Educator Resource: Students' Learning Progressions for the *Ecosystems* Unit

The *Carbon TIME* curriculum is based on learning progression research. Learning progressions are descriptions of the informal and then successively more sophisticated (scientific) ways that students reason about phenomena. *Carbon TIME* researchers have investigated how students understand and learn to make sense of carbon-transforming processes. You will find many of our publications and presentations under the Research Tab on the *Carbon TIME* website. (See, for example, Learning Progressions and Climate Change, by Joyce Parker, et al.)

Focus of the Ecosystems Unit: Carbon Cycling and Energy Flow

The ecology-related performance expectations in the *Next Generation Science Standards* are organized around two major strands in the discipline of ecology:

1. *Ecosystem science:* studying how matter and energy are transformed in ecosystems
2. *Community ecology:* studying adaptations, relationships among populations, niches, habitats, changes in populations over time

The *Ecosystems* unit focuses on the first strand: ecosystem science. This is important to realize because many middle- and high-school students have lots of ecological knowledge and ideas, but mostly around the second strand—community ecology. (Nature films and documentaries, for example, focus mostly on content related to community ecology.)

So, a major challenge in the *Ecosystems* unit is to help students analyze ecosystems not only as communities of plants, animals, and decomposers, but also as *systems* that transform matter and energy. Here, we offer a brief overview of the specific learning challenges that your students are likely to face. We focus on students' practices associated with their roles as questioners, investigators, and explainers, as explained in the *Carbon TIME* Instructional Model.

Students as Questioners

Some students are curious about ecosystems and have lots of questions, other students less so. But even curious students must learn how to ask productive questions that focus on matter cycling and energy flow. Students' questions play an essential role as they work on the Expressing Ideas and Questions Tool and the Evidence-based Arguments Tool.

The Expressing Ideas and Questions Tool asks students for their questions, and consensus questions are an important outcome for this discourse routine. These questions will drive later activities and discussions. However, you may find that students' initial questions focus more on community ecology—relationships among different kinds of plants and animals. These are useful and important questions, but they don't always lead toward ecosystem science.

The most productive questions for the unit ask about *connecting scales* (e.g., How does the ecosystem enable all the individual plants and animals to live and grow?) and about *tracing matter and energy* (e.g., Where does the foxes' matter and energy come from?). Though you do not want to discourage students' community ecology questions, there are ways to help students identify productive questions on connecting scales and tracing matter and energy. For example:

- You can ask students to connect what they know about food webs and food chains with what they know about matter and energy: What is the "food" in food chains? Why do all the organisms in the food chain need it?

- You can remind students about what they have learned about how different organisms acquire and use food: What do the rabbits get from the grass that enables them to grow and move? What do the foxes get from the rabbits?
- You can ask students to remember what they have learned about different kinds of organisms in the *Animals, Plants,* and/or *Decomposers* units and what the implications are for organisms' roles in ecosystems? How are plants different from animals and decomposers? What might mean for the role of plants in ecosystems?

Later in the unit, students completing the Evidence-based Arguments Tool generally need help identifying questions that result from limitations in their investigations and results. For example, the investigation provides evidence about the organic matter pyramid: In the end there is always more grass than rabbits and more rabbits than foxes.

Some students may recognize this pattern as "the 10% rule:" organic matter at each trophic level is about 10% of the organic matter at the level below. But the 10% rule doesn't explain *why* organic matter is smaller at higher trophic levels. When students ask why, they are ready to connect this pattern with what they have learned about how organisms use and change matter and energy.

Students as Investigators

In *Carbon TIME'*s macroscopic-scale units (*Systems and Scale, Animals, Plants,* and *Decomposers*) students can use tools such as balances and BTB to trace movement of matter and energy directly, with real organisms. This is much more difficult for the large-scale units, *Ecosystems* and *Human Energy Systems.* The systems are too big for students to study directly and detect patterns associated with the movement of matter and energy. Therefore, the investigation for *Ecosystems* relies on the online Meadow Simulation, where students can manipulate populations of grass, rabbits, and foxes to see how they change over time.

Students are naturally inclined to pursue "engineering investigations" in which they seek to control the system, making it do what they want. And they start with an engineering challenge: Finding the initial conditions that will maximize the fox population after 100 years. They may be frustrated that no matter what they do, they can never produce a fox organic matter of more than 9 or units.

So, students become better investigators when they recognize that their frustration reveals a basic pattern in data about the system—what we call the organic matter pyramid. Furthermore, recognizing that pattern leads to an important question that drives the rest of the unit: *Why* does the fox organic matter eventually become much smaller than the rabbit and grass organic matteres? They can answer this question by tracing matter and energy through the ecosystem.

Students as Explainers

Our learning progression research shows three levels as students become more scientifically sophisticated in their explanations. Almost all students start the unit with lower-level or middle-level explanations. The *Ecosystems* unit goals—and NGSS performance expectations—require high-level explanations.

Lower-level explanations based on nature stories. Many middle-school and high-school students answer questions about ecosystems in ways that have nothing to do with matter cycling and energy flow. Instead they provide what could be called "nature story" explanations focusing on actions and relationships among different kinds of plants and animals.

You will be familiar with these stories; they are common in nature documentaries and other media. For example, consider *March of the Penguins,* which focuses on how emperor penguins walk up to 70 miles from the edge of Antarctic pack ice to their inland nesting sites.

This raises interesting questions about matter and energy: For example, how do the penguins store and use the matter and energy they need to survive for months without eating, while laying eggs and feeding chicks? But that's not the story that *March of the Penguins* tells. Here's the beginning of the story:

> *So, in some ways this is a story of survival. A tale of life over death. But it's more than that, really. This is a story about love. Like most love stories, it begins with an act of utter foolishness. The emperor penguin is technically a bird although one that makes his home in the sea. So, if you're wondering what he's doing up here on the ice, well, that's part of our story.*

There is nothing wrong with this story, and we're glad if students learn to tell it. However, if this is the *only* story that students can tell, then their ability to analyze and explain ecosystems is limited. In particular, it's important for students to also tell stories that trace matter and energy.

Middle-level explanations based on nutrient and oxygen-carbon dioxide cycles. Lower-level explanations of ecosystems include ideas about "the cycle of life" (e.g., *The Lion King*), but these explanations focus on how organisms help one another in their life cycles rather than on matter and energy.

Middle-level explanations recognize that organisms pass matter and energy through food chains and food webs, and the decomposition recycles nutrients, but as Figure 1 shows, their notions of cycling are different from scientifically acceptable accounts.

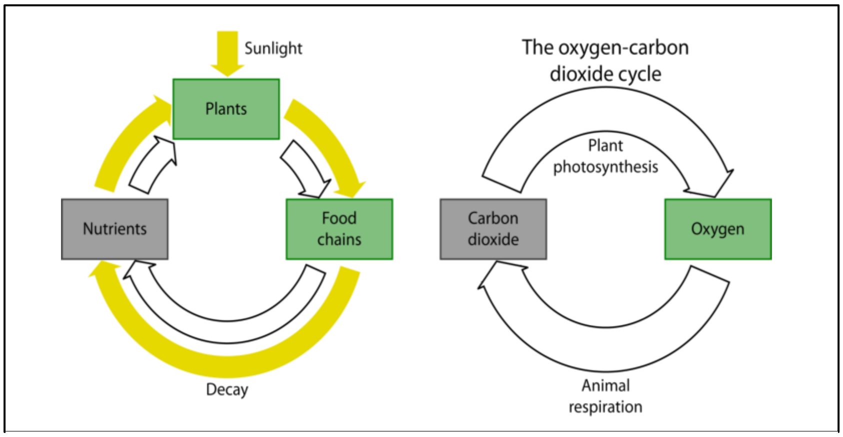

Figure 1: Middle level--separate nutrient and O_2-CO_2 cycles.

Middle-level explanations involve two separate cycles:

- The nutrient cycle, in which matter and energy move together through food chains, and both matter and energy are recycled when decay releases soil nutrients.
- The oxygen-carbon dioxide cycle, in which animals breathe in oxygen and breathe out carbon dioxide while plants do the opposite.

These separate cycles make a lot of intuitive sense. It makes sense, for example, to say that plants and animal can exchange one colorless, odorless gas for another (while it seems crazy that huge trees could get their mass mostly from the air). It makes sense that if soil nutrients help plants grow lush and vigorous, then they must be supplying the plants with energy. Unfortunately, these intuitive ideas are not scientifically correct.

Goal-level explanations based on pool-and-flux models of matter cycling and energy flow. Our goal is that students learn to explain patterns such as the organic matter pyramid using *carbon fluxes* that move materials from one *carbon pool* to another. Carbon fluxes depend on processes, such as photosynthesis and cellular respiration, that take place inside individual organisms. They involve physical movement and chemical changes in matter, driven by changes in energy. Students study the carbon pools and fluxes shown in Figure 2 below.

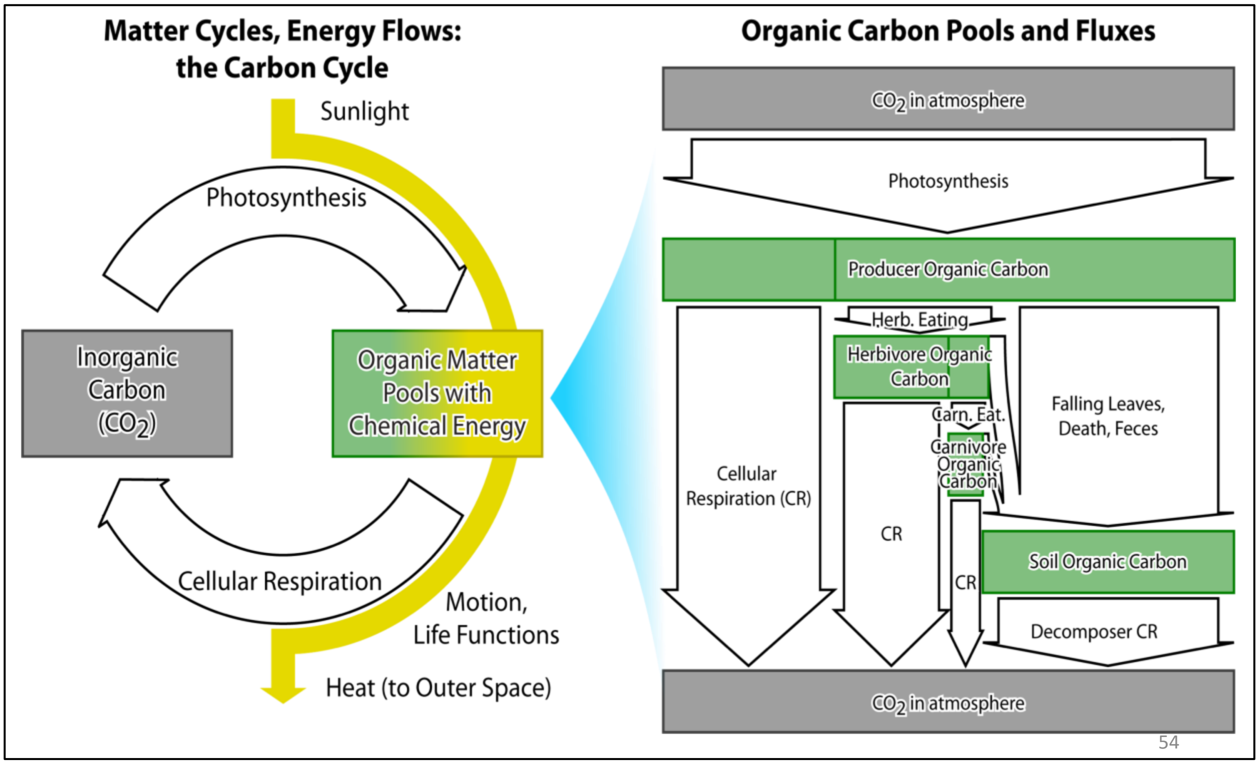

Figure 2: Carbon cycling and energy flow in terrestrial ecosystems

The left side of Figure 2 shows the general pattern of carbon cycling and energy flow in all ecosystems:

- There are two big carbon pools: Carbon dioxide in the air and organic matter in living and dead organisms.
- There are two big carbon fluxes: Photosynthesis changes carbon dioxide and water into organic carbon and oxygen; cellular respiration completes the cycle, turning organic carbon and oxygen back into carbon dioxide and water.
- Energy flows through the ecosystem: Sunlight is converted into chemical energy in organic matter, which is released through cellular respiration, ultimately becoming heat that the Earth radiates into outer space.

The right side of Figure 3 shows details of pools and fluxes inside the large organic matter pool. Food chains and food webs are a part of this story, but not the whole story. (Note that the organic matter pyramid is in the middle of the right side: producer organic carbon, herbivore organic carbon, and carnivore organic carbon.) Plants use the organic materials that they create with photosynthesis for growth and energy (cellular respiration). The materials in plant bodies move to other pools when the plants are eaten or when dead plant materials become detritus in the soil. Ultimately organic materials are oxidized to carbon dioxide and water through cellular respiration in plants, animals, and decomposers.[1]

The activities and tools in Lessons 3, 4, and 5 are all designed to scaffold the students' explanations as they make the difficult progression from lower-level to goal-level explanations. They apply these explanations to a variety of different ecosystems and explain how seasons, human management, and disturbances affect carbon cycling and energy flow.

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[1] Some soil carbon can remain in the soil for a very long time, ultimately becoming fossil fuels. These processes are discussed in the *Human Energy Systems* Unit.