach, strategies and goals for inquiry and argumentation, as compared to the scientific approach.

With respect to pattern-based inquiry and argumentation, many have described the difficulties that kids have with understanding measurements, for example student understanding of variability in data, simple statistics and modeling data (Lehrer et al 2011; Lehrer & Kim, 2009; Lehrer et al 2007; Petrosino et al 2003), or in student analysis of bivariate data (Cobb et al. 2003). We also investigated student's approaches to pattern-finding argumentation when asked to reason about a set of data, as compared to the scientific approach.

Carbon-transforming processes as a focus for inquiry. Others have described student inquiry and argumentation practices using learning progressions, for example, Berland & McNeil (2012) that describe a increasing levels of sophistication about argumentation using three dimensions of increasing complexity: 1) instructional context, 2) argumentative product and 3) argumentative process. They discuss ways to support student argumentation in the classroom by simplifying the instructional context and developing useful classroom norms. Schwarz et al. (2009) describe empirical levels of student modeling practices that moved from constructing illustrative to using models to explain, then evaluating and revising models.

These learning progression frameworks were created independently of a particular content domain, in contrast to our work, which is specific to inquiry learning goals about carbon-transforming processes for environmental literacy. Inquiry practices, including pattern-based and model-based arguments from evidence, are an important component of environmental science literacy. An environmentally literate student has a capacity to understand and participate in evidence-based discussions about complex socio-ecological systems. Here we focus on one specific domain of knowledge and inquiry practice—carbon-transforming processes (processes that generate, transform and oxidize organic carbon). This domain is important because the primary cause of global climate change is the current worldwide imbalance among these processes due to human activities.

We have developed a learning progression framework focusing on student accounts (explanations and predictions) of carbon-transforming processes (Jin and Anderson, 2012; Mohan et al., 2009). In the accounts learning progression, we have documented how students move from informal discourse about carbon-transforming processes to more scientific accounts, in elementary, middle, and high school contexts (Mohan et al., 2009). Our inquiry learning research will be a companion work and the aim is to develop a learning progression framework about student inquiry while conducting investigations of carbon transforming processes. Inquiry practices, including arguments from evidence, lead to a student's ability to define a problem and determine what evidence matters to the problem.

We are especially interested in how students can use arguments from evidence as a part of inquiry into phenomena that involve carbon-transforming processes. Specifically, we are interested in how students reason during investigations where macroscopic measurements and observations provide evidence about chemical change at an atomic-molecular scale. Investigations of this nature involve tracing of matter and energy during a process of either quantitatively accounting for the amount (particularly in terms of mass) or qualitatively accounting for the source (particularly identifying the type of energy).

An example of an investigation of carbon-transforming practices comes from our *Carbon: Transformations in Matter and Energy (Carbon TIME)* curriculum. The investigation begins with questions about what happens when mealworms move around. How do mealworms have energy to move? Students observe that mealworms moving around a container lose weight and breathe out carbon dioxide, indicated by a color change in bromothymol blue (BTB) from blue to yellow. Students must develop accounts of how mealworms get energy to move that are consistent with this evidence. This type of investigation requires students to make careful measurements, look for patterns in the data across student groups, and to reason by using atomic-molecular conceptual models and by tracing matter and energy.

Methods

Our initial lens for building a learning progression framework for arguments from evidence included the idea of uncertainty. Our first iteration of the learning progression framework is about students noticing and managing uncertainty in terms of measurements, pattern finding, and argumentation. Strategies for reducing uncertainty in pattern-based arguments include the following:

- A strategy for measurement: How accurate and precise are the measurements? Can I trust the data?
- A strategy for pattern finding: What is the central tendency and variability of the data? Is there a signal in the noise?

Strategies for reducing uncertainty in model-based arguments include:

- A strategy for formulating hypotheses: How can we develop claims or tentative models that can be evaluated with evidence?
- A strategy for testing models or alternative hypotheses with evidence: What conclusions can we draw based on the evidence?

We expected that less accomplished students would either feel false certainty (i.e., not recognizing sources of uncertainty in their data and conclusions), or fail to notice the relevance of data to claims about processes (e.g., not seeing that weight gain must mean that matter is entering a system from somewhere). We expected that more accomplished students would be able to identify, and sometimes quantify, sources of uncertainty in their investigations and to develop strategies to reduce uncertainty in their data and conclusions. In this paper we report on our progress in testing these hypotheses with data and refining our tentative learning progression framework.

To study student inquiry practices across a range of ages, we collected interview data from two populations: undergraduate pre-service elementary school teachers at a large Midwestern university and middle and high school students participating in the *Carbon TIME (Transformations in Matter and Energy)* program. The undergraduate students were in a general science class that is organized around topics that are found in the state K-8 science curriculum (e.g. climate, astronomy, ecology and chemistry) with an overarching theme of matter and energy in chemical and physical change. The course has been described elsewhere (Rice et al. submitted) and is taught based on principle-based reasoning, using physical models of matter and energy at multiple scales, using precise language and examples drawn from students' lives. The second population from *Carbon TIME* was 6th to 12th grade students in Michigan, Washington, California, Colorado, Maryland and Pennsylvania during 2011-2012 and 2012-2013.

In the interviews, undergraduate students only (n=20), were asked to evaluate the quality of a small data set of plant weights before and after growing. Both undergraduate students (n=20) and middle and high school students (n=22) evaluated the quality of two arguments that included numerical evidence about the source of mass (air or soil) of a growing plant. Our interview questions probed students' strategies for developing pattern-based arguments (the Plant Data question: Appendix A) or model-based arguments (the Karen and Mike question, Appendix B). Responses to the interviews were analyzed using a grounded approach with multiple iterations of analyzing student responses and developing our framework. For the undergraduate students, the interviews were administered before and after the teaching of chemistry (matter and energy), biology and ecology. For *Carbon TIME*, the interview and written assessments were administered before and after the teaching of at least three out of six *Carbon TIME* units (at least 6 weeks of instruction). The investigations in these units involve measurements of changes in mass of organisms and changes in color of BTB, as described above for the cellular respiration of mealworms.

Results and Findings

We used the patterns identified during the interview analysis process to develop a tentative framework that describes four types of student reasoning, each associated with a different way of framing the purpose of an investigation. Although our goal was to describe a learning progression in terms of hierarchical levels of sophistication, we instead found three alternate student strategies observed across all three age groups that were highly dependent on context, so that often a single student engaged in multiple types during one interview. First we describe these four patterns in student reasoning and then excerpts are used to illustrate typical student responses that fit into the framework for A) pattern-based arguments using the "Plant data" interview questions and B) model-based arguments using the "Karen and Mike" interview questions.

General Framework: Four Approaches to Inquiry about Carbon-transforming Processes

We characterized the students we interviewed as exhibiting four general strategies or approaches to inquiry, based on different ideas about the purposes of inquiry, and consequently different strategies or procedures for engaging in or evaluating inquiry.

1. Scientific inquiry. Using a scientific framing during investigations about carbon-transforming processes results in practices that we consider our goal for environmentally literate students (Figure 1 and Table 1). These practices include a strategy for measurement by noticing and even attempting to quantify:

experimenter error, systemic error (accuracy), and limitations of instruments or techniques (precision). During pattern finding a student engaged in Scientific Inquiry would consider both central tendency and variability in data; during argumentation a student engaged in Scientific Inquiry would reason about a claim or formulate a hypothesis, by tracing matter or energy, and evaluate evidence using an atomic-molecular model and using principles of conservation to constrain the argument. In scientific inquiry conclusions are warranted by the data and by scientific reasoning.

2. Naïve inquiry. Like Scientific Inquiry, Naïve Inquiry is associated with Rath and Brown's "exploration mode" or Schauble, et al.'s "scientific model." Students using a Naïve Inquiry approach, however, focused primarily on the cause of a phenomenon rather than trying to trace matter and to relied on personal experience in addition to considering the data. For example, "sunlight caused the plant to grow, but darkness did not cause the plant to grow" (Table 1).

This framing shares with Scientific Inquiry a drive towards understanding the world, but students who use Naïve Inquiry understand only in terms of natural, logical results. We would connect Naïve Inquiry with force-dynamic explanations in our learning progression for student accounts (Mohan et al. 2009), where students' explanations are focused on actors and enablers rather than atomic-molecular explanations of a process. Braaten and Windshitl's (2011) described different types of scientific explanations using philosophical theories. Naïve inquiry is similar to Braaten and Windshitl's (2011) "covering law" scientific explanations, which are about "deductive arguments explaining events as natural, logical results of regularities expressed by law." Students engage in this type of explaining without reasoning about underlying scientific mechanism. For example, a "covering law" could be a student's perception of natural tendency, or the Aristotelian notion that objects have a natural motion of things returning to their original place in the world. For example, decay is an Aristotelian natural motion, and life forces are what keep living things from decaying (Jin and Anderson, 2012).

A key aspect of Naive Inquiry is that it offers an alternate way to deal with uncertainty that depends on cumulative experience rather than privileging data collected under controlled conditions. Evidence could come from a variety of sources, including student experience and authoritative books or people that cumulatively create a pattern. Areas of uncertainty are bivariate: the evidence is either confirmatory or not. If students evaluate the data during arguments about pattern finding, the evaluation is in terms of direction, but not in terms of magnitude, central tendency or variability. A student taking a Naïve Inquiry approach might identify areas of uncertainty in measurement primarily as errors caused by the experimenter (e.g., not putting the plant in enough sunlight, leaving a closet door open) without critique of the data in terms of validity or reliability. The student may not notice any areas of uncertainty during model-based arguments, but instead adopts any evidence, including personal experience or explanations, that confirm the relationship between cause and effect. During hypothesis or model-testing the focus is on verification rather than falsification, and students do not rigorously consider alternative hypotheses.

3. Naïve Engineering. Another alternative framing for inquiry implicitly adopts an engineering frame for inquiry as described by Schauble et al. (1991) and Rath & Brown (1996). Students taking a Naïve Engineering approach frame the investigation around "finding the winner." (Table 1). The goal, rather than to understand a process, is to manipulate or control variables to produce a desired outcome. Shauble et al. (1991) showed that during cause and effect investigations students who adopt an engineering model instead of a scientific model had a poorer strategy for managing uncertainty; they were less selective in interpretation of evidence and gave less attention to establishing causality in variables. In this case, students may use measures of central tendency such as the average to determine "winners" and "losers." Students taking a naïve engineering approach may be less concerned about issues of generalizability than students focusing on inquiry (or a more mature engineering approach). For these students the winner is the winner; they are less concerned about what might happen at other times or in other contexts.

4. School science inquiry. A third alternative framing for inquiry, "School Science Inquiry," is about "replicating the right answer" (Table 1). School Science Inquiry resembles Rath & Brown's "procedural mode (an imitation and step-following orientation)." In this case, the right answer is known ahead of time and based on the authority of science—received knowledge from the teacher, textbooks, or other authoritative sources. Inquiry experiences are meant to replicate these authoritative findings. From this perspective, there is no underlying uncertainty about how the world works; there is only uncertainty about the ability of the student to follow procedures correctly and arrive at the right answer, which translates into concern about the accuracy of measurement and procedures that follow "the scientific method." And for students, a critique of methods becomes a process of finding the mistakes that may prevent the student from getting the right answer.

	Pattern-based arguments		***Model-based arguments***	
Perceived Purpose of Investigation	***Strategies for measurement validity and reliability***	***Strategies for patterns in data***	***Strategies for formulating hypotheses***	***Strategies for testing hypotheses***
Scientific inquiry Notice and manage uncertainty: What conclusions are warranted by the data and by scientific reasoning?	Avoid systemic error (accuracy) Consider and quantify limitations of instruments or techniques (precision)	Focus exclusively on finding patterns in validated and replicable data. Considering both central tendency and variability.	Claim involves tracing matter or energy. Evaluate claims with evidence.	Evidence is evaluated by reasoning: using an atomic-molecular models and principle of conservation to constrain the argument. Test models or alternative hypotheses using evidence.
Naïve inquiry Find the cause: What made an event happen?	Consider data collected in an investigation as part of the totality of personal and vicarious experience.	Look for patterns in overall experience, not just data presented. Confirmation bias: Look for evidence that confirms the cause.	Claim is cause and effect regardless of stated research question.	Evidence, including personal experience, shows connection between cause and effect. Focus on verification rather than falsification and do not rigorously consider alternate hypotheses.
Naïve engineering Find the winner or the best approach (engineering approach): What way works best?	Look for data that determines "the winner" or the best way to accomplish a goal.	Fair test: Consider central tendency only to choose the winner or to decide what works.	Claim is about what works or how to make something happen.	Evidence, including personal experience, identifies winner or what works. Focus on finding the winner without respect to whether the winner represents a more general mechanism.
School science inquiry Replicate the right answer: How can I make the correct measurements to arrive at the correct result?	Design experiments and collect data "the right way," following rules that may or may not be relevant to the hypothesis being tested (e.g, controls, numbers and kinds of measurements)	Confirmation bias. Look for data that give the right answer.	Claim is scientific correct answer regardless of stated research question.	Evidence is authority of canonical science, confirmed by data. Data collection or experimental design strategies occur for their own sake, without regard to whether they help to evaluate the hypotheses.

Table 1: Purpose of the investigation frames student strategies for pattern-based arguments and model-based arguments

Pattern-based Arguments

We used the Plant Data question (Appendix A) to investigate students' approaches to developing pattern-based arguments. As described above, we saw pattern-based arguments as requiring two kinds of strategies for reducing uncertainty: validity and reliability in measurement, and pattern finding. The Plant Data question prompted students to decide if there are patterns in the data that support the claim (specifically, is there a signal indicating positive relationship between plant growth and increase in mass?). "Scientific Inquiry" practices in pattern-finding involve considering the central tendency of the data and also variability in the data. So, in this interview question, a good response would include noticing that there is little pattern in the data (small effect size) if the outlier is not included. The data are not statistically significant for an increase in mass.

An example of a Scientific Inquiry response comes from Josh (undergraduate):

> JOSH: All right. So the data that he collected on these … I think it's six plants. The only one that I saw was a significant weight change was like the third plant, where it gained just over a gram. The other plants, they didn't really have any type of significant weight gain or loss. And some of them did actually lose weight. So that doesn't support his theory that as they're growing, they gain weight. Unless he's not watering them; to see whether he's watering the other ones or taking care of them, however.
> But the weight gain and loss was pretty miniscule, I thought. So I didn't think it was anything really to give any conclusive evidence. And then I think like the one that did gain over a gram was just kind of a fluke.
> INTERVIEWER: Okay. Why do you say that?
> JOSH: Just because of all of the other numbers. It just doesn't match up.

In considering whether the general conclusion that plants gain weight as they grow, Josh looks at both central tendency and variation in the data. He noticed that none of the plants have a large change in weight, except one sample which was likely a "fluke" or outlier. Because of this, the data do not "give any conclusive evidence." Josh also noted potential sources of unreliability that are not addressed in the description of the investigation.

The majority of students gave responses that did not match our criteria for Scientific Inquiry. The approach of most students was to implicitly assume that data were trustworthy unless someone made a mistake. For example Maggie (undergraduate):

> MAGGIE: I think that it does support the predictions, because on average they did gain more weight… and there's probably other contributing factors as to why the other ones lost weight.
> INTERVIEWER: Okay. Are there particular lines of data that support the claim and some that do not?
> MAGGIE: Yes. The first one, the third one, and the fourth one support the claim, whereas the second, the fifth, and sixth don't support it.
> INTERVIEWER: Okay. So what are the possible sources of error in the experiment?
> ….

> MAGGIE: There's - they could have again just weighed it wrong or mis-wrote down a number, because I know I did that sometimes. Like maybe some soil fell out and so that was so weight lost. Other ones might not have gotten as much sunlight as the others. They didn't grow as much so they didn't weigh as much.
> Soil, like maybe it fell out of one and fell into the other which would be like why this one gained so much weight; the third one like gained a lot more weight than the others.
> INTERVIEWER: Okay. Do you have any comments or thoughts about the quality of the data from this experiment?
> MAGGIE: It doesn't say how long she weighed it.

We note the contrast between Josh, who observes that the data themselves are inadequate for the purpose of establishing a general pattern, and Maggie, who implicitly assumed that the data merely needed to determine “a winner.” Thus Maggie’s concerns focused not on whether the patterns in the data are generalizable but on whether there might be a mistake that would make the individual measurements inaccurate. Most of the students, like Maggie, were able to discuss areas of internal validity, primarily potential errors in measurement, instrumentation, contamination and extraneous factors like the plant’s history and exposure. Few students discussed reliability or noticed the outlier and its impact on the quality of the data.

Maggie, like most of the students we interviewed, did not discuss patterns in the data in terms of effect size or variability. She noted the difference in average and discussed individual points that were positive or negative, but did not discuss magnitude (effect size), or variability in the data. This type of reasoning does not provide Maggie with a way to manage uncertainty in terms of identifying a signal in the data that might support or refute a claim. Most students also readily accepted the claim because they expected it to be true, exhibiting what Kahneman (2011) describes as a confirmation bias.

The Plant Data questions does not always clearly reveal students’ strategies for pattern finding, due to the nature of the interview question, which was about the causal relationship between growth and plant mass. We feel that this is itself an important finding, though: In many inquiry situations, students who already feel that they know the “right answer” do not look skeptically at data that seem to confirm what they already believe.

Model-based Arguments

During argumentation, scientists ask if the data support the claim. Strategies for doing classroom inquiry using a claims-evidence-reasoning framework have been described by others (McNeill & Krajcik 2008; McNeill & Krajcik 2012). Students are taught to argue by connecting empirical evidence to a model-based claim with reasoning that involves using a scientific principle that describes why the evidence supports or does not support the claim. It is well documented that people of all ages have difficulty in constructing well-substantiated arguments (Sadler, 2004), although the practices of students who are not environmentally literate have not been well described. The purpose of this paper is to describe practices of students as they progress towards more sophisticated evidence-based arguments.

We used the Karen and Mike question (Appendix B) to assess students’ approaches to model-based arguments from evidence. We asked students a series of questions about two hypothetical students, Karen and Mike, and their respective claims and evidence. These interview questions prompt students to add their reasoning about these two arguments. Good answers to these questions use weight data to trace matter to describe a model for how plants gain weight. Good answers also apply the principle of conservation of matter to constrain the results of the investigation. For example, Kobi (12th grade) and Carlos (undergraduate):

> **Karen's experiment**
> TEACHER: Can you explain Karen's argument?
> KOBI: Yes. Because the seed started out as one gram and the plant ended up as 50, which means 49 grams came from somewhere to be part of the plant now. And if only two grams of soil were used, then the other 47 grams must have come from the air.
> TEACHER: Okay. How does Karen's argument support her idea that the plant gains weight from materials that come from air?
> KOBI: Because the 47 grams that didn't come from the soil had to have come from somewhere.
>
> **Mike's experiment**
> INTERVIEWER: So first can you explain Mike's argument?
> CARLOS: So I guess what he's saying is by adding the fertilizer; adding more nutrients to the soil so the plant is growing more, you know, so trying to prove his argument that plants get most of their mass from the soil.
> INTERVIEWER: Mm-hmm. How does Mike's argument support his idea that plan gains weight from materials that came from the soil?
> CARLOS: Well he's adding more materials to the soil with the fertilizer and trying to prove that since there's more material in the soil with the fertilizer, more atoms to be taken up, the plant grew more I suppose.
> INTERVIEWER: Can you use any of the numbers to kind of support what you're saying?
> CARLOS: Well - so the plant without fertilizer weighs 50 grams and that says the plant grown with three grams of fertilizer weighs 65 grams.
> So I mean, he's arguing that if, you know, there's more in the soil - there's more nutrients in the soil, but really there's only three grams more soil and nutrients in the soil and the plant still grew more. So it still has to be something else going on there besides the extra fertilized soil.

Kobi reasons about Karen's experiment by applying conservation of matter saying that the plant's weight "had to have come from somewhere" which constrains the interpretation of the experiment. This student also recognizes that the purpose of the experiment is about tracing matter, a practice characterized by "Scientific Inquiry" in our framework (Table 1). Carlos also practices "Scientific Inquiry" by recognizing that the purpose of the experiment is about tracing matter when reasoning about Mike's experiment. Using this frame for the experiment and constraining the interpretation of the evidence using conservation of matter, Carlos evaluates Mike's hypothesis by correctly notices that the three grams of fertilizer cannot account for all of the 15 grams that the plant gained.

In contrast, the majority of students that we interviewed did not use the mass data to trace matter. Instead of seeing the purpose of the experiment as tracing matter and developing a model for the source of materials for plant growth, they framed the purpose of the experiment to: 1) find the cause of an event (Naïve Inquiry), 2) find the winner or best approach (Naïve Engineering), or 3) replicate the right answer (School Science Inquiry). Here is how Jess (8th grade) responded to Karen's experiment:

> **Karen's experiment**
> TEACHER: And Karen says you grow a big plant in a small pot without a lot of soil. And here we have a seed that weighs a gram and the soil that weighs 80 grams and she's planting the seed. And a

year later the soils weighs 78 grams but now the plant weighs 50 grams. What does that do to what Karen is saying here? Do you agree with her?
JESS: That's kind of hard. I agree with her because …
TEACHER: How could you explain with what Karen did?
JESS: I think she … what she did was put soil in there.
TEACHER: And there wasn't very much.
JESS: Yeah, there wasn't much and watered it a little, put the seed in there when she was putting the soil in there and I'm thinking she probably stuck it next to a window where it could get the sun on it and that way it can grow. But I agree with both of them because like … I don't know.
TEACHER: Does her argument though that she has in her experiment, does it support the idea that plants gain their weight from air?
…
JESS: I think it supports her statement because …the seed weighs one gram now because it's just a tiny little thing and nothing has grown out of it and the soil is going to weigh more. I kind of agree with her now.
TEACHER: Well, what's the evidence that proves to you that she's right that plants gain their weight from air? Because that's what Karen says, right?
…
JESS: The plant needs air to grow.
…
TEACHER: Okay. So, how does her experiment prove it? What does your data show?
JESS: It shows that she didn't put that much soil in her little flowerpot. Then she got the seeds in there and then she watered it. And then the air helps the plant grow and get stronger and now the plant weighs 50 grams and then the soil weighs less, so I just …
TEACHER: So, where do you think that 50 grams came from? Do you think it came from the soil?
JESS: The soil and …
TEACHER: It was 80 and 78, right?
JESS: Yeah. I think it came from the soil because the plant has to like, eat from the soil and all the nutrients. So, it weighs less because the plant ate it all up and now it's like 50 grams now because it needed that food and the air.
TEACHER: Well how much did the soil lose? Eighty and 78, right? So, how many grams did the soil lose?
JESS: Like 2.
TEACHER: Two grams, right?
JESS: Yeah.
TEACHER: And how many grams did the plant gain?
JESS: Like a lot.
TEACHER: So, you think … what do you think? Do you think it came from the dirt?
JESS: Yes, I do. I do because … I mean if the soil weighs like less now then I think the plant ate it all.

We characterize Jess as giving a Naïve Inquiry-type response. Jess agrees with Karen's claim, but she is substituting Karen's stated claim "the plant gains most of its weight from materials that came from the air" with an easier causal claim "the plants need air to grow" (substituting an easier question, Kahneman, 2011). So in spite of repeated prompting by interviewer, Jess does not, like Kobi, conclude that "49 grams came from somewhere to be part of the plant now." Jess also sees no contradiction between agreeing with Karen that the mass came from the air and agreeing with Mike that the mass came from the soil. For Jess the mass data are not central to the story about plants that "the air helps the plant grow and get stronger" and "the plant ate it all [soil].” Jess is seeking evidence that connects the cause to effect, in particular things that might cause the plant to grow, including “air” and “the soil and all the nutrients.”

Below is a response to the interview question about Mike’s experiment from Mabel (7th grade):

> **Mike’s experiment**
> TEACHER: So, Mike adds some evidence to his argument and explains that the plant with no fertilizer weighed 50 grams, and a plant grown with three grams of fertilizer weighed 65 grams. Can you explain what Mike’s argument was?
> MABEL: His argument was that the plant was growing better with the fertilizer because it is—it has nutrients in it and it helps the roots grow and it takes the nutrients up through the roots and puts it towards the trunk of the tree.
> TEACHER: Okay. So, how does—how is Mike’s argument supported by this evidence?
> MABEL: It’s supported by the weight. He weighed it, one without fertilizer, and then, he added three grams of fertilizer and weighed it after the same amount of time and it grew more.
> TEACHER: Okay. Would you say there are some weaknesses in his argument?
> MABEL: There are some weaknesses because he could’ve used a different pot, like a different brand of pot and it could’ve weighed more. Or he could’ve used more dirt to put in it and that could’ve made it weigh more.

Here the student, Mabel, engages in Naïve Engineering by substituting the experiment’s stated claim “the plant gains most of its weight from materials that came from nutrients in the soil,” with a different claim that the best approach is about “the plant was growing better with fertilizer.” In this case, the “best approach” is the fertilizer, which helps the plant grow better, and Mabel considers this a satisfying result without reasoning using the data to trace mass from the soil to the plant. To Mabel, the plant increased in mass indicating that it grew better with fertilizer, but Mabel did not notice that the plant’s increase in mass was greater than the mass of the fertilizer added. Mabel could also be engaging in School Science Inquiry, especially when prompted about weakness in Mike’s argument. Here Mabel substitutes the experiment’s real claim with “How can I make the correct measurements to arrive at the correct result?” In this type of reasoning the only weaknesses in Mike’s argument are procedural mistakes that the experimenter might have made, such as the choice of pots that was used in the experiment or the amount of soil that was used.

Students doing School Science Inquiry tended to pay less attention to evaluating Karen and Mike’s claims than to whether they used the correct measurements to arrive at the correct result. In this case, students critique the experimental design or methods of the study for their own-sake, without regard to the claim or hypothesis. For example, Abby (9th grade):

> **Karen’s experiment**
> TEACHER: OK, so how does Karen’s argument support the idea though that the materials came from the air?
> ABBY: She isn’t really, well, she doesn’t really add a lot of data about how the air can actually help it grow.
> TEACHER: OK. So how that mentioned anything about the air specifically in there, so that is a weakness in her argument. Can you think of anything that might support her idea that it came from the air from the data that she did collect?
> ABBY: If she had more plants and grow in bigger pots or in smaller pots and different pots and was able to prove that you can get it from air, then yeah.

> TEACHER: OK, so you think that if you had done it several times, more pots, different sizes of pots that would strengthen her argument.
> ABBY: Yeah.

This student, Abby, is able to offer some criticism of the experiments related to experimental design and methods by discussing the size of pots and the number of replications in Karen's experiment. This is useful criticism, although, it is offered without engaging in claims, evidence, reasoning or tracing matter. Instead of reasoning about the evidence, these students are asking: "how can I make the correct measurements to arrive at the right answer?" This way of reasoning about an experiment may be related to students experiences in classrooms where investigations are focused on procedure, rather than reasoning.

Discussion

As is common in learning progression work, we began this research with some unexamined assumptions that are called into question once we hear what students have to say. In this study, the unexamined assumptions about the purposes of investigations are implicit in Figure 1, which is how we frame scientific inquiry. We designed tasks to elicit students' performances with respect to two key aspects of scientific inquiry: (a) collecting measurements and finding patterns in data and (b) developing or using models to explain those patterns. In scientific practice, each of these performances is associated with particular forms of arguments from evidence that identify and account for sources of uncertainty in the claims being made.

Not surprisingly, we found that many of the students weren't very good at the scientific performances we were interested in. One approach to our research could be to map out specific deficiencies in their performances—faults in their claims, evidence, and reasoning. However, we see a more important pattern in our data: many students weren't *trying* to be good at the scientific performances we were interested in. Instead, they were making different assumptions about the nature and goals of the tasks we gave them. Here are some thoughts about those differences.

Pattern-based Arguments

We find it useful to consider a quote from Chico Marx in *Duck Soup*: "Who are you going to believe, me or your own eyes?" Students engaged in Scientific Inquiry, in Naïve Inquiry or Engineering, and in School Science Inquiry have different answers to this question:

- *Scientific Inquiry:* The task in scientific inquiry is generally to find patterns in and explain *only* observations that have been made according to recognized scientific protocols. Ignoring past experience and sometimes the evidence of our own senses, since our senses can deceive us in multiple ways.
- *Naïve Inquiry and Engineering:* Students engaged in Naïve Inquiry and Engineering generally choose to believe their own eyes. In their responses to our tasks, this means that they often referred to their own experiences and conclusions, even when discussing the data provided in the interview tasks. Those bits of additional data were not sufficient to change beliefs based on their own depth of experience.
- *School Science Inquiry:* Students taking a School Science Inquiry approach do not look to the data as a meaningful source of information about the interpretation of phenomena. They know that the correct explanations come from scientific authority, so their concerns with data and measurement focus mostly on whether procedures were done correctly to arrive at the known result.

Thus the practices of data collection and finding patterns in data are “unknown unknowns” to most of the students we interviewed. Descriptive and inferential statistics—the means by which scientists identify, assess, quantify, and manage the uncertainties inherent in observation and measurement—provide a solution to a problem that does not exist for them.

Model-based Arguments

We see similar issues in students’ approaches to model-based arguments. The model-based argumentation task discussed in this paper, the Karen and Mike question, involved contradictory claims about tracing matter—the origins of the matter from which plants are made. Both Karen and Mike provided evidence in support of their claims, but in both cases the reasoning connecting claims with evidence was flawed. In this case, students taking different approaches interpreted the claims, and therefore the supporting evidence and reasoning, quite differently.

- *Scientific Inquiry:* Students taking a Scientific Inquiry approach recognized conservation of mass as an important constraint and used this principle to evaluate Karen and Mike’s reasoning by connecting the claims made to the evidence provided, and then connecting both claims and evidence to an explanatory model. They noted that although Karen’s evidence supports a claim that the mass of the plant does NOT come mostly from the soil, it does not support Karen’s claim that the mass DOES come from the air. In Mike’s case, they noted that the evidence actually contradicts his claim, since the small amount of added fertilizer could not account for the large amount of plant growth. This practice allows the students to engage in hypothesis formulation and model testing, eventually connecting the evidence to a theoretical explanatory framework, like photosynthesis.
- *Naïve Inquiry:* Students taking a Naïve Inquiry approach reinterpreted Karen and Mike’s matter tracing claims as causal claims—claims about what plants need to grow. Given this interpretation, these students didn’t see a need to choose between Karen and Mike—they could both be right. They didn’t see much of a point in the data that Karen collected; they already knew from experience that plants needed air. They liked Mike’s experiment, interpreting it as truly showing that fertilizer helps plants grow. Rather than testing models, these students looked for verification of what is already known or expected.
- *Naïve Engineering:* Students taking a Naïve Engineering approach reinterpreted the claims in yet another way; as claims about what works to make plants grow. They liked Mike’s experiment, since it showed that plants grow better with fertilizer. They didn’t see much point in Karen’s experiment: “How can you make a claim about air if you aren’t even changing the air?”
- *School Science Inquiry:* Students taking a School Science perspective separated the claims from their critique of the evidence. They decided whether the claims were right or wrong based on their understanding of the correct scientific answer (often favoring Mike). Their critique of the evidence, though, was not based on whether it supported the claims; instead they described how Karen and Mike had deviated from the “right way” to do an investigation: How many plants, what variables to control, how many measurements, etc.

Conclusion

We began this study with the goal of developing a learning progression for inquiry and argumentation about carbon-transforming processes. At this point we have learned a lot, but have not achieved that goal. We feel relatively comfortable with our definition of the goal for environmentally literate students: the two types of arguments from evidence that we describe are attainable by students and are well-established strategies for building scientific knowledge and managing uncertainty. We have also identified three alternate strategies, but we have not been successful in meeting our expectation that we would arrange them hierarchically, from the least to the most sophisticated. Rather, they represent three alternate approaches to learning from experience about the world, each useful in its own context but limited in critical ways. We conclude with some thoughts about possible implications for teachers and for curriculum development.

Implications for teaching. We think that some of the alternative conceptions of the purpose of investigations could be related to the way that inquiry is conducted in the classroom, and that our framework connects with other studies of teacher practices. Many teachers define inquiry as "science process skills" and focus on the practice of inquiry removed from a science content context (Lehrer et al. 2007, Lehrer & Kim 2009, Wilson et al. 2010). In these situations inquiry is a classroom activity performed for its own sake rather than to develop or critique arguments from evidence. Other researchers have described teacher practice about inquiry as disconnected from content. Talanquer et al. (2013) described how pre-service teachers pay attention to students' demonstration of science process skills, and much less attention to the student's analysis of "epistemological validity" or scientific plausibility of student's ideas. Windschitl et al (2004) showed that pre-service teachers predominantly design inquiry that is relation-based reasoning (Driver et al., 1996) where the focus is on correlating variables or finding linear causal sequence, rather than model-based reasoning to test or develop a model or theory. These teachers were focused on the activities (means) rather than the ends of argumentation.

We think that these studies indicate how a "School Science Inquiry" framework has become a dominant practice for high school and undergraduate students. The NRC's *Framework* (2012) also supports this idea: "when such procedures [scientific method] are taught in isolation from science content, they become the aims of instruction in and of themselves rather than a means of developing a deeper understanding of the concepts and purposes of science" (p. 43). Our study also highlights the importance of providing supports for teachers to engage in inquiry activities in the classroom that connect the investigation to student reasoning about a scientific concept.

Implications for curriculum development. We are using the findings in this paper as a basis for revisions in teaching units that make the investigations more *robust* and *meaningful* to students and that improve their ability to identify and mitigate sources of uncertainty in their evidence and conclusions. We define productive inquiry in classroom as robust, meaningful to student and connected to accounts. *Robust* means that the investigation protocols produce reliable and predictable results when carried out by middle school or high school students. *Meaningfulness* is about: when students are doing investigations in the classroom, what is meaningful to them? They may be "going through the motions" without engagement, or there might be missing knowledge that impedes the student from making sense of the experiment. For example, some students may not see weight as evidence that atoms have moved from one location to another. *Connected to accounts* means that the investigation in the classroom is explicitly linked to content via student explanations of a phenomenon.

Our analyses of teaching data from 2011-2012 (Kim et al., 2013) indicate that most teachers enjoy the investigations in our carbon teaching units and feel that they are valuable to students. However, our analyses of student data from 2011-2012 suggest that for many students the investigations are NOT meeting our criteria of robustness, meaningfulness to students, and connection to accounts. For the second iteration of our carbon-transforming curriculum in 2012-2013 we improved robustness by simplifying the experiments and after performing the experiment multiple times ourselves, refined the classroom tools and instructions. We improved meaningfulness by creating "rules" that students must apply to the investigation:

- **Atoms last forever** in combustion and living systems, and all materials (solids, liquids, and gases) are made of atoms

- Carbon atoms are bound to other atoms in molecules, and **atoms can be rearranged to make new molecules**
- **Energy lasts forever** in combustion and living systems, and C-C and C-H bonds have more stored chemical energy than C-O and H-O bonds

These rules arose from our research on student learning that revealed student difficulty understanding that gases have mass, that when mass changes that means atoms have moves, and difficulty applying the laws of conservation of matter and energy. Finally, we improved connection to accounts by giving students a "Three Question" framework for interpretation of the investigation where students must answer:

- **The Location/Movement Question: Where are atoms moving?** Where are atoms moving from? Where are atoms going to?
- **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?
- **The Energy Question: What is happening to chemical energy?** What forms of energy are involved? How is energy changing from one form to another?

These Three Questions are explicitly linked to the investigation. Some questions can be answered at a macroscopic scale, but others must be answered at an atomic-molecular scale. To answer the first question students must measure changes in mass using a scale. To partially answer the second question students measure the production or draw-down of carbon dioxide using BTB. But the investigation does not tell us where those carbon atoms originate, so to complete the question we must use molecular models. To partially answer the third question students can observe some forms of energy during the investigation: light, heat energy and motion. But to fully answer the third question students must discuss chemical energy, which can be discovered based on the atomic-molecular level using molecular models.

In conclusion, our future research we will continue to improve our framework for inquiry about carbon-transforming processes and refine our ideas with addition interviews about investigations of carbon-transforming processes. Additionally, we will create assessments to test the effectiveness of our curriculum in terms of student inquiry practices about carbon-transforming processes. Understanding student practices within a specific conceptual domain is useful for uncovering student difficulties in context. We will use this work to continue to develop teaching and learning materials to improve student inquiry practices.

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Appendix A. Plant Data Interview Protocol

Written Portion:

A student has 6 plants growing in pots. A student predicted that the weight of the plants in the pots would increase while the plants are growing.

The student collected the following data:

Weight of the container with the plant **Before (g)**	Weight of the container with the plant **After (g)**	**Change** in weight of the container with the plant (g)
5.23	5.45	+0.22
5.03	4.82	-0.21
4.77	5.96	+1.19
5.16	5.29	+0.13
4.87	4.77	-0.10
5.12	5.08	-0.04
Average: 5.03 g	**Average: 5.23 g**	**Average: + 0.20 g**

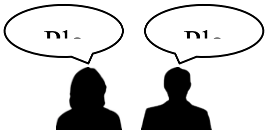
Do the data support OR not support the prediction of the student?

Why or why not?

Interview Portion:

1. Explain your answers to the written portion.
2. Are their certain lines of data that support the claim, and others that do not?
3. What are possible sources of error in the experiment?
4. Do you have any comments on the quality of the data from this experiment? What is good or bad about these data?

Appendix B. Karen and Mike Interview Protocol

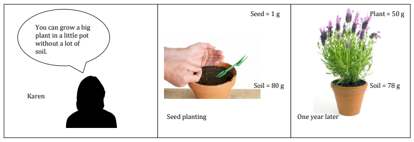


[Show the image of Mike and Karen silhouettes.]

“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.’

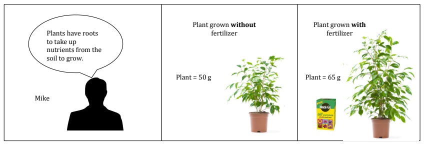
1. *“Who do you think is right?”*

“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 weighted 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 their 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 weighted 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 their some weaknesses in Mike’s argument? Explain what they are.”*
8. *What evidence would strengthen Mike’s argument?*