Educator Resource: Students' Learning Progressions for the *Human Energy Systems* 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 Human Energy Systems Unit: Climate Change and Carbon Cycling

The performance expectations in the *Next Generation Science Standards* for this unit are organized around two big ideas in Earth systems science. The unit has two phases, each focusing on one of these big ideas:

1. *What is happening to the planet? Investigating and explaining climate change.* In this phase students question, investigate, and explain four phenomena associated with climate change: Arctic sea ice, global sea levels, global average temperatures, and atmospheric CO_2 concentrations.
    a. They investigate different data representations to conclude that each of these variables has been changing over the last 50 years.
    b. They study the Greenhouse effect and use it to explain the connections among the long-term trends: Increasing CO_2 levels are causing increases in global temperatures through the mechanism of the greenhouse effect; the increasing temperatures are causing sea level to rise and ice to melt. Thus, atmospheric CO_2 is the driver—the factor that causes change in the other variables.
2. *What causes changes in atmospheric CO_2? Explaining and predicting global carbon cycling.* In this phase students investigate and explain "what drives the driver"—what is causing changes in atmospheric CO_2 levels.
    a. Students use three different kinds of pool-and-flux models to explain two patterns of change in CO_2 concentrations: (a) an annual cycle caused by changing balances between carbon fluxes associated with photosynthesis and cellular respiration, and (b) a long-term upward trend caused primarily by the unbalanced flux from combustion of fossil fuels.
    b. They explore how human activities, including their own lifestyles, depend on combustion of fossil fuels—often in hidden ways.
    c. They make projections for how different scenarios will affect global temperatures as atmospheric CO_2 concentrations rise.

So, a major challenge in the *Human Energy Systems* unit is to help students analyze Earth systems 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 (a) discuss important prior learning from other *Carbon TIME* units and (b) learning challenges for each phase of *Human Energy Systems,* focusing on students' practices associated with their roles as questioners, investigators, and explainers, as explained in the *Carbon TIME* Instructional Model.

Learning from Prior Carbon TIME Units

The *Human Energy Systems* unit is the culminating unit in the *Carbon TIME* unit sequence. It relies on student mastery of some key ideas and practices from previous units. Educator resources describing key findings from our learning progression research are available for each unit: *Systems and Scale*, *Animals*, *Plants*, *Decomposers*, and *Ecosystems*. Briefly, we have found that most middle- and high-school students have well-developed ideas about how things burn and about how organisms engage in life processes—growing, breathing, eating, moving, dying, decaying—that do NOT focus on transformations of matter and energy; they focus instead on organisms as actors who are able to engage in life processes when their needs are met.

Based on this research, the first four units focus on how macroscopic scale systems (flames, animals, plants, and decomposers) transform matter and energy. They learn to trace matter and energy through these systems by connecting their macroscopic-scale observations of these systems to carbon-transforming processes that occur on the atomic-molecular scale. Three key processes are responsible for the global carbon fluxes that students study in *Human Energy Systems:* combustion, cellular respiration, and photosynthesis. The unit posttests for these units provide three-dimensional assessments that elicit students' understanding of these processes. We can also suggest two specific activities from these earlier units that you can use to review key ideas with your students and assess their understanding:

- You can use the Comparing Animals and Flames Worksheet from Activity 6.2 of the *Animals* unit to check on students' understanding of combustion and cellular respiration as processes that oxidize organic carbon.
- You can use the Comparing a Growing Tree and a Growing Child Worksheet from Activity 6.3 of the *Plants* unit to check on students' understanding of photosynthesis and cellular respiration as reverse processes: photosynthesis creates organic carbon materials from inorganic CO_2 and water; cellular respiration oxidizes organic carbon materials into inorganic CO_2 and water.

There are two large scale units in the Carbon TIME unit sequence: *Ecosystems* followed by *Human Energy Systems*.. The *Ecosystems* unit provides students with two kinds of experiences that are particularly helpful as preparation for *Human Energy Systems.*

- *Connecting systems at different scales:* Activities such as the Carbon Dice Game help students see how individual organisms engaging in life processes—growing, breathing, eating, moving, dying, decaying—are responsible for carbon cycling and energy flowing through ecosystems
- *Quantitative modeling of carbon pools and fluxes:* Lesson 4 introduces students to pool-and-flux models as a way to explain how ecosystems change over time. If students have not previously completed the *Ecosystems Unit*, consider having them complete the simpler version of Tiny World Modeling in *Ecosystems Unit* Activity 4.1 before completing *Human Energy Systems Unit* Activity 4.3 which adds the fossil fuel pool and the combustion flux.

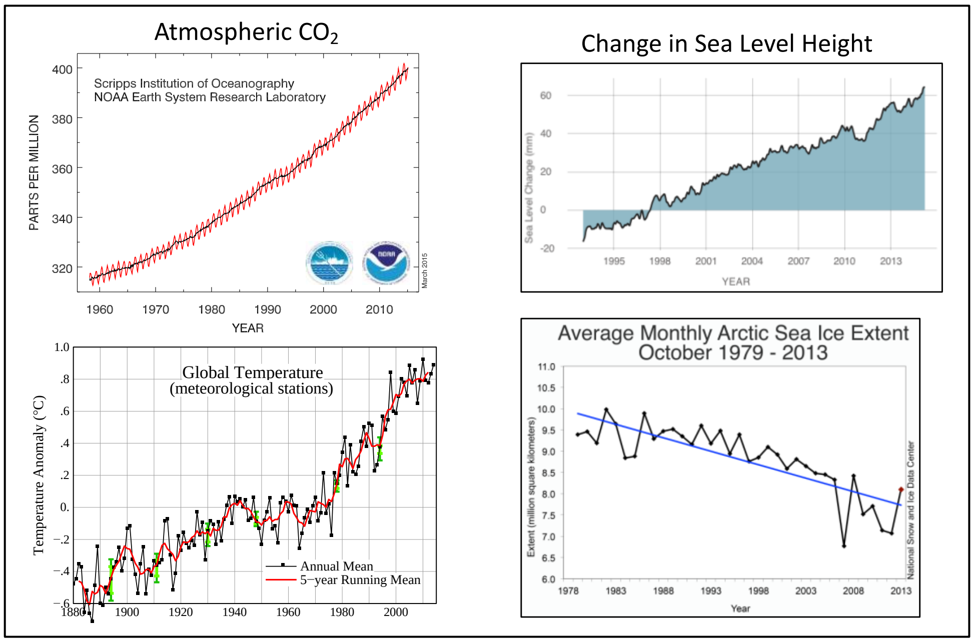
Phase 1: What is happening to the planet? Investigating and explaining climate change

In the first phase of *Human Energy Systems* students study how Earth systems are changing and how CO_2 and other greenhouse gases are driving those changes. This poses important challenges for students in each of their learning roles. As questioners and investigators students need to interpret and analyze data about changes in Earth systems. As explainers they need to make sense of how greenhouse gases cause the other changes.

Questioning and investigating Earth systems data representations

Other *Carbon TIME* units focus on systems and phenomena that students can *see:* flames, organisms, ecosystems such as farms and forests. In contrast, during Lessons 1 and 2 of *Human Energy Systems* students question and investigate changes in global systems—changes occurring at large spatial and temporal scales. Students' personal experiences and the media give them familiarity with local conditions and short-term variability, and they have some notions of "normal" conditions for a time and place that often aren't quantified or represented in weather reports.

But when we try to represent changes in Earth systems, we're dealing with how "normal" is changing over time and distributed across space. The representations we use to show this (e.g., graphs, maps, diagrams, false-color maps and animations) are unfamiliar to students and related in complicated ways to their experiences of local conditions and short-term variability.



In Lessons 1 and 2 students investigate multiple representations of data about four global phenomena, comparing the representations to look for patterns in the data. The data show four long-term trends:

- The extent of Arctic sea ice is decreasing
- Sea levels are rising
- Global average temperatures are rising
- Global concentrations of CO_2 are rising

Students working with these data representations encounter four interconnected issues:

1. *Representation*: Students see many different representations of data about Earth systems. For example, in Activities 2.2 and 2.3 students see (a) animations of satellite data showing maps that change over time, (b) tables with numerical representations of sea ice extent, and (c) graphs showing patterns and trends. Students need to recognize that even though they look different, these are all representations of the same phenomena. They also need to recognize that the same variables (e.g., time, location, temperature, CO_2 concentration) are represented in different ways, and that there are different choices about which data to represent from a larger data set.
2. *Generalizability*: Data about Earth systems are usually selected to be representative of patterns in systems, but the relationship between the patterns in the representation and the patterns in the Earth systems can be difficult and confusing. For example, the graphs of CO_2 concentrations show measurements taken in a single location—Moana Loa in Hawaii. How are patterns in these data connected to data from other places, such as Michigan or Antarctica? Other representations make other choices about time scale and geographic location, or show averages rather than data points from a single time and place.

3. *Short-term variability:* The data sets that student look at show two different patterns in short-term variability:
    a. The Arctic sea ice, temperature, and sea level data show random variation from one year to the next; there is no good way to predict whether these variables will go up or down in the next year, or how much. Most humans are very good at inferring patterns, even when they don't really exist (this is why games of chance are so popular). So students need to recognize randomness and understand how it limits our ability to make claims about short-term patterns or predictions of how these data will change in the next year.
    b. In contrast, the Moana Loa CO_2 data show a regular seasonal pattern. Students need to be able to recognize and analyze this pattern, and to expect that there *should* be an explanation for this pattern. (They will study the explanation for this seasonal cycle in Lesson 4.)
4. *Long-term trends:* The other Earth systems are like Arctic sea ice in that they show clear trends over longer periods of time (though in the opposite direction—as Arctic sea ice goes down, temperature, sea level, and CO_2 concentrations are all going up). Students need to use strategies they studied in Lesson 1 to identify these long-term trends.

Explaining patterns in Earth systems data

Students need to recognize that random patterns in short-term variability are very difficult or impossible to explain, but that good explanations for long-term trends are often possible. Some students will probably suggest that these variables are related, and that they are connected with "climate change" or "global warming." They need to recognize that this kind of explanation—recognizing relationships between variables—is useful, but doesn't go very far. Scientists look to understand *mechanisms:* Which variables are causing the trends, and which are effects? How do those cause-effect relationships work?

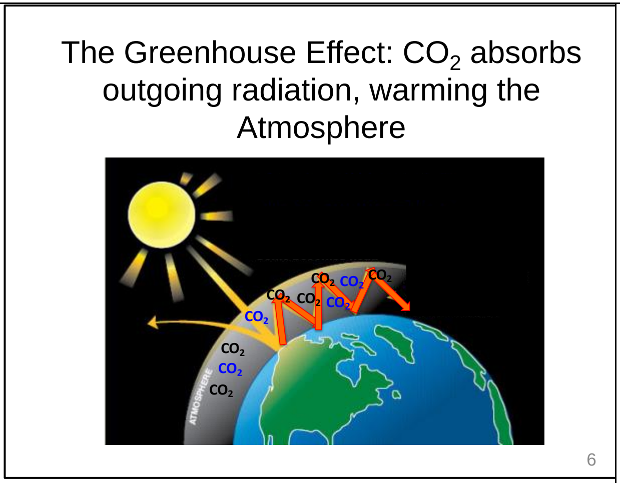
Lesson 3 focuses on how CO_2 and other greenhouse gases affect the Earth's temperature. Your students may be familiar with the metaphor that greenhouse gases act like a blanket to keep the Earth warm. That's not a terrible metaphor, in that both blankets and greenhouse gases slow down heat transfer, but it has significant limitations. The mechanisms are different: blankets reduce heat transfer by reducing convection, while greenhouse gases reduce heat transfer by reducing radiation.

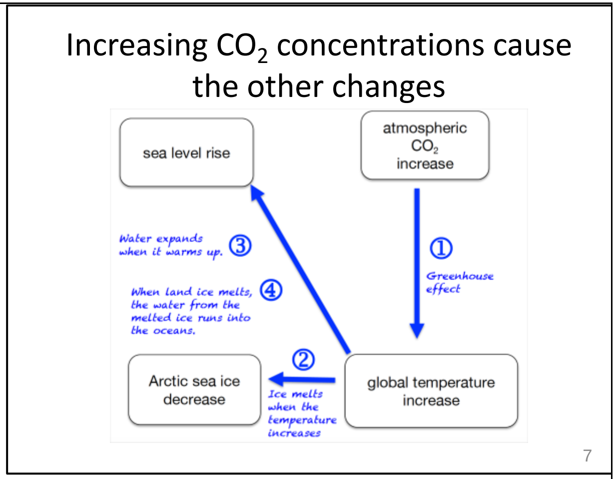
More importantly, a key goal for the *Human Energy Systems* unit is to help students explain changes by tracing pools and fluxes of energy and matter. Lessons 4 and 5 focus on matter; Lesson 3 focuses on energy. Students need to understand that the Earth's temperature depends on the balance between two different energy fluxes:

- The sun's radiation coming in (mostly in the form of visible light)
- Infrared radiation going out (mostly in the form of infrared light)

During a typical day there is more radiation coming in, so the Earth's pool of thermal energy gets larger and the temperature rises. During a typical night there is more radiation going out, so the Earth's pool of thermal energy gets smaller and the temperature falls. Greenhouse gases have their effects because they absorb infrared but not visible light, so they slow down only the outgoing energy flux, causing the Earth's temperature to gradually rise.

Students can use the Greenhouse effect to explain the connections among the long-term trends: Increasing CO_2 levels are causing increases in global temperatures; the increasing temperatures are causing sea level to rise and ice to melt. Thus, atmospheric CO_2 is the driver—the factor that causes change in the other variables.





Phase 2: What causes changes in atmospheric CO_2? Explaining and predicting global carbon cycling

In the second half of the unit students use pool-and-flux models to investigate and explain "what drives the driver"—what is causing changes in atmospheric CO_2 concentrations. They also investigate how human actions contribute to the key unbalanced flux in global carbon cycling, from combustion of fossil fuels. Finally, they model how different scenarios could affect future atmospheric CO_2 concentrations and global temperatures.

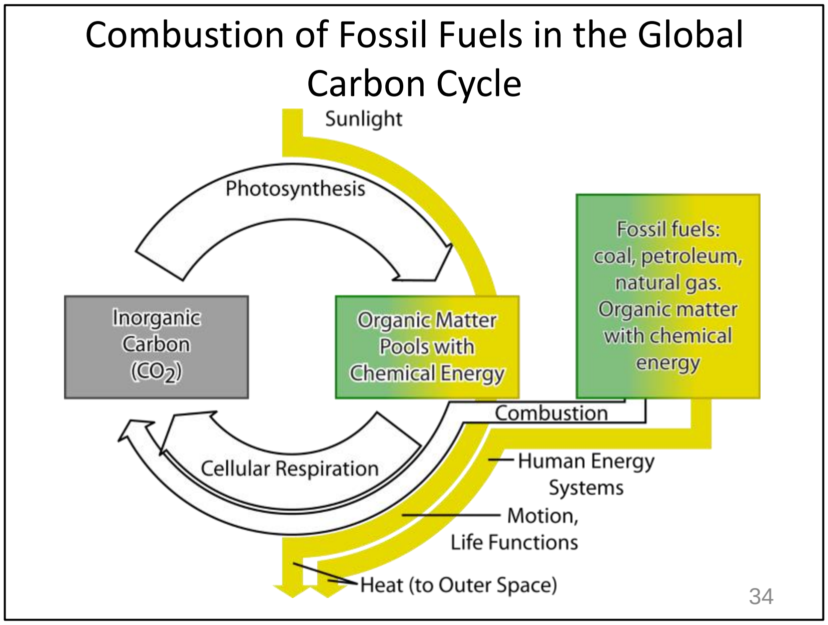
Understanding how the Keeling Curve represents patterns in the Earth's atmosphere. The Keeling Curve is often presented as easily interpretable evidence that the concentration of CO_2 in the Earth's atmosphere is increasing, but our research shows that interpreting this graph presents many challenges for students. In particular:

- The variable measured—concentration of CO_2 in parts per million—is not easy for students to understand.
- It is not at all clear to students how measurements of CO_2 concentration on a mountain in Hawaii might be related to CO_2 concentrations in other parts of the world. The Pumphandle Video, introduced to students in Lesson 2, shows the complex relationships among measures of CO_2 concentration taken at different locations on Earth.

Explaining patterns of change in CO_2 concentrations. We assume that students studying this unit will be familiar with carbon-transforming processes (photosynthesis, cellular respiration, combustion, digestion, biosynthesis) in individual plants and possibly animals and decomposers. In Lesson 4 they consider how these processes affect carbon pools on a global scale.

There are two patterns evident in the Keeling Curve: an annual cycle caused primarily by changing rates of photosynthesis in the Northern Hemisphere and a long-term increase caused primarily by burning of fossil fuels and land-use changes that release carbon from biomass or soil carbon into the atmosphere. This lesson focuses on helping students use *pool-and-flux* models to explain those patterns. There are many fluxes that move carbon into or out of the atmosphere, but most of those are balanced by other fluxes. The flux from fossil fuel combustion, in particular, is not balanced: it moves carbon permanently from the fossil fuel pool into the atmosphere.

However, most students rely on simpler heuristics or rules of thumb rather than pool-and-flux models to explain patterns of change, including *the good vs. bad heuristic* and the *correlation heuristic.*

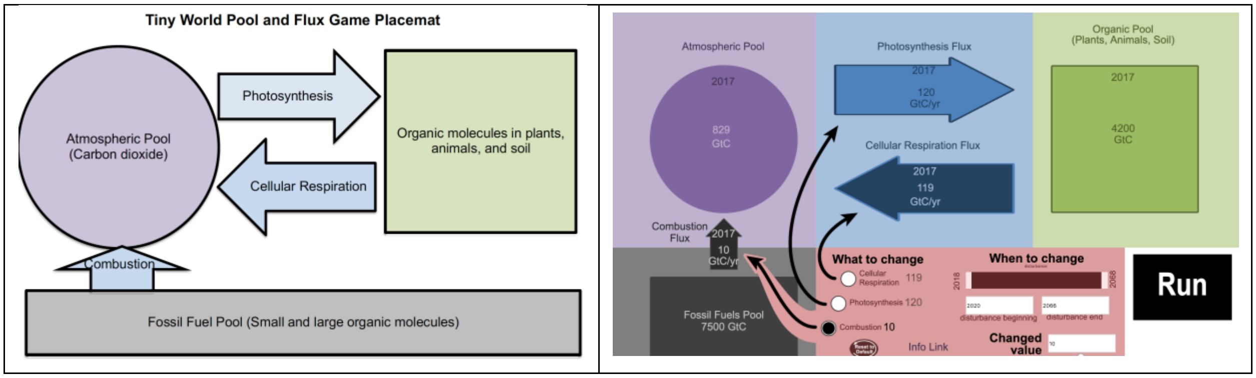


- *Good vs. bad heuristic:* Students use an informal frame that describes things that happen to the environment as good (e.g., less pollution) or bad (e.g., using fossil fuels). For instance, here is a reason that one student gave for cutting fossil fuel use: "*If it cuts down and maintain a low level use, the air will clear up and it will be good for animals and humans to breath clean air."* Students using this heuristic also connect bad actions to bad outcomes: "*[b]ecause I think we've reached a point where we've done too much damage to earth, personally. And I don't think we can come back from that."*
- *Correlation heuristic*: These students often applied the correlation heuristic, conflating changes in flux (slope of the graphed line) with changes in pool size (value on the Y-axis). The following written response reflects this type of thinking: "*fossil fuels help to produce CO_2 so if we cut it in half it would decrease."* Note how this student used "it" twice in the same sentence, perhaps without recognizing that each "it" had a different meaning:
  - …*if we cut it* (CO_2 emissions—the flux arrow) *in half,*
  - *…it* (CO_2 concentration—a measure of the size of the atmospheric CO_2 pool) *would decrease.*

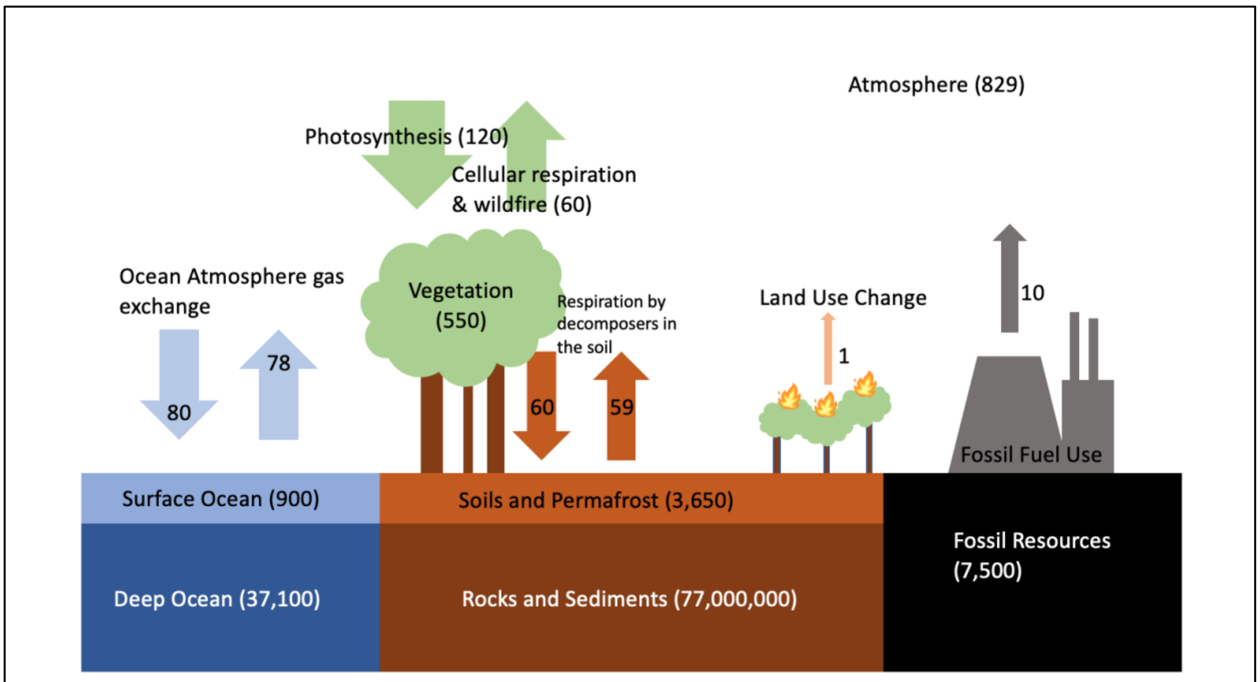
Predicting patterns of change in CO_2 concentrations. The good vs. bad heuristic and the correlation heuristic can be useful for many purposes, helping us to identify environmentally responsible actions and processes that cause climate change. However, these approaches often lead to spurious quantitative reasoning, such as when students conflate a change in flux with a change in pool size: Cutting CO_2 emissions in half does NOT decrease CO_2 concentration in the atmosphere; it merely makes the concentration go more slowly. So in order to make accurate predictions, students must use quantitative reasoning to balance all the CO_2 fluxes into and out of the atmosphere.

Activities 4.3, 4.4, and 4.5 engage students in using the balance of fluxes to make predictions about changes in pool sizes in increasingly sophisticated ways. Students use three different kinds of pool-and-flux models to explain both the annual cycle and the long-term trend in CO_2 concentrations:

- The Tiny World Game (Activity 4.3) is a hands-on activity in which students move counters to investigate the effect of different balances among photosynthesis, cellular respiration, and combustion fluxes on atmospheric, environmental organic carbon, and fossil fuel pools.
- The Global Carbon Model (Activity 4.4) is an online model that students can manipulate to predict how different changes in carbon fluxes will affect carbon pools.



- The Global Carbon Cycling Diagram (Optional Activity 4.5) adds the oceans as another carbon pool. Students make predictions that include carbon fluxes into and out of the oceans using the diagram.



All values in GtC. Carbon pool numbers have (parentheses), and flux numbers are with arrows. Data taken from USDA and U.S. Forest Service

Explaining how human actions affect the fossil fuel CO_2 flux. In Lesson 5 students explore how human activities, including their own lifestyles, depend on combustion of fossil fuels—often in hidden ways. Most students will see that some human actions, such as driving cars or using a gas stove, cause CO_2 to go into the atmosphere. But what about other human actions? Does driving a “zero emissions” electric car contribute to the CO_2 flux? What about making the car? Paving a road? Eating a hamburger? Each of these human actions also contributes to the CO_2 flux, but in more indirect ways.

In Lesson 5 students study the consequences of our lifestyles and the technologies that support them. In particular, they learn to trace how combustion of fossil fuels drives transformations of matter and energy in human technological systems. Students investigate how lifestyles associated with different countries (United States, France, China, and Ethiopia) lead to vastly different rates of fossil fuel combustion. They also examine how their own everyday activities (e.g., buying a pizza, washing dishes) use energy from fossil fuels. In this way they come to appreciate the many ways in which our daily activities and the technological systems that support those activities contribute to the unbalanced CO_2 flux.

The unit concludes with a series of activities in which students make projections of how different scenarios will affect global temperatures and atmospheric CO_2 concentrations. In Lesson 6, they return to the global scale, considering how this unbalanced flux affects other aspects of Earth systems, such as global temperatures, sea level, and Arctic sea ice. They use computer models to map out different scenarios for the future, studying how the future of the planet will depend on humans' activities and decisions. Our goal is to help students see how those models are grounded in the scientific models and principles that they have studied, and to appreciate both the power and the limits of those models.